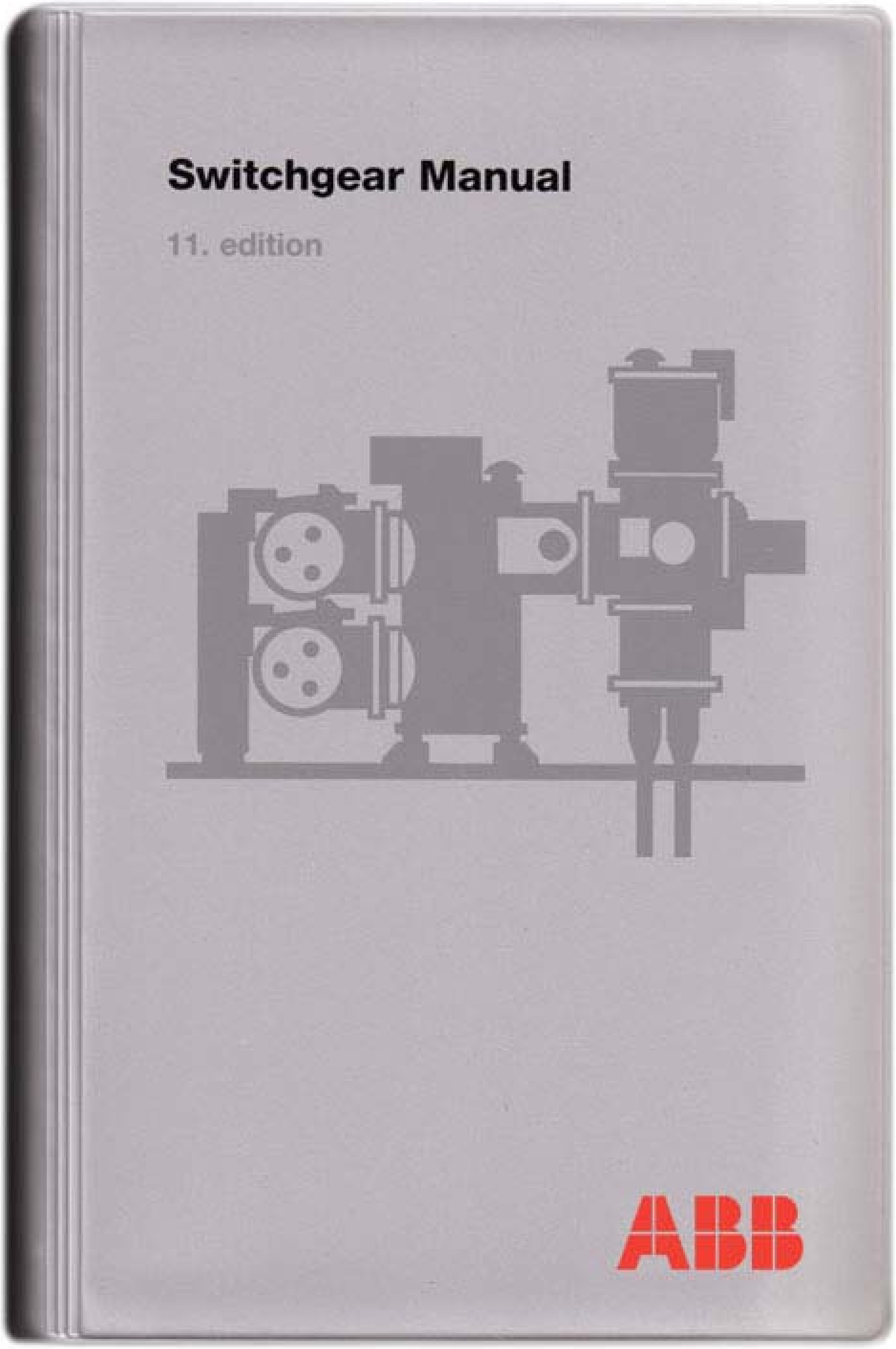
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Table of Contents

1 Fundamental Physical and Technical Terms

1.1 Units of physical quantities

1.1.1 The International System of Units (SI)

The statutory units of measurement are[1)]

1. the basic units of the International System of Units (SI units) for the basic quantities length, mass, time, electric current, thermodynamic temperature and luminous intensity,
2. the units defined for the atomic quantities of quantity of substance, atomic mass and energy,
3. the derived units obtained as products of powers of the basic units and atomic units through multiplication with a defined numerical factor,
4. the decimal multiples and sub-multiples of the units stated under 1-3.

Table 1-1

Basic SI units

Quantity	Units Symbol	Units Name
Length	m	metre
Mass	kg	kilogramme
Time	s	second
Electric current	A	ampere
Thermodynamic temperature	K	kelvin
Luminous intensity	cd	candela
Quantity of substance	mol	mole

Table 1-2
Decimals
Multiples and sub-multiples of units

Decimal power	Prefix	Symbol			
10^{18}	Exa	E	10^{-1}	Dezi	d
10^{15}	Peta	P	10^{-2}	Zenti	c
10^{12}	Tera	T	10^{-3}	Milli	m
10^{9}	Giga	G	10^{-6}	Mikro	µ
10^{6}	Mega	M	10^{-9}	Nano	n
10^{3}	Kilo	k	10^{-12}	Piko	p
10^{2}	Hekto	h	10^{-15}	Femto	f
10^{1}	Deka	da	10^{-18}	Atto	a

[1)]DIN 1301

Table 1-3

List of units

1	*2*	*3*	*4*	*5*	*6*	*7*	*8*
No.	Quantity	SI unit		Other units		Relationship	Remarks
		Name	Symbol	Name	Symbol		
1	**Length, area, volume**						
1.1	Length	metre	m				
1.2	Area	square metre	m^2				
				are	a	$1\ a = 10^2\ m^2$	for land measurement only
				hectare	ha	$1\ ha = 10^4\ m^2$	
1.3	Volume	cubic metre	m^3				
				litre	l	$1\ l = 1\ dm^3 = 10^{-3}\ m^3$	
1.4	Reciprocal length	reciprocal metre	1/m				
				dioptre	dpt	1 dpt = 1/m	only for refractive index of optical systems
1.5	Elongation	metre per metre	m/m				Numerical value of elongation often expressed in per cent

(continued)

Table 1-3 (continued)

List of units

1	*2*	*3*	*4*	*5*	*6*	*7*	*8*
No.	Quantity	SI unit		Other units		Relationship	Remarks
		Name	Symbol	Name	Symbol		
2 Angle							
2.1	Plane angle (angle)	radian	rad			1 rad = 1 m/m	
				full angle		1 full angle = 2 π rad	
				right angle	∟	1∟ = (π/2) rad	
				degree	°	1 ° = (π/180) rad	see DIN 1315
				minute	’	1’ = 1°/60	In calculation the unit rad as a factor can be replaced by numerical 1.
				second	”	1” = 1’/60	
				gon	gon	1 gon = (π/200) rad	
2.2	Solid angle	steradian	sr			1 sr = 1 m^2/m^2	see DIN 1315

(continued)

Table 1-3 (continued)

List of units

1	2	3	4	5	6	7	8
No.	Quantity	SI unit		Other units		Relationship	Remarks
		Name	Symbol	Name	Symbol		
3	**Mass**						
3.1	Mass	kilogramme	kg				Units of mass are also used to designate weight as the result of weighing quantities of goods (DIN 1305)
				gramme	g	1 g $= 10^{-3}$ kg	
				tonne	t	1 t $= 10^{3}$ kg	
				atomic mass unit	u	1 u $= 1.6605655 \cdot 10^{-27}$ kg	
				metric carat	Kt	1 Kt $= 0.2 \cdot 10^{-3}$ kg	only for gems
3.2	Mass per unit length	kilogramme per metre	kg/m				
				Tex	tex	1 tex $= 10^{-6}$ kg/m $= 1$ g/km	only for textile fibres and yarns, see ISO 1144

(continued)

Table 1-3 (continued)

List of units

1	*2*	*3*	*4*	*5*	*6*	*7*	*8*
No.	Quantity	SI unit		Other units		Relationship	Remarks
		Name	Symbol	Name	Symbol		
3.3	Density	kilogramme per cubic metre	kg/m^3				see DIN 1306
3.4	Specific volume	cubic metre per kilogramme	m^3/kg				see DIN 1306
3.5	Mass moment of inertia[1)]	kilogramme-square metre	$kg \cdot m^2$				see DIN 1304-1 and Note to No. 3.5

[1)] See also notes on page 15.

(continued)

Table 1-3 (continued)

List of units

1	*2*	*3*	*4*	*5*	*6*	*7*	*8*
No.	Quantity	SI unit		Other units		Relationship	Remarks
		Name	Symbol	Name	Symbol		
4	**Time**						
4.1	Time	second	s	minute hour day year	min h d a	1 min = 60 s 1 h = 60 min 1 d = 24 h	In the power industry a year is taken as 8760 hours.
4.2	Frequency	hertz	Hz			1 Hz = 1/s	
4.3	Revolutions per second	reciprocal second	1/s	reciprocal minute	1/min	1/min = 1/(60 s)	

(continued)

Table 1-3 (continued)

List of units

1	*2*	*3*	*4*	*5*	*6*	*7*	*8*
No.	Quantity	SI unit		Other units		Relationship	Remarks
		Name	Symbol	Name	Symbol		
4.4	Cyclic frequency	reciprocal second	1/s				The 2π fold of the period frequency is called angular frequency
4.5	Velocity	metre per second	m/s	kilometre per hour	km/h	$1\ \text{km/h} = \frac{1}{3.6}\ \text{m/s}$	
4.6	Acceleration	metre per second squared	m/s^2				
4.7	Angular velocity	radian per second	rad/s				
4.8	Angular acceleration	radian per second square	rad/s^2				

(continued)

Table 1-3 (continued)

List of units

1	2	3	4	5	6	7	8
No.	Quantity	SI unit Name	SI unit Symbol	Other units Name	Other units Symbol	Relationship[1)]	Remarks
5	**Force, energy, power**						
5.1	Force	newton	N			1 N = 1 kg m/s^2	Also called weight see DIN 1305.
5.2	Momentum	newton-second	N · s			1 N · s = 1 · kg m/s	
5.3	Pressure	pascal	Pa			1 Pa = 1 N/m^2	
				bar	bar	1 bar = 10^5 Pa	see DIN 1314

(continued)

Table 1-3 (continued)

List of units

1	*2*	*3*	*4*	*5*	*6*	*7*	*8*
No.	Quantity	SI unit		Other units		Relationship[1)]	Remarks
		Name	Symbol	Name	Symbol		
5.4	Mechanical stress	newton per square metre, pascal	N/m^2, Pa			1 Pa = 1 N/m^2 1 MPa = 1 N/mm^2 1 GPa = 1 kN/mm^2	
5.5	Energy, work, quantity of heat	joule	J			1 J = 1 Nm = 1 Ws = 1 kg m^2/s^2	see DIN 1345
				kilowatt-hour electron volt	kWh eV	1 kWh = 3.6 MJ 1 eV = $1.60219 \cdot 10^{-19}$ J	
5.6	Torque	newton-metre	N · m			1 N · m = 1 J = 1 W · s	
5.7	Angular momentum	newton-second-metre	N · s · m			1 N · s · m = 1 kg · m^2/s	

(continued)

Table 1-3 (continued)

List of units

1	*2*	*3*	*4*	*5*	*6*	*7*	*8*
No.	Quantity	SI unit		Other units		Relationship	Remarks
		Name	Symbol	Name	Symbol		
5.8	Power energy flow, heat flow	watt	W			1 W = 1 J/s =1 N · m/s = 1 V · A	apparent power (V · A) reactive power (var)
6	**Viscometric quantities**						
6.1	Dynamic viscosity	pascal-second	Pa · s			1 Pa · s = 1 N · s/m^2 = 1 kg/(s · m)	see DIN 1342
6.2	Kinematic viscosity	square metre per second	m^2/s				see DIN 1342

(continued)

Table 1-3 (continued)

List of units

1	*2*	*3*	*4*	*5*	*6*	*7*	*8*
No.	Quantity	SI unit		Other units		Relationship	Remarks
		Name	Symbol	Name	Symbol		
7	**Temperature and heat**						
7.1	Temperature[1]	kelvin	K				Thermodynamic temperature; see Note to No. 7.1 and DIN 1345. Kelvin is also the unit for temperature differences and intervals.
				degree Celsius (centigrade)	° C	The degree Celsius is the special name for kelvin when expressing Celsius temperatures.	Expression of Celsius temperatures and Celsius temperature differences, see Note to No 7.1.
7.2	Thermal diffusivity	square metre per second	m^2/s				see DIN 1341
7.3	Entropy, thermal capacity	joule per kelvin	J/K				see DIN 1345
7.4	Thermal conductivity	watt per kelvin-metre	W/(K · m)				see DIN 1341

[1] See also notes on page 15.

(continued)

Table 1-3 (continued)

List of units

1	*2*	*3*	*4*	*5*	*6*	*7*	*8*
No.	Quantity	SI unit		Other units		Relationship	Remarks
		Name	Symbol	Name	Symbol		
7.5	Heat transfer coefficient	watt per kelvin-square metre	$W/(K \cdot m^2)$				see DIN 1341
8	**Electrical and magnetic quantities**						
8.1	Electric current, magnetic potential difference	ampere	A				see DIN 1324
8.2	Electric voltage, electric potential	volt	V			1 V =1 W/A	see DIN 1324
8 3	Electric conductance	siemens	S			1 S = A/V	see Note to columns 3 and 4 and also DIN 1324
8.4	Electric resistance	ohm	Ω			1 Ω = 1/S	see DIN 1324

(continued)

Table 1-3 (continued)

List of units

1	*2*	*3*	*4*	*5*	*6*	*7*	*8*
No.	Quantity	SI unit		Other units		Relationship	Remarks
		Name	Symbol	Name	Symbol		
8.5	Quantity of electricity, electric charge	coulomb	C	ampere-hour	Ah	1 C = 1 A · s 1 A · h = 3600 A · s	see DIN 1324
8.6	Electric capacitance	farad	F			1 F = 1 C/V	see DIN 1304
8.7	Electric flux density	coulomb per square metre	C/m^2				see DIN 1324
8.8	Electric field strength	volt per metre	V/m				see DIN 1324
8.9	Magnetic flux	weber	Wb			1 Wb = 1 V · s	see DIN 1324
8.10	Magnetic flux density, (induction)	tesla	T			1 T = 1 Wb/m^2	see DIN 1324
8.11	Inductance (permeance)	henry	H			1 H = 1 Wb/A	see DIN 1324

(continued)

Table 1-3 (continued)

List of units

1	*2*	*3*	*4*	*5*	*6*	*7*	*8*
No.	Quantity	SI unit		Other units		Relationship	Remarks
		Name	Symbol	Name	Symbol		
8.12	Magnetic field intensity	ampere per metre	A/m				see DIN 1324
9	**Photometric quantities**						
9.1	Luminous intensity	candela	cd				see DIN 5031 Part 3.
9.2	Luminance	candela per square metre	cd/m^2				see DIN 5031 Part 3
9.3	Luminous flux	lumen	lm			1 lm = 1 cd · sr	see DIN 5031 Part 3
9.4	Illumination	lux	lx			$1\ lx = 1\ lm/m^2$	see DIN 5031 Part 3

Notes to Table 1-3

To No. 3.5:

When converting the so-called “flywheel inertia GD^2” into a mass moment of inertia J, note that the numerical value of GD^2 in kp m^2 is equal to four times the numerical value of the mass moment of inertia J in kg m^2.

To No. 7.1:

The (thermodynamic) temperature *(T)*, also known as “absolute temperature”, is the physical quantity on which the laws of thermodynamics are based. For this reason, only this temperature should be used in physical equations. The unit kelvin can also be used to express temperature differences.

Celsius (centigrade) temperature *(t)* *(ϑ)* is the special difference between a given thermodynamic temperature *T* and a temperature of $T_0 = 273.15$ K.

Thus,

$$t = T - T_0 = T - 273.15 \text{ K}. \tag{1}$$

When expressing Celsius temperatures, the standard symbol °C is to be used.

The difference Δt between two Celsius temperatures, e. g. the temperatures $t_1 = T_1 - T_0$ and $t_2 = T_2 - T_0$, is

$$\Delta t = t_1 - t_2 = T_1 - T_2 = \Delta T \tag{2}$$

A temperature difference of this nature is no longer referred to the thermodynamic temperature T_0, and hence is not a Celsius temperature according to the definition of Eq. (1).

However, the difference between two Celsius temperatures may be expressed either in kelvin or in degrees Celsius, in particular when stating a range of temperatures, e. g. (20 ± 2) °C

Thermodynamic temperatures are often expressed as the sum of T_0 and a Celsius temperature *t*, i. e. following Eq. (1)

$$T = T_0 + t \tag{3}$$

and so the relevant Celsius temperatures can be put in the equation straight away. In this case the kelvin unit should also be used for the Celsius temperature (i. e. for the “special thermodynamic temperature difference”). For a Celsius temperature of 20 °C, therefore, one should write the sum temperature as

$$T = T_0 + t = 273.15 \text{ K} + 20 \text{ K} = 293.15 \text{ K} \tag{4}$$

1.1.2 Other units still in common use; metric, British and US measures

Some of the units listed below may be used for a limited transition period and in certain exceptional cases. The statutory requirements vary from country to country.

ångström	Å	length	1 Å = 0.1 nm = 10^{-10}m
Astronomie unit	AE	length	1 AE = 149,59787 · 10^{-9} m
atmosphere physical	atm	pressure	1 atm = 1,01325 bar
atmosphere technical	at, ata	pressure	1 at = 0,980665 bar
barrel	bbl	volume	1 bbl = 158,988 l
British thermal unit	Btu	quantity of heat	1 Btu ≈ 1055.056 J
calorie	cal	quantity of heat	1 cal = 4.1868 J
centigon	c	plane angle	1 c = 1 cgon = 5 π · 10^{-5} rad
degree	deg	temperature difference	1 deg = 1 K
degree fahrenheit	°F	temperature	$T_K = 273.15 + (5/9) \cdot (t_F - 32)$
dyn	dyn	force	1 dyn = 10^{-5} N
erg	erg	energy	1 erg = 10^{-7} J
foot	ft	length	1 ft = 0.3048 m
gallon (UK)	gal (UK)	volume	1 gal (UK) ≈ 4.54609 · 10^{-3} m^3
gallon (US)	gal (US)	liquid volume	1 gal (US) ≈ 3.78541 · 10^{-3} m^3
gauss	G	magnetic flux density	1 G = 10^{-4}T
gilbert	Gb	magnetic potential difference	1 Gb = (10/4 π) A
gon	g	plane angle	1 g = 1 gon = 5 π · 10^{-3} rad
horsepower	hp	power	1 hp ≈ 745.700 W
hundredweight (long)	cwt	mass	1 cwt ≈ 50.8023 kg
inch (inches)	in, "	length	1 in = 25.4 mm = 254 · 10^{-4} m
kilogramme-force, kilopond	kp, kgf	force	1 kp = 9.80665 N ≈ 10 N
knot	kn	time	1 kn = 1 sm/h = 0,5144 m/s
Light-year	lj	lenght	1 Lj = 9,46053 · 10^{15} m = 63240 AE
Unit of mass	ME	mass	1 ME = 9.80665 kg
maxwell	M, Mx	magnetic flux	1 M = 10 nWb = 10^{-8} Wb

metre water column	mWS	pressure	1 mWS = 9806,65 Pa ≈ 98,0665 mbar
micron	µ	length	1 µ = 1 µm = 10^{-6} m
mile	mile	lenght	1 mile = 1609,344 m
millimetres of mercury	mm Hg	pressure	1 mm Hg ≈ 133.322 Pa
milligon	cc	plane angle	1 cc = 0.1 mgon = $5\pi \cdot 10^{-7}$ rad
oersted	Oe	magnetic field strength	1 oe = $(250/\pi)$ A/m ≈ 80 A/m
ounce	oz	mass	1 oz = 28.3495 g
Pferdestärke, cheval-vapeur	PS, CV	power	1 PS = 735.49875 W
Pfund	Pfd	mass	1 Pfd = 0.5 kg
pieze	pz	pressure	1 pz = 1 mPa = 10^{-3} Pa
pint	pt	volume	1 pt = 568,262 ml
poise	P	dynamic viscosity	1 P = 0.1 Pa · s
pond, gram -force	p, gf	force	1 p = $9.80665 \cdot 10^{-3}$ N ≈ 10 mN
pound[1)]	lb	mass	1 lb = 0,45359237 kg
poundal	pdl	force	1 pdl ≈ 0.138255 N
poundforce	lbf	force	1 lbf ≈ 4.44822 N
sea mile, international	sm	length (marine)	1 sm = 1852 m
short hundredweight	sh cwt	mass	1 sh cwt ≈ 45.3592 kg
stilb	sb	luminance	1 sb = 10^4 cd/m^2
stokes	St	kinematic viscosity	1 St = 10^{-4} m^2/s
torr	Torr	pressure	1 Torr = 1.333224 mbar
typographical point	p	length (printing)	1 p = (1.00333/2660) m ≈ 0.4 mm
yard	yd	length	1 yd = 0.9144 m
Zentner	Ztr	mass	1 Ztr = 50 kg

1) UK and US pounds avoirdupois differ only after the sixth decimal place.

Table 1-4

Metric, British and US linear measure

Metric units of length			British and US units of length				
Kilometre	Metre	Millimetre	Mile	Yard	Foot	Inch	Mil
km	m	mm	mile	yd	ft	in or "	mil
1	1 000	1 000 000	0.6213	1 093.7	3 281	39 370	$3\,937 \cdot 10^{4}$
0.001	1	1 000	$0.6213 \cdot 10^{-3}$	1.0937	3.281	39.370	39 370
0.000001	0.001	1	$0.6213 \cdot 10^{-6}$	0.001094	0.003281	0.03937	39.37
1.60953	1 609.53	1 609 528	1	1 760	5 280	63 360	$6\,336 \cdot 10^{4}$
0.000914	0.9143	914.32	$0.5682 \cdot 10^{-3}$	1	3	36	36 000
$0.305 \cdot 10^{-3}$	0.30479	304.79	$0.1894 \cdot 10^{-3}$	0.3333	1	12	12 000
$0.254 \cdot 10^{-4}$	0.02539	25.3997	$0.158 \cdot 10^{-4}$	0.02777	0.0833	1	1 000
$0.254 \cdot 10^{-7}$	$0.254 \cdot 10^{-4}$	0.02539	$0.158 \cdot 10^{-7}$	$0.0277 \cdot 10^{-3}$	$0.0833 \cdot 10^{-3}$	0.001	1

Special measures: 1 metric nautical mile = 1852 m; 1 Brit. or US nautical mile = 1855 m; 1 metric land mile = 7500 m; 1 micron (μ) = 1/1000 mm = 10 000 Å

Table 1-5

Metric, British and US square measure

Metric units of area					British and US units of area				
Square kilometres	Square metre	Square decim.	Square centim.	Square millim.	Square mile	Square yard	Square foot	Square inch	Circular mils
km^2	m^2	dm^2	cm^2	mm^2	sq.mile	sq.yd	sq.ft	sq.in	cir.mils
1	$1 \cdot 10^{6}$	$100 \cdot 10^{6}$	$100 \cdot 10^{8}$	$100 \cdot 10^{10}$	0.386013	$1\,196 \cdot 10^{3}$	$1076 \cdot 10^{4}$	$1\,550 \cdot 10^{6}$	$197.3 \cdot 10^{13}$
$1 \cdot 10^{-6}$	1	100	10 000	1 000 000	$0.386 \cdot 10^{-6}$	1.1959	10.764	1 550	$197.3 \cdot 10^{7}$
$1 \cdot 10^{-8}$	$1 \cdot 10^{-2}$	1	100	10 000	$0.386 \cdot 10^{-8}$	0.01196	0.10764	15.50	$197.3 \cdot 10^{5}$
$1 \cdot 10^{-10}$	$1 \cdot 10^{-4}$	$1 \cdot 10^{-2}$	1	100	$0.386 \cdot 10^{-10}$	$0.1196 \cdot 10^{-3}$	$0.1076 \cdot 10^{-2}$	0.1550	$197.3 \cdot 10^{3}$
$1 \cdot 10^{-12}$	$1 \cdot 10^{-6}$	$1 \cdot 10^{-4}$	$1 \cdot 10^{-2}$	1	$0.386 \cdot 10^{-12}$	$0.1196 \cdot 10^{-5}$	$0.1076 \cdot 10^{-4}$	0.00155	1 973
2.58999	2 589 999	$259 \cdot 10^{6}$	$259 \cdot 10^{8}$	$259 \cdot 10^{10}$	1	$30\,976 \cdot 10^{2}$	$27\,878 \cdot 10^{3}$	$40\,145 \cdot 10^{5}$	$5\,098 \cdot 10^{12}$
$0.8361 \cdot 10^{-6}$	0.836130	83.6130	8 361.307	836 130.7	$0.3228 \cdot 10^{-6}$	1	9	1296	$1\,646 \cdot 10^{6}$
$9.290 \cdot 10^{-8}$	$9.290 \cdot 10^{-2}$	9.29034	929.034	92 903.4	$0.0358 \cdot 10^{-6}$	0.11111	1	144	$183 \cdot 10^{6}$
$6.452 \cdot 10^{-10}$	$6.452 \cdot 10^{-4}$	$6.452 \cdot 10^{-2}$	6.45162	645.162	$0.2396 \cdot 10^{-9}$	$0.7716 \cdot 10^{-3}$	0.006940	1	$1.27 \cdot 10^{6}$
$506.7 \cdot 10^{-18}$	$506.7 \cdot 10^{-12}$	$506.7 \cdot 10^{-10}$	$506.7 \cdot 10^{-8}$	$506.7 \cdot 10^{-6}$	$0.196 \cdot 10^{-15}$	$0.607 \cdot 10^{-9}$	$0.00547 \cdot 10^{-6}$	$0.785 \cdot 10^{-6}$	1

Special measures:

1 hectare (ha) = 100 are (a)
1 are (a) = 100 m^2
1 Bad. morgen = 56 a = 1.38 acre
1 Prussian morgen = 25.53 a = 0.63 acre
1 Wuerttemberg morgen = 31.52 a = 0.78 acre
1 Hesse morgen = 25.0 a = 0.62 acre
1 Tagwerk (Bavaria) = 34.07 a = 0.84 acre
1 sheet of paper = 86 x 61 cm
gives 8 pieces size A4 or 16 pieces A5
or 32 pieces A6

USA:
1 section (sq.mile) = 64 acres = 2,589 km^2
1 acre = 4840 sq.yds = 40.468 a
1 sq. pole = 30.25 sq.yds = 25.29 m^2

Brit.:
1 acre = 160 sq.poles = 4840 sq.yds = 40.468 a
1 yard of land = 30 acres = 1214.05 a
1 mile of land = 640 acres = 2.589 km^2

Table 1-6

Metric, British and US cubic measures

Metric units of volume				British and US units of volume			US liquid measure		
Cubic metre	Cubic decimetre	Cubic centimetre	Cubic millimetre	Cubic yard	Cubic foot	Cubic inch	Gallon	Quart	Pint
m^3	dm^3	cm^3	mm^3	cu.yd	cu.ft	cu.in	gal	quart	pint
1	1 000	$1\,000 \cdot 10^3$	$1\,000 \cdot 10^6$	1.3079	35.32	$61 \cdot 10^3$	264.2	1 056.8	2 113.6
$1 \cdot 10^{-3}$	1	1 000	$1\,000 \cdot 10^3$	$1.3079 \cdot 10^{-3}$	0.03532	61.023	0.2642	1.0568	2.1136
$1 \cdot 10^{-6}$	$1 \cdot 10^{-3}$	1	1 000	$1.3079 \cdot 10^{-6}$	$0.3532 \cdot 10^{-4}$	0.061023	$0.2642 \cdot 10^{-3}$	$1.0568 \cdot 10^{-3}$	$2.1136 \cdot 10^{-3}$
$1 \cdot 10^{-9}$	$1 \cdot 10^{-6}$	$1 \cdot 10^{-3}$	1	$1.3079 \cdot 10^{-9}$	$0.3532 \cdot 10^{-7}$	$0.610 \cdot 10^{-4}$	$0.2642 \cdot 10^{-6}$	$1.0568 \cdot 10^{-6}$	$2.1136 \cdot 10^{-6}$
0.764573	764.573	764 573	$764\,573 \cdot 10^3$	1	27	46 656	202	808	1 616
0.0283170	28.31701	28 317.01	28 317 013	0.037037	1	1 728	7.48224	29.92896	59.85792
$0.1638 \cdot 10^{-4}$	0.0163871	16.38716	16387.16	$0.2143 \cdot 10^{-4}$	$0.5787 \cdot 10^{-3}$	1	0.00433	0.01732	0.03464
$3.785 \cdot 10^{-3}$	3.785442	3 785.442	3 785 442	0.0049457	0.1336797	231	1	4	8
$0.9463 \cdot 10^{-3}$	0.9463605	946.3605	946 360.5	0.0012364	0.0334199	57.75	0.250	1	2
$0.4732 \cdot 10^{-3}$	0.4731802	473.1802	473 180.2	0.0006182	0.0167099	28.875	0.125	0.500	1

Conversion : 1 inch = 0,03937 x l/m

1.1.3 Fundamental physical constants

Universell gas constant: $R = 8.314472\ J\ K^{-1}\ mol^{-1}$
is the work done by one mole of an ideal gas under constant pressure (1013 hPa) when its temperature rises from 0 °C to 1 °C.

Avogadro's constant: N_A (Loschmidt's number N_L): $N_A = 6.0221415 \cdot 10^{23}\ mol^{-1}$
number of molecules of an ideal gas in one mole.

Base of natural logarithms: $e = 2.718282$

Bohr's radius: $a_o = 0.5291772108 \cdot 10^{-10}\ m$
radius of the innermost electron orbit in Bohr's atomic model

Boltzmann's constant: $k = 1.3806505 \cdot 10^{-23}\ J \cdot K^{-1}$
is the mean energy gain of a molecule or atom when heated by 1 K.

Elementary charge: $e_o = F/N_A = 1.60217653 \cdot 10^{-19}\ As$
is the smallest possible charge a charge carrier (e.g. electron or proton) can have.

Electron-volt: $eV = 1.60217653 \cdot 10^{-19}\ J$

Energy mass equivalent: $m_e c^2 = 8.1871047 \cdot 10^{-14}\ J = 0.510998918\ MeV$
according to Einstein, following $E = m \cdot c^2$, the mathematical basis for all observed transformation processes in sub-atomic ranges.

Faraday's constant: $F = 96485.3383\ C \cdot mol^{-1}$
is the quantity of current transported by one mole of univalent ions.

Field constant, electrical: $\varepsilon_0 = 0.885418781762 \cdot 10^{-12}\ F \cdot m^{-1}$
a proportionality factor relating charge density to electric field strength.

Field constant, magnetic: $\mu_0 = 4 \cdot \pi \cdot 10^{-7}\ H \cdot m^{-1}$
a proportionality factor relating magnetic flux density to magnetic field strength.

Gravitational constant: $\gamma = 6.6742 \cdot 10^{-11}\ m^3 \cdot kg^{-1} \cdot s^{-2}$
is the attractive force in N acting between two masses each of 1 kg weight separated by a distance of 1 m.

Velocity of light in vacuo: $c = 2.99792485 \cdot 10^8\ m \cdot s^{-1}$
maximum possible velocity. Speed of propagation of electro-magnetic waves.

Mole volume: $V_m = 22.710981 \cdot 10^{-3} \cdot m^3 \cdot mol^{-1}$
the volume occupied by one mole of an ideal gas at 0 °C and 1013 mbar. A mole is that quantity (mass) of a substance which is numerically equal in grammes to the molecular weight (1 mol H_2 = 2 g H_2)

Planck's constant: $h = 6.6260693 \cdot 10^{-34}\ J \cdot s$
a proportionality factor relating energy and frequency of a light quantum (photon).

Stefan Boltzmann's constant: $\sigma = 5.6704 \cdot 10^{-8}\ W \cdot m^{-2} \cdot K^{-4}$ relates radiant energy to the temperature of a radiant body. Radiation coefficient of a black body.

Temperature of absolute zero: $T_0 = -273.16\ °C = 0\ K$.

Wave impedance of space: $Z_0 = 376.73031346152\ \Omega$
coefficient for the H/E distribution with electromagnetic wave propagation.

$$Z_0 = \sqrt{\mu_0/\varepsilon_0} = \mu_0 \cdot c = 1/(\varepsilon_0 \cdot c)$$

Weston standard cadmium cell: $E_0 = 1.0186\ V$ at 20 °C.

Wien's displacement constant: $b = 2.8977685 \cdot 10^{-3}\ m \cdot K$
enables the temperature of a light source to be calculated from its spectrum.

1.2 Physical, chemical and technical values

1.2.1 Electrochemical series

If different metals are joined together in a manner permitting conduction, and both are wetted by a liquid such as water, acids, etc., an electrolytic cell is formed which gives rise to corrosion. The amount of corrosion increases with the differences in potential. If such conducting joints cannot be avoided, the two metals must be insulated from each other by protective coatings or by constructional means. In outdoor installations, therefore, aluminium/copper connectors or washers of copper-plated aluminium sheet are used to join aluminium and copper, while in dry indoor installations aluminium and copper may be joined without the need for special protective measures.

Table 1-7

Electrochemical series, normal potentials in volts, at 25 °C.

Li/LI^{+}	−3.05	Mn/Mn^{2+}	−1.18	Fe/Fe^{3+}	−0.04
K/K^{+}	−2.93	Zn/Zn^{2+}	−0.76	H_2/H^{+}	0.00
Ba/Ba^{2+}	−2.91	Cr/Cr^{3+}	−0.74	Cu/Cu^{2+}	+ 0.34
Ca/Ca^{2+}	−2.87	Fe/Fe^{2+}	−0.44	Cu/Cu^{+}	+ 0.52
Na/Na^{+}	−2.71	Cd/Cd^{2+}	−0.40	Hg/Hg_2^{2+}	+ 0.79
Mg/Mg^{2+}	−2.37	In/In^{3+}	−0.34	Ag/Ag^{+}	+ 0.80
Be/Be^{2+}	−1.85	Co/Co^{2+}	−0.28	Pd/Pd^{2+}	+ 0.99
Al/Al^{3+}	−1.66	Ni/Ni^{2+}	−0.25	Pt/Pt^{+}	+ 1.20
Ti/Ti^{2+}	−1.63	Sn/Sn^{2+}	−0.14	Au/Au^{3+}	+ 1.50
Zr/Zr^{4+}	−1.53	Pb/Pb^{2+}	−0.13	Au/Au^{+}	+ 1.70

Note: The electrode designation to the left of the slash indicates the electrode material and to the right of the slash to ion layer which forms in front of the electrode surface (dependent on various influences).

If two metals included in this table come into contact, the metal mentioned first will corrode.

The less noble metal becomes the anode and the more noble acts as the cathode. As a result, the less noble metal corrodes and the more noble metal is protected.

Metallic oxides are always less strongly electronegative, i. e. nobler in the electrolytic sense, than the pure metals. Electrolytic potential differences can therefore also occur between metal surfaces which to the engineer appear very little different. Even though the potential differences for cast iron and steel, for example, with clean and rusty surfaces are small, as shown in Table 1-8, under suitable circumstances these small differences can nevertheless give rise to significant direct currents, and hence corrosive attack.

Table 1-8

Standard potentials of different types of iron against hydrogen, in volts			
SM steel, clean surface	approx. −0.40	cast iron, rusty	approx. −0.30
cast iron, clean surface	approx. −0.38	SM steel, rusty	approx. −0.25

1.2.2 Faraday's law

1. The amount m (mass) of the substances deposited or converted at an electrode is proportional to the quantity of electricity $Q = I \cdot t$.

   $$m \sim I \cdot t$$

2. The amounts m (masses) of the substances converted from different electrolytes by equal quantities of electricity $Q = I \cdot t$ behave as their electrochemical equivalent masses M^*. The equivalent mass M^* is the molar mass M divided by the electrochemical valency n (a number). The quantities M and M^* can be stated in g/mol.

   $$m = \frac{M^*}{F} I \cdot t$$

If during electroysis the current I is not constant, the product $I \cdot$ t must be represented by the integral $\int_{t_1}^{t_2} I \, dt$.

The quantity of electricity per mole necessary to deposit or convert the equivalent mass of 1 g/mol of a substance (both by oxidation at the anode and by reduction at the cathode) is equal in magnitude to Faraday's constant (F = 96480 As/mol).

Table 1-9

Electrochemical equivalents[1)]

	Valency n	Equivalent mass[2)] g/mol	Quantity precipitated, theoretical g/Ah	Approximate optimum current efficiency %
Aluminium	3	8.9935	0.33558	85 … 98
Cadmium	2	56.20	2.0970	95 … 95
Caustic potash	1	56.10937	2.0036	95
Caustic soda	1	30.09717	1.49243	95
Chlorine	1	35.453	1.32287	95
Chromium	3	17.332	0.64672	—
Chromium	6	8.666	0.32336	10 … 18
Copper	1	63.54	2.37090	65 … 98
Copper	2	31.77	1.18545	97 … 100
Gold	3	65.6376	2.44884	—
Hydrogen	1	1.00797	0.037610	100
Iron	2	27.9235	1.04190	95 … 100
Iron	3	18.6156	0.69461	—
Lead	2	103.595	3.80543	95 … 100
Magnesium	2	12.156	0.45358	—
Nickel	2	29.355	1.09534	95 … 98
Nickel	3	19.57	0.73022	—
Oxygen	2	7.9997	0.29850	100
Silver	1	107.870	4.02500	98 … 100
Tin	2	59.345	2.21437	70 … 95
Tin	4	29.6725	1.10718	70 … 95
Zinc	2	32.685	1.21959	85 … 93

1) Relative to the carbon-12 isotope = 12.000.

2) Chemical equivalent mass is molar mass/valency in g/mol.

Example:

Copper and iron earthing electrodes connected to each other by way of the neutral conductor form a galvanic cell with a potential difference of about 0.7 V (see Table 1-7). These cells are short-circuited via the neutral conductor. Their internal resistance is determined by the earth resistance of the two earth electrodes. Let us say the sum of all these resistances is 10 Ω. Thus, if the drop in "short-circuit emf" relative to the "open-circuit emf" is estimated to be 50 % approximately, a continuous corrosion current of 35 mA will flow, causing the iron electrode to decompose. In a year this will give an electrolytically active quantity of electricity of

$$35\ \text{mA} \cdot 8760\ \frac{\text{h}}{\text{a}} = 306\ \frac{\text{Ah}}{\text{a}}.$$

Since the equivalent mass of bivalent iron is 27.93 g/mol, the annual loss of weight from the iron electrode will be

$$m = \frac{27.93\ \text{g/mol}}{96480\ \text{As/mol}} \cdot 306\ \text{Ah/a} \cdot \frac{3600\ \text{s}}{\text{h}} = 320\ \text{g/a}.$$

1.2.3 Thermoelectric series

If two wires of two different metals or semiconductors are joined together at their ends and the two junctions are exposed to different temperatures, a thermoelectric current flows in the wire loop (Seebeck effect, thermocouple). Conversely, a temperature difference between the two junctions occurs if an electric current is passed through the wire loop (Peltier effect).

The thermoelectric voltage is the difference between the values, in millivolts, stated in Table 1-10. These relate to a reference wire of platinum and a temperature difference of 100 K.

Table 1-10

Thermoelectric series, values in mV, for platinum as reference and temperature difference of 100 K

Bismut ll axis	−7.7	Rhodium	0.65
Bismut ⊥ axis	−5.2	Silver	0.67 … 0.79
Constantan	−3.37 … −3.4	Copper	0.72 … 0.77
Cobalt	−1.99 … −1.52	Steel (V2A)	0.77
Nickel	−1.94 … −1.2	Zinc	0.6 … 0.79
Mercury	−0.07 … +0.04	Manganin	0.57 … 0.82
Platinum	± 0	Irdium	0.65 … 0.68
Graphite	0.22	Gold	0.56 … 0.8
Carbon	0.25 … 0.30	Cadmium	0.85 … 0.92
Tantalum	0.34 … 0.51	Molybdenum	1.16 … 1.31
Tin	0.4 … 0.44	Iron	1.87 … 1.89
Lead	0.41 … 0.46	Chrome nickel	2.2
Magnesium	0.4 … 0.43	Antimony	4.7 … 4.86
Aluminium	0.37 … 0.41	Silicon	44.8
Tungsten	0.65 … 0.9	Tellurium	50
Common thermocouples			
Copper/constantan (Cu/const)	up to 500 °C	Nickel chromium/nickel (NiCr/Ni)	up to 1 000 °C
Iron/constantan (Fe/const)	up to 700 °C	Platinum rhodium/ platinum	up to 1 600 °C
Nickel chromium/ constantan	up to 800 °C	Platinum rhodium/ platinum rhodium	up to 1 800 °C

1.2.4 pH value

The pH value is a measure of the "acidity" of aqueous solutions. It is defined as the logarithm to base 10 of the reciprocal of the hydrogen ion concentration CH_3O[1].

$$\mathrm{pH} \equiv -\log \frac{c(H^+)}{\mathrm{mol} \cdot L^{-1}}$$

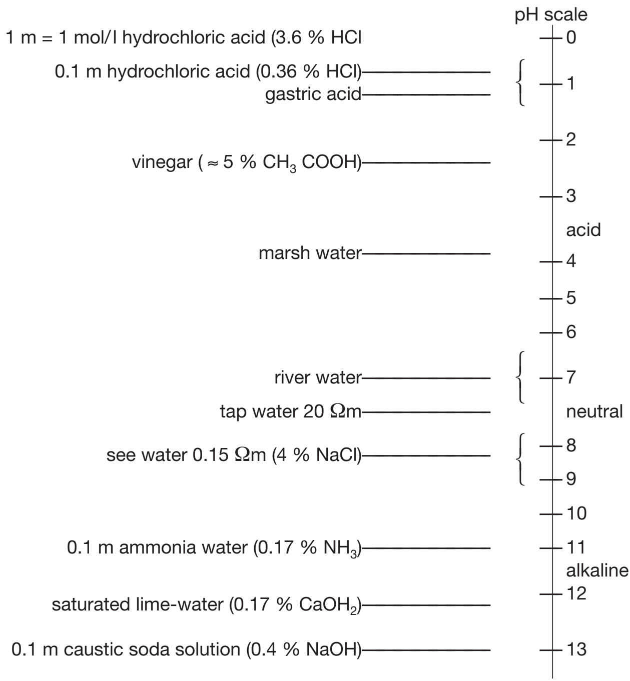


Fig. 1-1

pH value of some solutions

1.2.5 Heat transfer

Heat content (enthalpy) of a body: $Q = V \cdot \rho \cdot c \cdot \Delta\vartheta$
V volume, ρ density, c specific heat, $\Delta\vartheta$ temperature difference

Heat flow is equal to enthalpy per unit time:

$$\Phi = Q/t$$

Heat flow is therefore measured in watts (1 W = 1 J/s).

Specific heat (specific thermal capacity) of a substance is the quantity of heat required to raise the temperature of 1 kg of this substance by 1 °C. Mean specific heat relates to a temperature range, which must be stated. For values of c and λ, see Section 1.2.7.

Thermal conductivity is the quantity of heat flowing per unit time through a wall 1 m^2 in area and 1 m thick when the temperatures of the two surfaces differ by 1 °C. With many materials it increases with rising temperature, with magnetic materials (iron, nickel) it first falls to the Curie point, and only then rises (Curie point = temperature at which a ferro-magnetic material becomes non-magnetic, e. g. about 800 °C for Alnico). With solids, thermal conductivity generally does not vary much (invariable only with pure metals); in the case of liquids and gases, on the other hand, it is often strongly influenced by temperature.

Heat can be transferred from a place of higher temperature to a place of lower temperature by

- conduction (heat transmission between touching particles in solid, liquid or gaseous bodies).
- convection (circulation of warm and cool liquid or gas particles).
- radiation (heat transmission by electromagnetic waves, even if there is no matter between the bodies).

The three forms of heat transfer usually occur together.

Heat flow with conduction through a wall:

$$\Phi = \frac{\lambda}{s} \cdot A \cdot \Delta\vartheta$$

A transfer area, λ thermal conductivity, s wall thickness, $\Delta\vartheta$ temperature difference.

Heat flow in the case of transfer by convection between a solid wall and a flowing medium:

$$\Phi = \alpha \cdot A \cdot \Delta\vartheta$$

α heat transfer coefficient, A transfer area, $\Delta\vartheta$ temperature difference.

Heat flow between two flowing media of constant temperature separated by a solid wall:

$$\Phi = k \cdot A \cdot \Delta\vartheta$$

k thermal conductance, A transfer area, $\Delta\vartheta$ temperature difference.

In the case of plane layered walls perpendicular to the heat flow, the thermal conductance coefficient k is obtained from the equation

$$\frac{1}{k} = \frac{1}{\alpha_1} + \sum \frac{s_n}{\lambda_n} + \frac{1}{\alpha_2}$$

Here, α_1 and α_2 are the heat transfer coefficients at either side of a wall consisting of n layers of thicknesses s_n and thermal conductivities λ_n.

For two parallel black surfaces of equal size the heat flow exchanged by radiation is

$$\Phi_{12} = \sigma \cdot A\,(T_1^4 - T_2^4)$$

With grey radiating surfaces having emissivities of ε_1 and ε_2, it is

$$\Phi_{12} = C_{12} \cdot A\,(T_1^4 - T_2^4)$$

$\sigma = 5.6704 \cdot 10^{-8}\ W \cdot m^{-2} \cdot K^{-4}$ radiation coefficient of a black body (Stefan Boltzmann's constant), A radiating area, T absolute temperature.

Index 1 refers to the radiating surface, Index 2 to the radiated surface.

C_{12} is the effective radiation transfer coefficient. It is determined by the geometry and emissivity ε of the surface (table 1-12).

Special cases: $A_1 \ll A_2$ $\quad C_{12} = \sigma \cdot \varepsilon_1$

$A_1 \approx A_2$ $\quad C_{12} = \dfrac{\sigma}{\dfrac{1}{\varepsilon_1} + \dfrac{1}{\varepsilon_2} - 1}$

A_2 includes A_1 $\quad C_{12} = \dfrac{\sigma}{\dfrac{1}{\varepsilon_1} + \dfrac{A_1}{A_2} \cdot \left(\dfrac{1}{\varepsilon_2} - 1\right)}$

Table 1-11

Emissivity ε (average values ϑ < 200 °C)

Black body	1	Oil	0.82
Aluminium, polished	0.038 (230 °C)	Glass	0,94 (22 °C)
Aluminium, raw	0.079 (26 °C)	Porcelain, glazed	0,92 (22 °C)
Copper, polished	0.049 (23 °C)	Water	0.96
Copper, oxidized	0.63 (600 °C)	Wood (oak)	0,89 (21 °C)
Brass, polished	0.05 (19 °C)	Roofing felt	0,91 (21 °C)
Brass, dull	0.22 (56-338 °C)	enamel varnish	0,91 (24 °C)
Steel, dull, oxidized	0.96 (26-356 °C)	spirit varnish	0,82 (25 °C)
Steel, polished	0.29	Soot	0.93

Table 1-12

Heat transfer coefficients α in $W/(m^2 \cdot K)$ (average values)

Natural air movement in a closed space		
Wall surfaces		10
Floors, ceilings:	in upward direction	7
	in downward direction	5
Force-circulated air		
Mean air velocity w = 2 m/s		20
Mean air velocity w > 5 m/s		$6.4 \cdot w^{0.75}$

1.2.6 Acoustics, noise measurement and noise abatement

Audible sound comprises the mechanical oscillations and waves of an elastic medium in the frequency range of the human ear between 16 Hz and 20.000 Hz.

Oscillations below 16 Hz are termed infrasound and above 20.000 Hz ultrasound. Sound waves can occur not only in air but also in liquids (water-borne sound) and in solid bodies (solid-borne sound). Solid-borne sound is partly converted into audible air-borne sound at the boundary surfaces of the oscillating body. The frequency of oscillation determines the pitch of the sound. The sound generally propagates spherically from the sound source, as longitudinal waves in gases and liquids and as longitudinal and transverse waves in solids.

A sound source is characterized by its *sound power* W. The sound power is the sound energy radiated by a sound source in unit time. Its unit of measurement is the watt. *Sound propagation* gives rise to an alternating pressure, the root-mean-square value of which is termed the *sound pressure* p. It decreases approximately in proportion to the square of the distance from the sound source. The *sound intensity I* is the sound energy flowing perpendicularly through a surface in unit time; it is therefore a vectorial value. Its unit of measurement is the watt/m^2.

Since the sensitivity of the human ear is proportional to the logarithm of the sound pressure, a logarithmic scale is used to represent the various types of sound levels.

The *sound power level* L_w is defined as

$$L_w = 20 \lg W/W_o \text{ in dB.}$$

Here: W Sound power radiated from the sound source

W_o Reference power 10^{-12} W

The sound power level is determined indirectly by measuring sound pressure or sound intensity levels at an enveloping surface surrounding the source. ISO 3740, 3744 to 3748 or DIN 45635-1 standards can be applied as general stipulations for determining the sound power of machinery, and modified methods have also been developed for a series of machines. Power transformers are governed by IEC 610076-10 with typical sound power levels to VDI 3739.

The *sound intensity level* L_I is defined as the logarithm of the ratio of the sound intensity at the measuring point to the reference intensity I_o. Measurement is performed with a sound intensity probe in which two microphones are located at a short distance opposite each other. The sound intensity in the direction of the microphone axes is calculated using the sound pressure and the gradients of the sound pressure between the microphones.

$$L_I = 10 \lg I/I_o \text{ in dB}$$

I_o The reference intensity 10^{-12} W/m^2

I Measured intensity

The sound intensity measuring method permits determination of the sound power under non-ideal conditions, for instance in the presence of interference noise or reflections. Further stipulations on determination of the sound power by the sound intensity method can be found in ISO 9614, Parts 1 and 2.

The sound pressure level L_p is measured with a sound level meter as the logarithm of the ratio of the sound pressure to the reference pressure p_o. Measurement can be performed, for example, to IEC 61672-1 and -2.

$$L_p = 20 \lg p/p_o \text{ in dB}$$

Here: p_o Reference pressure, approximately corresponding to the audible threshold at 1000 Hz

p_o $2 \cdot 10^{-5}$ N/m^2 = $2 \cdot 10^{-5}$ Pa

p = Root-mean-square sound pressure

Example:

Sound pressure p = $2 \cdot 10^{-3}$ N/m^2, measured with a sound pressure meter

Sound level = $20 \lg (2 \cdot 10^{-3}) / (2 \cdot 10^{-5})$ = 40 dB.

The volume of a noise can be stated as a linear sound pressure level (to DIN 45630, Sheets 1 and 2) or as a frequency-dependent weighted sound pressure level (to DIN 45631, E. Zwicker method). The weighted sound pressure levels L_A, L_B and L_C,which are obtained by switching in defined weighting networks in the sound level meter, are stated in the unit dB with a suffix (A), (B) or (C).

The total sound power level of several sound sources is obtained by adding their sound powers, i.e. the individual levels are delogarithmized, added and the sum logarithmized again. Addition of two sound sources of equal strength increases the sound level by 3 dB (example: 2 sound sources of 85 dB together have 88 dB). With several sound sources with different volumes, the volume of the loudest sound source is dominant. (Example: 2 sound sources with 80 and 86 dB have a total volume of 87 dB.) It follows from this that with two equally loud sound sources both of them attenuate, and with sound sources of different loudness only the louder ones cause attenuation. Every increase in the level by 10 dB causes the perceived loudness to double, and every reduction by 10 dB causes it to halve.

There are legal limits to permissible noise immissions; in Germany, according to the Technical Directive on Protection against Noise (TAL) of 26.08.1998, the loudness of noises on average must not exceed the following values at the point of immission:

Area	Day (6 a.m. - 10 p.m.) dB (A)	Night (10 p.m. - 6 a.m.) dB (A)
Industrial	70	70
Commercial	65	50
Composite	60	45
generally residential	55	40
Purely residential	50	35
Therapy (hospitals, etc.)	45	35

Short-lived, isolated noise peaks can be disregarded (ISO 1996-1, -2, DIN 45641, 45645-1). Many standards and regulations, including the TAL, make further allowances of between 3 dB and 6 dB deducted from the measured sound pressure level for noises containing tones or pulses. Other limits apply in many other countries. There are various methods for assessing the tone content of a noise: one example is that of DIN 45681.

Disturbing noise is propagated as air-borne and solid-borne sound. When air-borne sound waves strike a wall, some are thrown back by reflection and others are absorbed by the wall. If air-borne noise striking a wall causes it to vibrate, the walls transmit the sound into the adjacent space. Solid-borne sound is converted into audible air-borne sound by radiation from the boundary surfaces. Ducts, air-shafts, piping systems and the like can transmit sound waves to other rooms. Special attention must therefore be paid to this when buildings are designed.

Sound pressure and sound intensity decrease with increasing distance from the sound source. A rough estimate of the sound level $L_p(r)$ to be expected at distance r from a sound source with sound power L_W can be calculated as follows:

$$L_p(r) = L_w - 10 \lg (2\pi r^2)$$

It is assumed here that the sound source is mounted on a reflecting level surface and the propagation conditions are otherwise homogeneous.

In the open air, sound propagation is not only affected by distance, but also by reflection and absorption on buildings and plant components, and by the acoustic properties of the ground, by plants and by meteorological influences such as wind and temperature gradients. ISO 9613-2 and VDI 2714 are often used as guidelines in forecasting sound propagation.

In general, noise emissions must be kept as low as possible at their point of origin. This can often only be achieved by enclosing the noise sources. VDI 2711 provides a guideline for the practical implementation of noise reducing enclosures. The acoustic effect of an enclosure results from a combination of sound reflection from the walls on the inside, and sound absorption. Without sound absorption, there would be an increase in sound pressure inside the enclosure as a result of the reflected sound, which would reduce the effectiveness of the enclosure. The most commonly used sound-absorbent materials are porous substances, plastics, cork, glass fibre and mineral wool, etc. Higher frequency noise components (> approx. 250 Hz) are easier to combat than lower frequency noises. For noise reduction by more than around 10 dB, not only the choice of materials for the enclosure walls, but also the careful sealing of all openings, is important. Openings to channel heat and gas are to be fitted with acoustic dampers. A further method of reducing noise immission is to erect an acoustic screen. The effect of an acoustic screen depends on its dimensions, position and distance from the sound source, distance of the receiver from the edge of the screen, and the absorption capacity of the wall (see VDI 2720).

When testing walls and ceilings for their behaviour regarding air-borne sound (DIN 52210, EN 20140-3, ISO 140-4), one determines the difference D in sound level L for the frequency range from 100 Hz to 3150 Hz.

$$D = L_1 - L_2 \text{ in dB where } L = 20 \lg p/p_o \text{ dB}$$

Here: L_1 = Sound level in room containing the sound source

L_2 = Sound level in room receiving the sound

Table 1-13

Noise attenuation figures of various construction materials in the range from 100 to 3200 Hz

Structural component	Attenuation dB	Structural	Attenuation dB
Brickwork, rendered, 12 cm thick	45	Single door without extra sealing	up to 20
Brickwork, rendered, 25 cm thick	50	Single door with good seal	30
Concrete wall, 10 cm thick	42	Double door without seal	30
Concrete wall, 20 cm thick	42	Double door without extra sealing	40
Wood wool mat, 8 cm thick	50	Single window without sealing	15
Straw mat, 5 cm thick	38	Spaced double window with seal	30

The reduction in level ΔL, obtainable in a room or enclosure by means of sound-absorbing materials or structures is:

$$\Delta L = 10 \lg A_2/A_1 = 10 \lg T_1/T_2 \text{ in dB}$$

Here: A Equivalent sound absorption area in the room concerned (from multiplication of the geometrical areas with their corresponding degrees of sound absorption α)

T Reverberation time of the room in s (Index 1 applies to the untreated room, and index 2 to the room treated with sound-absorbing materials)

Typical degrees of sound absorption a α:

Material	α
Smooth concrete, tiles, masonry	0.05
Room with furniture, rectangular machine room	0.15
Irregularly shaped room with furniture, machine room	0.2
Room with upholstered furniture, room with insulating material on parts of ceiling and walls	0.25
Room with insulating material on ceiling and walls	0.35
Room with large quantities of insulating material on ceiling and walls	0.5

The equivalent degree of sound absorption of a room can be determined experimentally using the reverberation time T:

$$A = 0{,}163\ V/T \text{ in } m^2$$

Here: V Room volume in m^3

T Reverberation time in s, in which the sound level L falls by 60 dB after sound emission ceases.

When a reduction in noise of approx. 10 dB and more is required, it should also be examined whether sound can be radiated by other components excited by the transmission of structure-borne noise. If necessary, the sound source is to be mounted on anti-vibration bearings. These can be simple rubber springs or dissipative steel springs, depending on the requirements. For high demands, an intermediate foundation which is also installed on anti-vibration mountings may also be necessary – see also VDI 2062.

1.2.7 Technical values of solids, liquids and gases

Table 1-14

Technical values of solids

Material	Density ρ kg/dm^3	Melting or freezing point °C	Boiling point °C	Linear thermal expansion α [1]	Thermal conductivity λ at 20 °C W/(m · K)	Mean spec. heat c at 0 . . 100 °C J/(kg · K)	Specific electrical resistance ρ at 20 °C $\Omega \cdot mm^2/m$	Temperature coefficient α of electrical resistance at 20 °C 1/K
Aluminium e.g. EAL 99.5(A)	2.70	658	2270	24	220	920	0.02876	0.0042
Al-alloy e.g. EAl MgSi(B)	2.70	≈ 630		23	190	920	0.0333	0.0036
Lead	11.34	327	1 730	28	34	130	0.21	0.0043
Bronze e.g. CuSn4Pb4Zn4	8.9	≈ 930		≈ 17.3	87	377	≈ 0.090	0.0007
Cadmium	8.64	321	767	31.6	92	234	0.762	0.0042
Chromium	6.92	1 800	2 400	8.5		452	0.028	
Iron, pure	7.88	1 530	2 500	12.3	71	464	0.10	0.0058
Iron, steel	≈ 7.8	≈ 1 350		≈ 11.5	46	485	0.25 . . 0.10	≈ 0.005
Iron, cast	≈ 7.25	≈ 1 200		≈ 11	46	540	0.6 . . 1	0.0045
Gold	19.29	1 063	2 700	14.2	309	130	0.022	0 0038
Constantan Cu + Ni	8 . . 8.9	1 600		16.8	22	410	0.48 . . 0.50	≈ 0.00005
Carbon diamond	3.51	≈ 3 600	4 200	1.3		502		
Carbon graphite	2.25			7.86	5	711		
Copper e.g. Cu-ETP R200	8.92	1 083	2 330	17	385	393	0.01754	0.00392
Magnesium	1.74	650	1110	25.0	167	1034	0.0455	0.004

[1] between 0 °C and 100 °C

(continued)

Table 1-14 (continued)

Technical values of solids

Material	Density ρ kg/dm³	Melting or freezing point °C	Boiling point °C	Linear thermal expansion α [1]	Thermal conductivity λ at 20 °C W/(m · K)	Mean spec. heat c at 0..100 °C J/(kg · K)	Specific electrical resistance ρ at 20 °C $\Omega \cdot mm^2/m$	Temperature coefficient α of electrical resistance at 20 °C 1/K
Brass e.g. CuZn37	8.5	912		18	120	377	≈ 0.0555	0.0024
Nickel	8.9	1 455	3 000	13	83	452	≈ 0.12	0.0046
Platinum	21.45	1 773	3 800	8.99	71	134	≈ 0.11	0.0039
Mercury	13.546	38.83	357	61	8.3	139	0.698	0.0008
Sulphur (rhombic)	2.07	113	445	90	0.2	720		
Selenium (metallic)	4.26	220	688	66		351		
Silver	10.50	960	1 950	19.5	421	233	0.0165	0.0036
Tungsten	19.3	3 380	6 000	4.50	167	134	0.06	0.0046
Zinc	7.23	419	907	16.50	121	387	0.0645	0.0037
Tin	7.28	232	2 300	26.7	67	230	0.119	0.004

[1] between 0 °C and 100 °C

Table 1-15

Technical values of liquids

Material	Chemical formula	Density ρ kg/dm^3	Melting or freezing point °C	Boiling point at 760 Torr °C	Expansion coefficient x 10^{-3} at 18 °C	Thermal conductivity λ at 20 °C W/(m · K)	Specific heat c_p at 0 °C J/(kg · K)	Relative dielectric constant ε_r at 180 °C
Acetone	C_3H_6O	0.791	– 95	56.3	1.43		2 160	21.5
Ethyl alcohol	C_2H_6O	0.789	–114	78.0	1.10	0.2	2 554	25.8
Ethyl ether	$C_4H_{10}O$	0.713	–124	35.0	1.62	0.14	2 328	4.3
Ammonia	NH_3	0.771	– 77.8	– 33.5		0.022	4 187	14.9
Aniline	C_6H_7N	1.022	– 6.2	184.4	0.84		2 064	7.0
Benzole	C_6H_6	0.879	+ 5.5	80.1	1.16	0.14	1 758	2.24
Acetic acid	$C_2H_4O_2$	1.049	+ 16.65	117.8	1.07		2 030	6.29
Glycerine	$C_3H_8O_3$	1.26	– 20	290	0.50	0.29	2 428	56.2
Linseed oil		0.94	– 20	316		0.15		2.2
Methyl alcohol	CH_4O	0.793	– 97.1	64.7	1.19	0.21	2 595	31.2
Petroleum		0.80			0.99	0.16	2 093	2.1
Castor oil		0.97			0.69		1 926	4.6
Sulphuric acid	H_2SO_4	1.834	– 10.5	338	0.57	0.46	1 385	> 84
Turpentine	$C_{10}H_{16}$	0.855	– 10	161	9.7	0.1	1 800	2.3
Water	H_2O	1.00[1)]	0	106	0.18	0.58	4 187	88

[1)] at 4 °C

Table 1- 16

Technical values of gases

Material	Chemical formula	Density ρ[1] kg/m³	Melting point °C	Boiling point °C	Thermal conductivity λ 10^{-2} W/(m · K)	Specific heat c_p at 0 °C J/(kg · K)	Relative[1] dielectric constant ε_r
Ammonia	NH_3	0.771	– 77.7	– 33.4	2.17	2 060	1.0072
Ethylene	C_2H_4	1.260	– 169.4	– 103.5	1.67	1 611	1.001456
Argon	Ar	1.784	– 189.3	– 185.9	1.75	523	1.00056
Acetylene	C_2H_2	1.171	– 81	– 83.6	1.84	1 511	
Butane	C_4H_{10}	2.703	– 135	– 0.5	0.15		
Chlorine	Cl_2	3.220	– 109	– 35.0	0.08	502	1.97
Helium	He	0.178	– 272	– 268.9	1.51	5 233	1.000074
Carbon monoxide	CO	1.250	– 205	– 191.5	0.22	1 042	1.0007
Carbon dioxide	CO_2	1.977	– 56	– 78.5	1.42	819	1.00095
Krypton	Kr	3.743	– 157.2	– 153.2	0.88		
Air	CO_2 free	1.293		– 194.0	2.41	1 004	1.000576
Methane	CH_4	0.717	– 182.5	– 161.7	3.3	2 160	1.000953
Neon	Ne	0.8999	– 248.6	– 246.1	4.6		
Ozone	O_3	2.22	– 252	– 112			
Propane	C_2H_8	2.019	– 189.9	– 42.6			
Oxygen	O_2	1.429	– 218.83	– 192.97	2.46	1 038	1.000547
Sulphur hexafluoride	SF_6	6.07[2]	– 50.8[3]	– 63	1.28[2]	670	1.0021[2]
Nitrogen	N_2	1.250	– 210	– 195.81	2.38	1042	1.000606
Hydrogen	H_2	0.0898	– 259.2	– 252.78	17.54	14 235	1.000264

[1] at 0 °C and 1013 mbar
[2] at 20 °C and 1013 mbar
[3] at 2.26 bar

1.3 Strength of materials

1.3.1 Fundamentals and definitions

External forces *F* acting on a cross-section A of a structural element can give rise to tensile stresses (σ_z), compressive stresses (σ_d), bending stresses (σ_b), shear stresses (τ_s) or torsional stresses (τ_t). If a number of stresses are applied simultaneously to a component, i. e. compound stresses, this component must be designed according to the formulae for compound strength. In this case the following rule must be observed:

Normal stresses σ_z. σ_d. σ_b,
Tangential stresses (shear and torsional stresses) τ_s, τ_t.

are to be added arithmetically;

Normal stresses σ_b with shear stresses τ_s,
Normal stresses σ_b with torsional stresses τ_t,

are to be added geometrically.

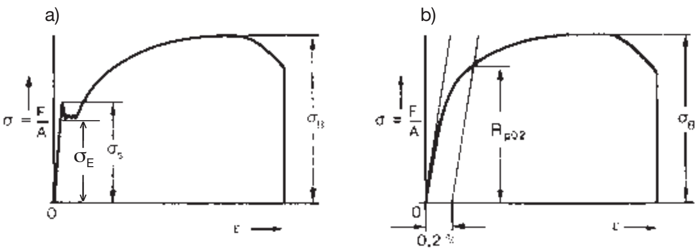


Fig. 1-2

Stress-strain diagram, a) Tensile test with pronounced yield point, material = structural steel; b) Tensile test without pronounced yield point, material = Cu/Al, ε Elongation, σ Tensile stress, σ_s Stress at yield point, σ_E Stress at proportionality limit, R_{p02} Stress with permanent elongation less than 0.2 %, σ_B Breaking stress.

Elongation $\varepsilon = \Delta l/l_0$ (or compression in the case of the compression test) is found from the measured length l_0 of a bar test specimen and its change in length $\Delta l = l - l_0$ in relation to the tensile stress σ_z, applied by an external force F. With stresses below the proportionality limit σ_E elongation increases in direct proportion to the stress σ (Hooke's law).

The ratio $\dfrac{\text{Stress } \sigma_E}{\text{Elongation } \varepsilon} = \dfrac{\sigma_E}{\varepsilon_E} = E$ is termed the elasticity modulus.

E is an imagined stress serving as a measure of the resistance of a material to deformation due to tensile or compressive stresses; it is valid only for the elastic region.

E is determined in terms of the load $\sigma_{0.01}$, i.e. the stress at which the permanent elongation is 0.01 % of the measured length of the test specimen.

If the stresses exceed the yield point σ_s, materials such as steel undergo permanent elongation. The ultimate strength, or breaking stress, is denoted by σ_B, although a bar does not break until the stress is again being reduced. Breaking stress σ_B is related to the elongation on fracture ε_B of a test bar. Materials having no marked proportional limit or elastic limit, such as copper and aluminium, are defined in terms of the so-called $R_{p0.2}$-limit, which is that stress at which the permanent elongation is 0.2 % after the external force has been withdrawn.

For reasons of safety, the maximum permissible stresses, σ_{max} or τ_{max} in the material must be below the proportional limit so that no permanent deformation, such as elongation or deflection, persists in the structural component after the external force ceases to be applied.

Table 1-17

Material	Elasticity modulus E[1)] kN/mm^2 [2)]
Steel	191-224
Cast iron	110-140
Bronze, CuAl5	123
Copper e.g. Cu-ETP	110
Al-alloy EAl MgSi(B)	70
Aluminium EAl 99,5(A)	65
Magnesium alloy MgMn2	45
Lead	16

[1)] Typical values [2)] 1 kN/mm^2 = 1 GPa

Fatigue strength (endurance limit) is present when the maximum variation of a stress oscillating about a mean stress is applied "infinitely often" to a loaded material (at least 10^7 load reversals in the case of steel) without giving rise to excessive deformation or fracture.

Cyclic stresses can occur in the form of a stress varying between positive and negative values of equal amplitude, or as a stress varying between zero and a certain maximum value. Cyclic loading of the latter kind can occur only in compression or only in tension.

Depending on the manner of loading, fatigue strength can be considered as bending fatigue strength, tension-compression fatigue strength or torsional fatigue strength. Structural elements which have to withstand only a limited number of load reversals can be subjected to correspondingly higher loads. The resulting stress is termed the fatigue limit.

One speaks of creep strength when a steady load with uniform stress is applied, usually at elevated temperatures.

1.3.2 Tensile and compressive strength

If the line of application of a force F coincides with the centroidal axis of a prismatic bar of cross section A (Fig.1-3), the normal stress uniformly distributed over the cross-section area and acting perpendicular to it is

$$\sigma = \frac{F}{A}\,.$$

With the maximum permissible stress σ_{max} for a given material and a given loading, the required cross section or the maximum permissible force, is therefore:

$$A = \frac{F}{\sigma_{max}} \text{ or } F = \sigma_{max} \cdot A.$$

Example:

A drawbar is to be stressed with a steady load of F = 180 000 N.

The chosen material is structural steel St 37 with σ_{max} = 120 N/mm².

Required cross section of bar:

$$A = \frac{E}{\sigma_{max}} = \frac{180\,000\ N}{120\ N/mm^2} = 1500\ mm^2.$$

Round bar of d = 45 mm *chosen.*

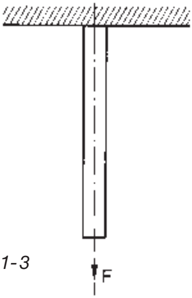


Fig. 1-3

1.3.3 Bending strength

The greatest bending action of an external force, or its greatest bending moment *M,* occurs at the point of fixing *a* in the case of a simple cantilever, and at point *c* in the case of a centrally loaded beam on two supports.

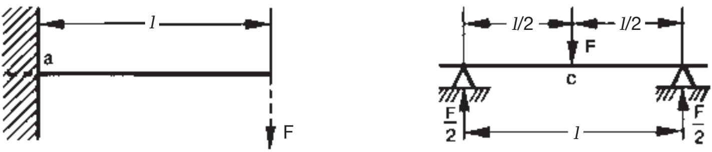


Fig. 1-4

Maximum bending moment at a: $M = F \cdot l$; *bei c:* $M = F \cdot l/4$

In position *a* and *c*, assuming the beams to be of constant cross section, the bending stresses σ_b are greatest in the filaments furthermost from the neutral axis. *M* may be greater, the greater is σ_{max} and the “more resistant” is the cross-section. The following cross sections have moments of resistance *W* in cm, if *a, b, h* and *d* are stated in cm.

The maximum permissible bending moment is $M = W \cdot \sigma_{max}$ and the required moment of resistance

$$W = \frac{M}{\sigma_{max}}\,.$$

Example:

A mild-steel stud $\left(\sigma_{max} = 70 \text{ N/mm}^2\right)$ with an unsupported length of l = 60 mm is to be loaded in the middle with a force F = 30 000 N. Required moment of resistance is:

$$W = \frac{M}{\sigma_{max}} = \frac{F \cdot l}{4 \cdot \sigma_{max}} = \frac{30\,000 \text{ N} \cdot 60 \text{ mm}}{4 \cdot 70 \text{ N/mm}^2} = 6.4 \cdot 10^3 \text{ mm}^3.$$

According to Table 1-21, the moment of resistance W with bending is $W \approx 0.1 \cdot d^3$.

The diameter of the stud will be: $d = \sqrt[3]{10\,W}$, $d = \sqrt[3]{64\,000}\ mm$ = 40 mm.

1.3.4 Loadings on beams

Table 1-18

Bending load

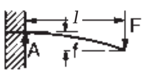
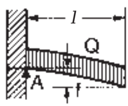
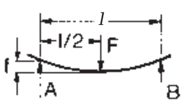
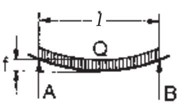
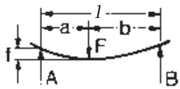
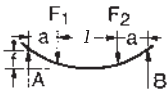
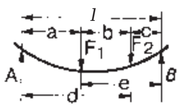
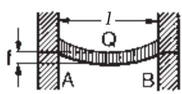
Case	Reaction force A, B Bending moment M	max. permissible load F, Q	Deflection f
	$A = F$ $M_{max} = F\,l$	$F = \frac{\sigma_{zul}\,W}{l}$	$f = \frac{F\,l^3}{3\,E\,J}$
	$A = Q$ $M_{max} = \frac{Q\,l}{2}$	$Q = \frac{2\,\sigma_{zul}\,W}{l}$	$f = \frac{Q\,l^3}{8\,E\,J}$
	$A = B = \frac{F}{2}$ $M_{max} = \frac{F\,l}{4}$	$F = \frac{4\,\sigma_{zul}\,W}{l}$	$f = \frac{F\,l^3}{48\,E\,J}$
	$A = B = \frac{Q}{2}$ $M_{max} = \frac{Q\,l}{8}$	$Q = \frac{8\,\sigma_{zul}\,W}{l}$	$f = \frac{5}{384} \cdot \frac{Q\,l^3}{E\,J}$

Table 1-18 (continued)

Bending load

Case	Reaction force A, B Bending moment M	max. permissible load F, Q	Deflection f
	$A = \frac{F\,b}{l}$ $B = \frac{F\,a}{l}$ $M_{max} = \frac{F \cdot a \cdot b}{l}$	$F = \frac{\sigma_{zul}\,W\,l}{a\,b}$	$f = \frac{F\,a^2\,b^2}{3\,E\,J\,l}$
	$A = B = F$ $M_{max} = F\,a$	$F = \frac{\sigma_{zul}\,W}{a}$	$f = \frac{F\,a}{24\,E\,J} \cdot [3\,(l + 2\,a)^2 - 4\,a^2]$
	$A = \frac{F_1\,e + F_2\,c}{l}$ $B = \frac{F_1\,a + F_2\,d}{l}$	$W_1 = \frac{A\,a}{\sigma_{zul}}$ $W_2 = \frac{B\,c}{\sigma_{zul}}$ determine beam for greatest "W"	$f = \frac{F_1\,a^2\,e^2 + F_2 l^2\,d^2}{3\,E\,J\,l}$
	$A = B = \frac{Q}{2}$ $M_{max} = \frac{Q\,l}{12}$	$Q = \frac{12\,\sigma_{zul}\,W}{l}$	$f = \frac{Q}{E\,J} \cdot \frac{l^3}{384}$

W selection modulus (bending)

F Single point load, *Q* Uniformly distributed load, *J* axial angular impulse

E elasticity modulus of material

1.3.5 Buckling strength

Thin bars loaded in compression are liable to buckle. Such bars must be checked both for compression and for buckling strength. Buckling strength is calculated with Euler's formula, a distinction being drawn between four cases.

Table 1-19

Buckling

	Case I One end fixed, other end free	$F = \dfrac{\pi^2 E J}{4 s l^2}$
	Case II Both ends free to move along bar axis	$F = \dfrac{\pi^2 E J}{s l^2}$
	Case III One end fixed, other end free to move along bar axis	$F = \dfrac{\left(\frac{\pi}{0.7}\right)^2 E J}{s l^2}$
	Case IV Both ends fixed, movement along bar axis	$F = \dfrac{4 \pi^2 E J}{s l^2}$

E Elasticity modulus of material
J Minimum axial angular impulse
F Maximum permissible force
l Length of bar

s Factor of safety:
for cast iron 8,
for mild carbon steel 5,
for wood 10.

1.3.6 Maximum permissible buckling and tensile stress for tubular rods

Threaded steel tube (gas pipe) or seamless steel tube

$$F_{buck} = \frac{10\,E}{s\,l^2} \cdot J = \frac{10\,E}{s\,l^2} \cdot \frac{D^4 - d^4}{20} \quad \text{where } J \approx \frac{D^4 - d^4}{20} \text{ from Table 1-22}$$

$$F_{ten} = A \cdot \sigma_{max}$$

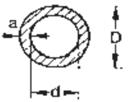


Fig. 1-5

in which

F	Force
E	Elasticity modulus (= 210 kN/mm²)
J	Axial angular impulse in cm⁴
s	Factor of safety (= 5)
σ_{max}	Max. permissible stress (= 350 N/mm²)
A	Cross-section area
D	Outside diameter
d	Inside diameter
l	Length

Table 1-20

Nominal diameter	Dimensions			Cross-sections	Moment of inertia	Weight of tube	F_{buck} for tube length $l \approx$						F_{ten}
	D inch	D mm	a mm	A mm²	J cm⁴	kg/m	0.5 m kN	1 m kN	1.5 m kN	2 m kN	2.5 m kN	3 m kN	kN
10	⅜	17.2	2.35	109.6	0.32	0.85	5.26	1.31	0.58	0.33	0.21	0.15	7.67
15	½	21.3	2.65	155.3	0.70	1.22	11.69	2.92	1.30	0.73	0.47	0.32	10.87
20	¾	26.9	2.65	201.9	1.53	1.58	25.48	6.37	2.83	1.59	1.02	0.71	14.13
25	1	33.7	3.25	310.9	3.71	2.44	61.84	15.46	6.87	3.87	2.47	1.72	21.76
	0.8	25	2	144.5	0.98	1.13	16.34	4.09	1.82	1.02	0.65	0.45	10.12
	0.104	31.8	2.6	238.5	2.61	1.88	43.48	10.87	4.83	2.72	1.74	1.21	16.70

1.3.7 Shear strength

Two equal and opposite forces F acting perpendicular to the axis of a bar stress this section of the bar in shear.

The stress is $\tau_s = \frac{F}{A}$;

or for given values of F and $\tau_{s\,max}$, the required cross section is $A = \frac{F}{\tau_{s\,zul}}$

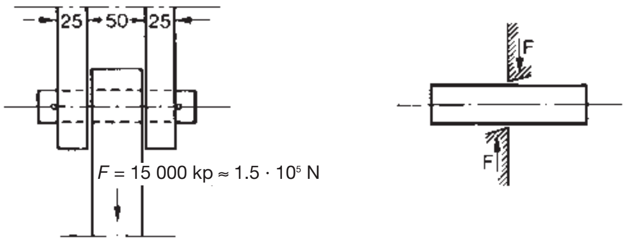


Fig. 1-6

Pull-rod coupling

Stresses in shear are always combined with a bending stress, and therefore the bending stress σ_b has to be calculated subsequently in accordance with the following example.

Rivets, short bolts and the like need only be calculated for shear stress.

Example:

Calculate the cross section of a shackle pin of structural steel, with $R_{p\,0.2\,min} = 300$ N/mm^2 and $\tau_{s\,max} = 0.8\, R_{p\,0.2\,min}$, for the pull-rod coupling shown in Fig. 1-6.

1. Calculation for shear force:

$$A = \frac{F}{2\,\tau_{s\,max}} = \frac{150\,000\ \text{N}}{2 \cdot (0.8 \cdot 300)\ \text{N/mm}^2} = 312\ \text{mm}^2$$

yields a pin diameter of $d \approx 20$ mm, with $W = 0.8 \cdot 10^3$ mm^3 (from $W \approx 0.1 \cdot d^3$, see Table 1-21).

2. Verification of bending stress:

The bending moment for the pin if $F\,l/4$ with a singlepoint load, and $F\,l/8$ for a uniformly distributed load. The average value is

$$M_b = \frac{\frac{F\,l}{4} + \frac{F\,l}{8}}{2} = \frac{3}{16}\,F\,l$$

when F $= 1.5 \cdot 10^5$ N, $l = 75$ mm becomes:

$$M_b = \frac{3}{16} \cdot 1.5 \cdot 10^5\ \text{N} \cdot 75\ \text{mm} \approx 21 \cdot 10^5\ \text{N} \cdot \text{mm};$$

$$\sigma_B = \frac{M_b}{W} = \frac{21 \cdot 10^5\ \text{N} \cdot \text{mm}}{0{,}8 \cdot 10^3\ \text{mm}^3} \approx 2{,}63 \cdot 10^3\ \frac{\text{N}}{\text{mm}^2}$$

i. e. a pin calculated in terms of shear with $d = 20$ mm will be too weak. The required pin diameter d calculated in terms of bending is

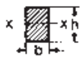
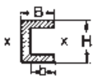
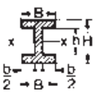
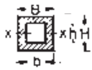
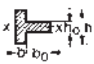
$$W = \frac{M_b}{\sigma_{max}} = \frac{21 \cdot 10^5\ \text{N} \cdot \text{mm}}{300\ \text{N/mm}^2} = 7 \cdot 10^3\ \text{mm}^3 = 0.7\ \text{cm}^3$$

$$d \approx \sqrt[3]{10 \cdot W} = \sqrt[3]{10 \cdot 7 \cdot 10^3\ \text{mm}^3} = 41{,}4\ \text{mm} \approx 42\ \text{mm}.$$

i. e. in view of the bending stress, the pin must have a diameter of 42 mm instead of 20 mm.

1.3.8 Moments of resistance and moments of inertia

Table 1-21

Cross-section	Moment of resistance torsion W[4]	bending[1] W[4]	Moment of inertia polar[1] J_p	axial[2] J
	$0.196\,d^3$ $\approx 0.2\,d^3$	$0.098\,d^3$ $\approx 0.1\,d^3$	$0.098\,d^4$ $\approx 0.1\,d^4$	$0.049\,d^4$ $\approx 0.05\,d^4$
	$0.196\,\frac{D^4-d^4}{D}$	$0.098\,\frac{D^4-d^4}{D}$	$0.098\,(D^4-d^4)$	$0.049\,(D^4-d^4)$
	$0.208\,a^3$	$0.118\,a^3$	$0.141\,a^4$	$0.083\,a^4$
	$0.208\,k_1\,b^2\,h$ [3]	$0.167\,b\,h^2$	$0.141 \cdot k_2\,b^4$	$0.083\,b\,h^3$
		$\frac{B\,H^3-b\,h^3}{6\,H}$		$\frac{B\,H^3-b\,h^3}{12}$
		$\frac{B\,H^3-b\,h^3}{6\,H}$		$\frac{B\,H^3-b\,h^3}{12}$
		$\frac{B\,H^3-b\,h^3}{6\,H}$		$\frac{B\,H^3-b\,h^3}{12}$
		$\frac{b\,h^3+b_o\,h_o^3}{6\,h}$		$\frac{b\,h^3+b_o\,h_o^3}{12}$

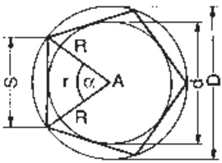
[1] Referred to CG of area.
[2] Referred to plotted axis.
[3] Values for k:

if $h:b$ =	1	1.5	2	3	4
then k_1 =	1	1,11	1,18	1,28	1,36
then k_2 =	1	1,39	1,62	1,87	1,99

[4] Symbol Z is also applicable, see DIN VDE 0103

1.4 Geometry, calculation of areas and solid bodies

1.4.1 Area of polygons



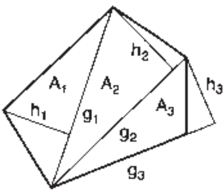
Regular polygons (n angles)

The area *A*, length of sides *S* and radii of the outer and inner circles can be calculated using the angle α and the number of sides n.
(α = 360 °/n).

$$A/S^2 = \frac{n}{4}\cot(\alpha/2) \qquad A/R^2 = \frac{n}{2}\sin\alpha$$

$$A/r^2 = n\tan(\alpha/2) \qquad S/R = 2\sin(\alpha/2)$$

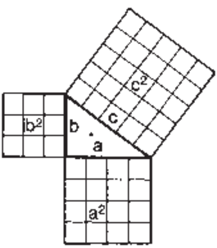
$$R/r = \cos(\alpha/2)$$



Irregular polygons

$$A = \frac{g_1 h_1}{2} + \frac{g_2 h_2}{2} + \dots$$

$$= \frac{1}{2}(g_1 h_1 + g_2 h_2 + \dots)$$

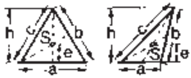
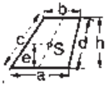
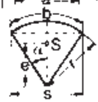
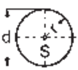
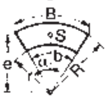
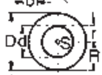
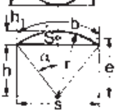
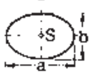


Pythagoras theorem

$$c^2 = a^2 + b^2; \qquad c = \sqrt{a^2 + b^2}$$
$$a^2 = c^2 - b^2; \qquad a = \sqrt{c^2 - b^2}$$
$$b^2 = c^2 - a^2; \qquad b = \sqrt{c^2 - a^2}$$

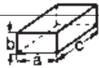
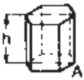
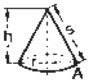
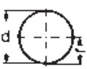
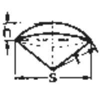
1.4.2 Areas and centres of gravity

Table 1-22

Shape of surface		A = area	U perimeter S centre of gravity (cg) e distance of cg
Triangle		$A = \frac{1}{2} a\, h$	$U = a + b + c$ $e = \frac{1}{3} h$
Trapezium		$A = \frac{a + b}{2} \cdot h$	$U = a + b + c + d$ $e = \frac{h}{3} \cdot \frac{a + 2\, b}{a + b}$
Rectangle		$A = a\, b$	$U = 2\,(a + b)$
Circle segment		$A = \frac{b\, r}{2} = \frac{\alpha}{180} r^2 \pi$ $b = r\, \pi \frac{\alpha}{90}$	$U = 2\, r + b$ $e = \frac{2}{3} r \frac{\sin \alpha}{\alpha} \cdot \frac{180}{\pi}$
Semicircle		$A = \frac{1}{2} \pi\, r^2$	$U = r\,(2 + \pi) \approx 5{,}14\, r$ $e = \frac{4}{3} \cdot \frac{r}{\pi} = 0{,}425\, r$
Circle		$A = r^2\, \pi = \pi \frac{d^2}{4}$	$U = 2\, \pi\, r = \pi\, d$
Annular segment		$A = \frac{\pi}{180} \alpha\, (R^2 - r^2)$	$U = 2\,(R - r) + \pi \cdot \frac{\alpha}{90} (R + r)$ $e = \frac{2}{3} \cdot \frac{R^2 - r^2}{R^2 - r^2} \cdot \frac{\sin \alpha}{\alpha} \cdot \frac{180}{\pi}$
Semi-annulus		$A = \frac{\pi}{2} \alpha\, (R^2 - r^2)$	$e = \frac{4}{3\, \pi} \cdot \frac{R^2 + R \cdot r + r^2}{R + r}$
Annulus		$A = \pi\, (R^2 - r^2)$	$U = 2\, \pi\, (R + r)$
Circular segment		$A = \frac{r^2}{2} \left(\frac{\pi \cdot \alpha}{90} - \sin 2\alpha \right)$ $s = 2 \sqrt{r^2 - h^2}$	$U = 2 \sqrt{r^2 - h^2} + \frac{\pi\, r\, \alpha}{90}$ $e = \frac{s^2}{12 \cdot A}$
Ellipse		$A = \frac{a\, b}{4} \pi$	$U = \frac{\pi}{2} \left[1{,}5\,(a + b) - \sqrt{ab} \right]$

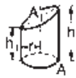
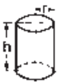
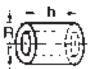
1.4.3 Volumes and surface areas of solid bodies

Table 1-23

Shape of body		*V* volume	*O* Surface *A* base surface M Nappe
Solid rectangle		$V = a\,b\,c$	$O = 2\,(a\,b + a\,c + b\,c)$
Cube		$V = a^3 = \frac{d^3}{2.828}$	$O = 6\,a^2 = 3\,d^2$
Prism		$V = A\,h$	$O = M + 2\,A$
Pyramid		$V = \frac{1}{3} A\,h$	$O = A + M$
Cone		$V = \frac{1}{3} A\,h$	$O = \pi\,r\,(r + s)$ $s = \sqrt{h^2 + r^2}$
Truncated cone		$V = (R^2 + r^2 + R\,r) \cdot \frac{\pi\,h}{3}$	$O = (R + r)\,\pi\,s + \pi\,(R^2 + r^2)$ $s = \sqrt{h^2 + (R - r)^2}$
Truncated pyramid		$V = \frac{1}{3} h\,(A + A_1 + \sqrt{AA_1})$	$O = A + A_1 + M$
Sphere		$V = \frac{4}{3} \pi\,r^3$	$O = 4\,\pi\,r^2$
Hemisphere		$V = \frac{2}{3} \pi\,r^3$	$O = 3\,\pi\,r^2$
Spherical segment		$V = \pi\,h^2 \left(r - \frac{1}{3} h\right)$	$O = 2\,\pi\,r\,h + \pi\,(2\,r\,h - h^2) =$ $\pi\,h\,(4\,r - h)$
Spherical sector		$V = \frac{2}{3} \pi\,r^2\,h$	$O = \frac{\pi\,r}{2}\,(4\,h + s)$

(continued)

Table 1-25 (continued)

Shape of body		V Volume	O Surface A Area
Zone of sphere		$V = \frac{\pi h}{6}(3a^2 + 3b^2 + h^2)$	$O = \pi(2rh + a^2 + b^2)$
Obliquely cut cylinder		$V = \pi r^2 \frac{h + h_1}{2}$	$O = \pi r(h + h_1) + A + A_1$
Cylindrical wedge		$V = \frac{2}{3} r^2 h$	$0 = 2rh + \frac{\pi}{2} r^2 + A$
Cylinder		$V = \pi r^2 h$	$O = 2\pi r h + 2\pi r^2$
Hollow cylinder		$V = \pi h(R^2 - r^2)$	$O = 2\pi h(R + r) + 2\pi(R^2 - r^2)$
Barrel		$V = \frac{\pi}{15} l \cdot$ $(2D^2 + Dd + 0.75\,d^2)$	$O = \frac{D + d}{2}\pi d + \frac{\pi}{2} d^2$ (approximate)
Body of rotation (ring)		$V = 2\pi \varrho A$ A = cross-section	O = circumference of cross-section x $2\pi\varrho$

2 General Electrotechnical Formulae

2.1 Electrotechnical symbols as per ISO 31 and IEC 60027

Table 2-1

Mathematical symbols for electrical quantities (general)

Symbol	Quantity	SI unit
Q	quantity of electricity, electric charge	C
E	electric field strength	V/m
D	electric flux density, electric displacement	C/m^2
U	electric potential difference	V
φ	electric potential	V
ε	permittivity, dielectric constant	F/m
ε_o	electric field constant, $\varepsilon_o = 0.885419 \cdot 10^{-11}$ F/m	F/m
ε_r	relative permittivity	1
C	electric capacitance	F
I	electric current intensity	A
J	electric current density	A/m^2
x, γ, σ	specific electric conductivity	S/m
ρ	specific electric resistance	$\Omega \cdot m$
G	electric conductance	S
R	electric resistance	Ω
θ	electromotive force	A

Table 2-2

Mathematical symbols for magnetic quantities (general)

Symbol	Quantity -	SI unit
Φ	magnetic flux	Wb
B	magnetic flux density	T
H	magnetic field strength	A/m
V	magnetomotive force	A
μ	permeability	H/m
μ_o	absolute permeability, $\mu_o = 4\,\pi \cdot 10^{-7} \cdot$ H/m	H/m
μ_r	relative permeability	1
L	inductance	H
L_{mn}	mutual inductance	H

Table 2-3

Mathematical symbols for alternating-current quantities and network quantities

Symbol	Quantity	SI unit
S	apparent power	W, (VA)
P	active power	W
Q	reactive power	W, (var)
φ	phase displacement	rad
ϑ	load angle	rad
λ	power factor, $\lambda = P/S$, λ $\cos \varphi$ [1]	1
δ	loss angle	rad
d	loss factor, $d = \tan \delta$ [1]	1
Z	impedance	Ω
Y	admittance	S
R	resistance	Ω
G	conductance	S
X	reactance	Ω
B	susceptance	S
γ	impedance angle, $\gamma = \arctan X/R$	rad

Table 2-4

Numerical and proportional relationships

Symbol	Quantity	SI unit
η	efficiency	1
s	slip	1
p	number of pole-pairs	1
w, N	number of turns	1
n_{tr} (t)	transformation ratio	1
m	number of phases and conductors	1
k	overvoltage factor	1
n	ordinal number of a periodic component	1
g	fundamental wave content	1
d	harmonic content, distortion factor	1
k_r	resistance factor due to skin effect,	1

1) Valid only for sinusoidal voltage and current.

2.2 Alternating-current quantities

With an alternating current, the instantaneous value of the current changes its direction as a function of time $i = f(t)$. If this process takes place periodically with a period of duration T, this is a periodic alternating current. If the variation of the current with respect to time is then sinusoidal, one speaks of a sinusoidal alternating current.

The frequency f and the angular frequency ω are calculated from the periodic time T with

$$f = \frac{1}{T} \text{ and } \omega = 2\pi f = \frac{2\pi}{T}.$$

The *equivalent d. c. value* of an alternating current is the average, taken over one period, of the value:

$$\overline{|i|} = \frac{1}{T}\int_0^T |i| \, dt = \frac{1}{2\pi}\int_0^{2\pi} |i| \, d\omega t.$$

This occurs in rectifier circuits and is indicated by a moving-coil instrument, for example.

The root-mean-square value (rms value) of an alternating current is the square root of the average of the square of the value of the function with respect to time.

$$I = \sqrt{\frac{1}{T}\cdot\int_0^T i^2 dt} = \sqrt{\frac{1}{2\pi}\cdot\int_0^{2\pi} i^2 d\omega t}.$$

As regards the generation of heat, the root-mean-square value of the current in a resistance achieves the same effect as a direct current of the same magnitude.

The root-mean-square value can be measured not only with moving-coil instruments, but also with hot-wire instruments, thermal converters and electrostatic voltmeters.

A non-sinusoidal current can be resolved into the fundamental oscillation with the fundamental frequency f and into harmonics having whole-numbered multiples of the fundamental frequency. If I_1 is the rms value of the fundamental oscillation of an alternating current, and I_2, I_3 etc. are the rms values of the harmonics having frequencies $2f$, $3f$, etc., the rms value of the alternating current is

$$I = \sqrt{I_1^2 + I_2^2 + I_3^2 + \dots}$$

If the alternating current also includes a direct-current component i_{-}, this is termed an undulatory current. The rms value of the undulatory current is

$$I = \sqrt{I_{-}^2 + I_1^2 + I_2^2 + I_3^2 + \dots}$$

The fundamental oscillation content g is the ratio of the rms value of the fundamental oscillation to the rms value of the alternating current

$$g = \frac{I_1}{I}.$$

The harmonic content d (distortion factor) is the ratio of the rms value of the harmonics to the rms value of the alternating current.

$$d = \frac{\sqrt{I_2^2 + I_3^2 + \dots}}{I} = \sqrt{1 - g^2}$$

The fundamental oscillation content and the harmonic content cannot exceed 1.

In the case of a sinusoidal oscillation

the fundamental oscillation content $g = 1$,
the harmonic content $d = 0$.

Forms of power in an alternating-current circuit

The following terms and definitions are in accordance with DIN 40110 for the sinusoidal wave-forms of voltage and current in an alternating-current circuit.

apparent power $S = UI = \sqrt{P^2 + Q^2}$,

active power $P = UI \cos \varphi = S \cos \varphi$,

reactive power $Q = UI \sin \varphi = S \sin \varphi$,

power factor $\cos \varphi = \frac{P}{S}$

reactive factor $\sin \varphi = \frac{Q}{S}$

When a three-phase system is loaded symmetrically, the apparent power is

$$S = 3\,U_1 I_1 = \sqrt{3}\,U\,I_1$$

where I_1 is the rms phase current, U_1 the rms value of the phase to neutral voltage and U the rms value of the phase to phase voltage. Also

active power $P = 3\,U_1 I_1 \cos \varphi = \sqrt{3}\,U\,I_1 \cos \varphi$

reactive power $Q = 3\,U_1 I_1 \sin \varphi = \sqrt{3}\,U\,I_1 \sin \varphi$

The unit for all forms of power is the watt (W). The unit watt is also termed volt-ampere (symbol VA) when stating electric apparent power, and Var (symbol var) when stating electric reactive power.

Resistances and conductances in an alternating-current circuit

impedance $Z = \frac{U}{I} = \frac{S}{I^2} = \sqrt{R^2 + X^2}$

resistance $R = \frac{U \cos \varphi}{I} = \frac{P}{I^2} = Z \cos \varphi = \sqrt{Z^2 - X^2}$

reactance $X = \frac{U \sin \varphi}{I} = \frac{Q}{I^2} = Z \sin \varphi = \sqrt{Z^2 - R^2}$

inductive reactance $X_i = \omega L$

capacitive reactance $X_c = \frac{1}{\omega C}$

admittance $Y = \frac{I}{U} = \frac{S}{U^2} = \sqrt{G^2 + B^2} = \frac{1}{Z}$

conductance $G = \frac{I \cos \varphi}{U} = \frac{P}{U^2} = Y \cos \varphi = \sqrt{Y^2 - B^2} = \frac{R}{Z^2}$

conductance $B = \frac{I \sin \varphi}{U} = \frac{Q}{U^2} = Y \sin \varphi = \sqrt{Y^2 - G^2} = \frac{X}{Z^2}$

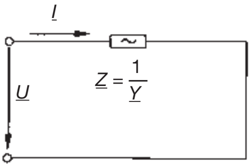
inductive susceptance $B_i = \frac{1}{\omega L}$

capacitive susceptance $B_c = \omega C$

$\omega = 2\,\pi f$ is the angular frequency and φ the phase displacement angle of the voltage with respect to the current. U, I and Z are the numerical values of the alternating-current quantities $\underline{U}$, $\underline{I}$ and $\underline{Z}$.

Complex presentation of sinusoidal time-dependent a. c. quantities

Expressed in terms of the load vector system:



$\underline{U} = \underline{I}\,\underline{Z}, \; \underline{I} = \underline{U}\,\underline{Y}$

The symbols are underlined to denote that they are complex quantities (DIN 1304).

Fig. 2- 1
Equivalent circuit diagram

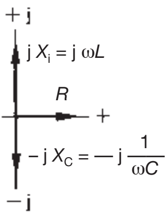


Fig. 2-2
Vector diagram of resistances

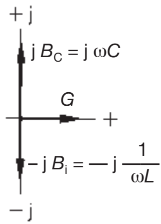


Fig. 2-3
Vector diagram of conductances

If the voltage vector $\underline{U}$ is laid on the real reference axis of the plane of complex numbers, for the equivalent circuit in Fig. 2-1 with $\underline{Z} = R + \mathrm{j}\,X_i$: we have

$$\underline{U} = U$$

$$\underline{I} = I_w - \mathrm{j}\,I_b = I\,(\cos\varphi - \mathrm{j}\sin\varphi)$$

$$I_w = \frac{P}{U} \qquad I_b = \frac{Q}{U}$$

$$\underline{S}^{1)} = U\,\underline{I}^* = U\,I\,(\cos\varphi + \mathrm{j}\sin\varphi) = P + \mathrm{j}\,Q,$$

$$S = |\underline{S}| = U\,I = \sqrt{P^2 + Q^2},$$

$$\underline{Z} = R + \mathrm{j}\,X_i = \frac{U}{\underline{I}} = \frac{U}{I\,(\cos\varphi - \mathrm{j}\sin\varphi)} = \frac{U}{I}\,(\cos\varphi + \mathrm{j}\sin\varphi),$$

where $R = \frac{U}{I}\cos\varphi$ and $X_i = \frac{U}{I}\sin\varphi$,

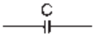
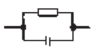
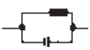
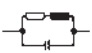
$$\underline{Y} = G - \mathrm{j}B = \frac{\underline{I}}{U} = \frac{I}{U}\,(\cos\varphi - \mathrm{j}\sin\varphi)$$

where $G = \frac{I}{U}\cos\varphi$ and $B_i = \frac{I}{U}\sin\varphi$.

[1] $\underline{S}$: See DIN 40110
$\underline{I}^*$ = conjugated complex current vector

Table 2-5

Alternating-current quantities of basic circuits

	Circuit	$\underline{Z}$	$\lvert\underline{Z}\rvert$
1.		R	R
2.		$j\,\omega L$	ωL
3.		$-j/(\omega C)$	$1/\omega C$
4.		$R + j\,\omega L$	$\sqrt{R^2 + (\omega L)^2}$
5.		$R - j/(\omega C)$	$\sqrt{R^2 + 1/(\omega C)^2}$
6.		$j\,(\omega L - 1/(\omega C))$ 1)	$\sqrt{(\omega L - 1/(\omega C))^2}$
7.		$R + j(\omega L - 1/(\omega C))$ 1)	$\sqrt{R^2 + (\omega L - 1/(\omega C))^2}$
8.		$\dfrac{R\,\omega L}{\omega L - jR}$	$\dfrac{R\,\omega L}{\sqrt{R^2 + (\omega L)^2}}$
9.		$\dfrac{R - j\,\omega C R^2}{1 + (\omega C)^2 R^2}$ 2)	$\dfrac{R}{\sqrt{1 + (\omega C)^2 R^2}}$
10.		$\dfrac{j\,\omega L}{1 - \omega^2 LC}$	$\dfrac{\omega L}{\sqrt{1 - \omega^2 LC}}$
11.	 4)	$\dfrac{1}{1/R + j\,(\omega C - 1/(\omega L))}$	$\dfrac{1}{\sqrt{1/R^2 + (\omega C - 1/(\omega L))^2}}$
12.	 5)	$\dfrac{R + j\,\omega\,(L\,(1 - \omega^2 LC) - R^2 C)}{(1 - \omega^2 LC)^2 + (R\,\omega C)^2}$	$\dfrac{\sqrt{R^2 + \omega^2\,[L\,(1 - \omega^2 LC) - R^2 C]^2}}{(1 - \omega^2 LC)^2 + (R\,\omega C)^2}$

1) Series resonance for $\omega L = 1/(\omega C)$: $f_{res} = \dfrac{1}{2\pi\sqrt{LC}}$

2) Series resonance for $\omega L = 1/(\omega C)$: $f_{res} = \dfrac{1}{2\pi\sqrt{LC}}$

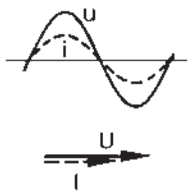
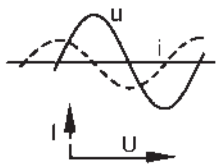
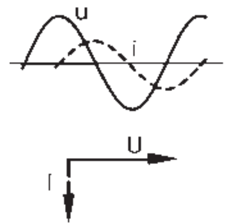
Table 2-6

Current / voltage relationships

Circuit-element		Ohmic resistance R	Capacitance (capacitor) C	Inductance (choke coil) L
General law	$u =$	$i\,R$	$\frac{1}{C}\int i\,\mathrm{d}t$	$L \cdot \frac{\mathrm{d}i}{\mathrm{d}t}$
	$i =$	$\frac{u}{R}$	$C \cdot \frac{\mathrm{d}u}{\mathrm{d}t}$	$\frac{1}{L}\int u\,\mathrm{d}t$
sinusoidal characteristic	$u =$	$\hat{u} \sin \omega t$	$\hat{u} \sin \omega t$	$\hat{u} \sin \omega t$
	$u =$	$\hat{\imath}\,R \sin \omega t = \hat{u} \sin \omega t$	$-\frac{1}{\omega C}\,\hat{\imath} \cos \omega t = -\,\hat{u} \cos \omega t$	$\omega L\,\hat{\imath} \cos \omega t = \hat{u} \cos \omega t$
	$i =$	$\frac{\hat{u}}{R} \sin \omega t = \hat{\imath} \sin \omega t$	$\omega C\,\hat{u} \cos \omega t = \hat{\imath} \cos \omega t$	$-\frac{1}{\omega L}\,\hat{u} \cos \omega t = -\,\hat{\imath} \cos \omega t$
Elements of characteristic	$\hat{\imath} =$	$\hat{u} / R$	$\omega C\,\hat{u}$	$\hat{u} / (\omega L)$
	$\hat{u} =$	$\hat{\imath}\,R$	$\hat{\imath} / (\omega C)$	$\hat{\imath}\,\omega L$
	$\varphi =$	0 u and i in phase	with R = 0: $\arctan \frac{1}{\omega C \cdot R} = -\frac{\pi}{2}$ i leads u by 90 ° vor	with R = 0: $\arctan \frac{\omega L}{R} = \frac{\pi}{2}$ i lags u by 90 ° nach
Frequency	$f =$	$\frac{\omega}{2\pi}$	$\frac{\omega}{2\pi}$	$\frac{\omega}{2\pi}$

(continued)

Table 2-6 (continued)

Circuit-element		Ohmic resistance *R*	Capacitance (capacitor) *C*	Inductance (choke coil) *L*
Alternating current impedance	$\underline{Z}$ =	R	$\frac{-\mathrm{j}}{\omega C}$	$\mathrm{j}\,\omega L$
	$\lvert\underline{Z}\rvert$ =	R	$\frac{1}{\omega C}$	ωL
Diagrams				

2.3 Electrical resistances

2.3.1 Definitions and specific values

An ohmic resistance is present if the instantaneous values of the voltage are proportional to the instantaneous values of the current, even in the event of time-dependent variation of the voltage or current. Any conductor exhibiting this proportionality within a defined range (e.g. of temperature, frequency or current) behaves within this range as an ohmic resistance. Active power is converted in an ohmic resistance. For a resistance of this kind is:

$$R = \frac{P}{I^2}$$

The resistance measured with direct current is termed the *d. c. resistance* R_-. If the resistance of a conductor differs from the d. c. resistance only as a result of skin effect, we then speak of the a. c. resistance $R_\sim$ of the conductor. The ratio expressing the increase in resistance is:

$$\zeta = \frac{R_\sim}{R_-} = \frac{\textit{a. c.}\ \text{resistance}}{\text{d. c. resistance}}$$

Specific values for major materials are shown in Table 2-7 and 1-14

Table 2-7

Numerical values for major materials

Conductor	Specific electric resistance ρ (mm² Ω/m)	Electric conductivity $x = 1/\rho$ (m/mm² Ω)	Temperature coefficient α (K⁻¹)	Density (kg/dm³)
Al-alloy Al Mg5	0.05…0.07	19…15	$2.0 \cdot 10^{-3}$	2.7
Al bronze, e.g. CuAl10Fe1	0.13	7.7	$3.2 \cdot 10^{-3}$	8.5
Bismuth	1.2	0.83	$4.5 \cdot 10^{-3}$	9.8
Bronze, e.g. CuSn4	0.087	11.5	–	8.9
CrAl 20 5 Fe75/Cr20/Al5	1.37	0.73	$0.05 \cdot 10^{-3}$	–
CrAl 30 5 Fe65/Cr30/Al5	1.44	0.69	$0.06 \cdot 10^{-3}$	–
Dynamo sheet	0.13	7.7	$4.5 \cdot 10^{-3}$	7.8
Dynamo sheet alloy (1 to 5 % Si)	0.27… 0.67	3.7…1.5	–	7.8
Graphite and retort carbon	13 …1000	0.077…0.01	$-0.8 \ldots -0.2 \cdot 10^{-3}$	2.5…1.5
Manganin e.g. CuMn12Ni4	0.45	2.22	$0.01 \cdot 10^{-3}$	8.4
Molybdenum	0.054	18.5	$4.3 \cdot 10^{-3}$	10.2
Monel metal Ni65/Cu33/Fe2	0.42	2.38	$0.019 \cdot 10^{-3}$	8.84
Nickel silver CuNi12Zn24	0.25	4	$0.4 \cdot 10^{-3}$	8.7
Ni Cr 30 20 Fe50/Ni30/Cr20	1.04	0.96	$0.24 \cdot 10^{-3}$	8.3
Ni Cr 60 15 Ni60/Fe25/Cr15	1.11	0.90	$0.13 \cdot 10^{-3}$	8.3
Ni Cr 80 20 Ni80/Cr20	1.09	0.92	$0.04 \cdot 10^{-3}$	8.3
Nickeline e.g. CuNi18Zn20	0.29	3.5	$0.23 \cdot 10^{-3}$	8.7
Red brass e.g. CuZn20	0.053	19	–	8.65
Silver	0.0165	60.5	$41 \cdot 10^{-3}$	10.5

(continued)

Table 2-7 (continued)

Numerical values for major materials

Conductor	Specific electric resistance ρ (mm² Ω/m)	Electric conductivity $x = 1/\rho$ (m/mm² Ω)	Temperature coefficient α (K⁻¹)	Density (kg/dm³)
Steel, 0.1% C, 0.5 % Mn	0.13…0.15	7.7…6.7	$4…5 \cdot 10^{-3}$	7.86
Steel, 0.25 % C, 0.3 % Si	0.18	5.5	$4…5 \cdot 10^{-3}$	7.86
Steel, spring, 0.8 % C	0.20	5	$4…5 \cdot 10^{-3}$	7.86
Tantalum	0.16	6.25	$3.5…10^{-3}$	16.6

Resistance varies with temperature, cf. Section 2.3.3

2.3.2 Resistances in different circuit configurations

Connected in series (Fig. 2-4)

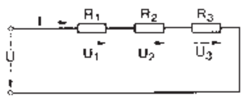


Fig. 2-4

Total resistance $R = R_1 + R_2 + R_3 + \ldots$
The component voltages behave in accordance with the resistances $U_1 = I\,R_1$ etc.

The current at all resistances is of equal magnitude $I = \frac{U}{R}$.

Connected in parallel (Fig. 2-5)

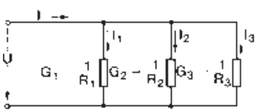


Fig. 2-5

Total conductance $= \frac{1}{R} = G = G_1 + G_2 + G_3 +$

The voltage at all the resistances is the same.

Total current $I = \frac{U}{R}$ Summe der Teilströme $I_1 = \frac{U}{R_1}$ usw

The currents behave inversely to the resistances

$$I_1 = I\frac{R}{R_1} \qquad I_2 = I\frac{R}{R_2} \qquad I_3 = I\frac{R}{R_3}$$

Transformation delta-star and star-delta (Fig. 2-6)

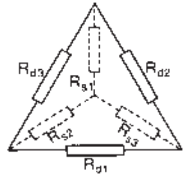


Fig. 2-6

Conversion from delta to star connection:

$$R_{S1} = \frac{R_{d2}\,R_{d3}}{R_{d1} + R_{d2} + R_{d3}}$$

$$R_{S2} = \frac{R_{d3}\,R_{d1}}{R_{d1} + R_{d2} + R_{d3}}$$

$$R_{S3} = \frac{R_{d1}\,R_{d2}}{R_{d1} + R_{d2} + R_{d3}}$$

Conversion from star to delta connection:

$$R_{d1} = \frac{R_{S1}\,R_{S2} + R_{S2}\,R_{S3} + R_{S3}\,R_{S1}}{R_{S1}}$$

$$R_{d2} = \frac{R_{S1}\,R_{S2} + R_{S2}\,R_{S3} + R_{S3}\,R_{S1}}{R_{S2}}$$

$$R_{d3} = \frac{R_{S1}\,R_{S2} + R_{S2}\,R_{S3} + R_{S3}\,R_{S1}}{R_{S3}}$$

Calculation of a bridge between points A and B (Fig. 2-7)

To be found:

1. the total resistance R_{tot} between points A and B
2. the total current I_{tot} between points A and B
3. the component currents in R_1 to R_5

Given:

voltage	U	= 220 V
resistance	R_1	= 10 Ω
	R_2	= 20 Ω
	R_3	= 30 Ω
	R_4	= 40 Ω
	R_5	= 50 Ω

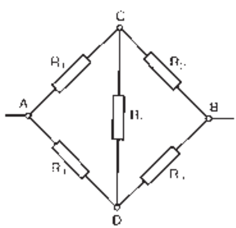


Fig. 2-7

First delta connection CDB is converted to star connection CSDB (Fig. 2-8):

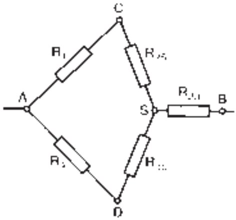


Fig. 2-8

$$R_{25} = \frac{R_2\,R_5}{R_2 + R_3 + R_5} = \frac{20 \cdot 50}{20 + 30 + 50}\ \Omega = 10\ \Omega$$

$$R_{35} = \frac{R_3\,R_5}{R_2 + R_3 + R_5} = \frac{30 \cdot 50}{20 + 30 + 50}\ \Omega = 15\ \Omega$$

$$R_{23} = \frac{R_2\,R_3}{R_2 + R_3 + R_5} = \frac{20 \cdot 30}{20 + 30 + 5}\ \Omega = 6\ \Omega,$$

$$R_{tot} = \frac{(R_1 + R_{25})\,(R_4 + R_{35})}{R_1 + R_{25} + R_4 + R_{35}} + R_{23} =$$

$$= \frac{(10 + 10)\,(40 + 15)}{10 + 10 + 40 + 15}\ \Omega + 6\ \Omega = 20.67\ \Omega$$

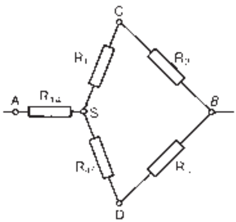


Fig. 2-9

$$I_{tot} = \frac{U}{R_{tot}} = \frac{220}{20.67}\ \text{A} = 10.65\ \text{A}$$

$$I_{R1} = I_{tot}\frac{R_4 + R_{35}}{R_1 + R_{25} + R_4 + R_{35}} = 10.65 \cdot \frac{55}{75}\ \text{A} = 7.81\ \text{A}$$

$$I_{R4} = I_{tot} - I_{R1} = 2.83\ \text{A}$$

By converting the delta connection CDA to star connection CSDA, we obtain the following values (Fig. 2-9): $R_{15} = 5\,\Omega$ $R_{45} = 20\,\Omega$ $R_{14} = 4\,\Omega$ $I_{R2} = 7.1\,\text{A}$ $I_{R3} = 3.55\,\text{A}$

2.3.3 The influence of temperature on resistance

The resistance of a conductor is

$$R = \frac{l \cdot \rho}{A} = \frac{l}{x \cdot A}$$

where

- l Total length of conductor
- A Cross-sectional area of conductor
- ρ Specific resistance (at 20 °C)
- x $\frac{1}{\rho}$ electric conductivity
- α Temperature coefficient.

Values for ρ, x and α are given in Table 2-7 for a temperature of 20 °C.

For other temperatures ϑ (ϑ in °C)

$$\rho_\vartheta = \rho_{20}\,[1 + \alpha\,(\vartheta - 20)]$$

The conductor resistance is:

$$R_\vartheta = \frac{l}{A} \cdot \rho_{20} \,[1 + \alpha\,(\vartheta - 20)]$$

Similarly for the conductivity

$$\varkappa_\vartheta = \varkappa_{20} \,[1 + \alpha\,(\vartheta - 20)]^{-1}$$

The temperature rise of a conductor or a resistance is calculated as:

$$\Delta\,\vartheta = \frac{R_w / R_k - 1}{\alpha} \,.$$

The values R_k and R_w are found by measuring the resistance of the conductor or resistance in the cold and hot conditions, respectively.

Example:

The resistance of a copper conductor of l = 100 m and A = 10 mm² at 20 °C is

$$R_{20} = \frac{100 \cdot 0{,}0175}{10}\ \Omega = 0{,}175\ \Omega.$$

If the temperature of the conductor rises to ϑ = 50 °C, the resistance becomes

$$R_{50} = \frac{100}{10} \cdot 0.0175\,[1 + 0.004\,(50 - 20)] \approx 0.196\ \Omega.$$

2.4 Relationships between voltage drop, power loss and conductor cross section

Especially in low-voltage networks is it necessary to check that the conductor cross-section, chosen with respect to the current-carrying capacity, is adequate as regards the voltage drop. It is also advisable to carry out this check in the case of very long connections in medium-voltage networks. (See also Sections 6.1.6 and 13.2.3).

Direct current (positiv and negativ conductor)

voltage drop $$\Delta\,U = R'_L \cdot 2 \cdot l \cdot I = \frac{2 \cdot l \cdot I}{\kappa \cdot A} = \frac{2 \cdot l \cdot P}{\kappa \cdot A \cdot U}$$

percentage voltage drop $$\Delta\,u = \frac{\Delta\,U}{U_n}\,100\,\% = \frac{R'_L \cdot 2 \cdot l \cdot I}{U_n}\,100\,\%$$

power loss $$\Delta\,P = I^2\,R'_L\,2 \cdot l = \frac{2 \cdot l \cdot P^2}{\kappa \cdot A \cdot U^2}$$

percentage power loss $$\Delta\,p = \frac{\Delta\,P}{P_n}\,100\,\% = \frac{I^2\,R'_L \cdot 2 \cdot l}{P_n}\,100\,\%$$

conductor cross section $$A = \frac{2 \cdot l \cdot I}{\kappa \cdot \Delta\,U} = \frac{2 \cdot l \cdot I}{\kappa \cdot \Delta\,u \cdot U}\,100\,\% = \frac{2 \cdot l \cdot P}{\Delta\,p \cdot U^2 \cdot \kappa}\,100\,\%$$

Single-phase alternating current (both conductors)

voltage drop $\Delta U \approx I \cdot 2 \cdot l\,(R'_L \cdot \cos\varphi + X'_L \cdot \sin\varphi)$

percentage voltage drop $\Delta u = \frac{\Delta U}{U_n} 100\ \% \approx \frac{I \cdot 2 \cdot l\,(R'_L \cdot \cos\varphi + X'_L \cdot \sin\varphi)}{U_n}$

power loss $\Delta P = I^2 R'_L \cdot 2 \cdot l$

percentage power loss $\Delta p = \frac{\Delta P}{P_n} 100\ \% = \frac{I^2 \cdot R'_L \cdot 2 \cdot l}{P_n} 100\ \%$

conductor cross-section[1)]

$$A \approx \frac{2 \cdot l \cos\varphi}{x \left(\frac{\Delta U}{I} - X'_L \cdot 2 \cdot l \cdot \sin\varphi \right)} = \frac{2 \cdot l \cos\varphi}{x \left(\frac{\Delta u \cdot U_n}{I \cdot 100\ \%} - X'_L \cdot 2 \cdot l \cdot \sin\varphi \right)}$$

Three-phase current

voltage drop $\Delta U = \sqrt{3} \cdot I \cdot l\,(R'_L \cdot \cos\varphi + X'_L \cdot \sin\varphi)$

percentage voltage drop $\Delta u = \frac{\Delta U}{U_n} 100\ \% \approx \frac{\sqrt{3} \cdot I \cdot l\,(R'_L \cdot \cos\varphi + X'_L \cdot \sin\varphi)}{U_n} 100\ \%$

power loss $\Delta P = 3 \cdot I^2 R'_L \cdot l$

percentage power loss $\Delta p = \frac{\Delta P}{P_n} 100\ \% = \frac{3\,I^2 \cdot R'_L \cdot l}{P_n} 100\ \%$

conductor cross-section[1)]

$$A \approx \frac{l \cdot \cos\varphi}{x \left(\frac{\Delta U}{\sqrt{3} \cdot I} - X'_L \cdot l \cdot \sin\varphi \right)}$$

$$= \frac{l \cdot \cos\varphi}{x \left(\frac{\Delta u \cdot U}{\sqrt{3} \cdot I \cdot 100\ \%} - X'_L \cdot l \cdot \sin\varphi \right)}$$

l one-way length of conductor

R'_L Resistance per km

P Active power to be transmitted ($P = P_n$)

U phase-to-phase voltage

X'_L Reactance per km

I phase-to-phase current

In single-phase and three-phase a.c. systems with cables and lines of less than 16 mm^2 the inductive reactance can usually be disregarded. It is sufficient in such cases to calculate only with the d.c. resistance.

1) Reactance is slightly dependent on conductor cross section.

Table 2-8

Effective resistances per unit length of PVC-insulated cables with copper conductors for 0.6/1 kV at 70 °C, cable type NYY

Number of conductors and cross-section	D. C. resistance	Ohmic resistance at	Inductive reactance	Effective resistance per unit length $R'_L \cdot \cos\varphi + X'_L \cdot \sin\varphi$ at cos φ 0.95	0.9	0.8	0.7	0.6
	$R'_{L\sim}$	$R'_{L\sim}$	X'_L					
mm²	Ω/km	Ω/km	Ω/km	Ω/km	Ω/km	Ω/km	Ω/km	Ω/km
4 × 1.5	14.47	14.47	0.114	13.8	13.1	11.60	10.2	8.80
4 × 2.5	8.87	8.87	0.107	8.41	8.03	7.16	6.29	5.41
4 × 4	5.52	5.52	0.107	5.28	5.02	4.48	3.94	3.40
4 × 6	3.69	3.69	0.102	3.54	3.37	3.01	2.66	2.30
4 × 10	2.19	2.19	0.094	2.11	2.01	1.81	1.60	1.39
4 × 16	1.38	1.38	0.090	1.34	1.28	1.16	1.030	0.900
4 × 25	0.870	0.870	0.088	0.854	0.82	0.75	0.672	0.592
4 × 35	0.627	0.627	0.085	0.622	0.60	0.55	0.500	0.444
4 × 50	0.463	0.463	0.085	0.466	0.454	0.42	0.385	0.346
4 × 70	0.321	0.321	0.082	0.331	0.325	0.306	0.283	0.258
4 × 95	0.231	0.232	0.082	0.246	0.245	0.235	0.221	0.205
4 × 120	0.183	0.184	0.080	0.200	0.200	0.195	0.186	0.174
4 × 150	0.148	0.150	0.081	0.168	0.170	0.169	0.163	0.155
4 × 185	0.119	0.1203	0.080	0.139	0.143	0.144	0.141	0.136
4 × 240	0.0902	0.0925	0.080	0.113	0.118	0.122	0.122	0.120

Example:

A three-phase power of 50 kW with cos φ = 0.8 is to be transmitted at 400 V over a line 100 m long. The voltage drop must not exceed 2 %. What is the required cross section of the line?

The percentage voltage drop of 2 % is equivalent to

$$\Delta U = \frac{\Delta u}{100\ \%} U_n = \frac{2\ \%}{100\ \%} 400\ \text{V} = 8.0\ \text{V}.$$

The current is

$$I = \frac{P}{\sqrt{3} \cdot U \cdot \cos\varphi} = \frac{50\ \text{kW}}{\sqrt{3} \cdot 400\ \text{V} \cdot 0.8} = 90\ \text{A}.$$

$$R'_L \cdot \cos\varphi + X'_L \cdot \sin\varphi = \frac{\Delta U}{\sqrt{3} \cdot I \cdot l} = \frac{8.0}{\sqrt{3} \cdot 90\ \text{A} \cdot 0.1\ \text{km}} = 0.513\ \Omega/\text{km}.$$

According to Table 2-8 a cable of 50 mm² with an effective resistance per unit length of 0.42 Ω/km should be used. The actual voltage drop will then be

$$\Delta U = \sqrt{3}\, I\, l\, (R'_L \cos\varphi + X'_L \cdot \sin\varphi)$$
$$= \sqrt{3} \cdot 90\ \text{A} \cdot 0.1\ \text{km} \cdot 0.42\ \Omega/\text{km} = 6.55\ \text{V}$$

This is equivalent to: $\Delta u = \frac{\Delta U}{U_n}\, 100\ \% = \frac{6.55\ \text{V}}{400\ \text{V}}\, 100\ \% = 1.6\ \%$

2.5 Current input of electrical machines and transformers

Direct current

Motors:

$$I = \frac{P_{mech}}{U \cdot \eta}$$

Generators:

$$I = \frac{P}{U}$$

Single-phase alternating current

Motors:

$$I = \frac{P_{mech}}{U \cdot \eta \cdot \cos\varphi}$$

Transformers and synchronous generators:

$$I = \frac{S}{U}$$

Three-phase current

Induction motors:

$$I = \frac{P_{mech}}{\sqrt{3} \cdot U \cdot \eta \cdot \cos\varphi}$$

Transformers and synchronous generators:

$$I = \frac{S}{\sqrt{3} \cdot U}$$

Synchronous motors:

$$I \approx \frac{P_{mech}}{\sqrt{3} \cdot U \cdot \eta \cdot \cos\varphi} \cdot \sqrt{1 + \tan^2\varphi}$$

In the formulae for three-phase current, *U* is the phase voltage.

Table 2-9

Motor current ratings for three-phase motors (typical values for squirrel-cage type)

Smallest possible short-circuit fuse (Service category gG[1)]) for three-phase motors. The highest possible value is governed by the switching device or motor relay.

Motor output data			Rated currents at 230 V		400 V		500 V		660 V	
			Motor	Fuse	Motor	Fuse	Motor	Fuse	Motor	Fuse
kW	$\cos\varphi$	η %	A	A	A	A	A	A	A	A
0.25	0.7	62	1.4	4	0.8	2	0.7	2	—	—
0.37	0.72	64	2.0	4	1.2	4	0.9	2	0.7	2
0.55	0.75	69	2.7	4	1.5	4	1.2	4	0.9	2
0.75	0.8	74	3.2	6	1.8	4	1.5	4	1.1	2
1.1	0.83	77	4.3	6	2.5	4	2.0	4	1.5	2
1.5	0.83	78	5.8	16	3.3	6	2.7	4	2.0	4
2.2	0.83	81	8.2	20	4.7	10	3.7	10	2.9	6
3	0.84	81	11.1	20	6.4	16	5.1	10	3.5	6

(continued)

Table 2-9 (continued)

Motor current ratings for three-phase motors (typical values for squirrel-cage type)

Smallest possible short-circuit fuse (Service category $g^{G1)}$) for three-phase motors. The highest possible value is governed by the switching device or motor relay.

Motor output data			Rated currents at							
			230 V		400 V		500 V		660 V	
			Motor	Fuse	Motor	Fuse	Motor	Fuse	Motor	Fuse
kW	cos φ	η %	A	A	A	A	A	A	A	A
4	0.84	82	14.6	25	8.4	20	6.7	16	5.1	10
5.5	0.85	83	19.6	35	11.3	25	9.0	20	6.8	16
7.5	0.86	85	25.8	50	14.8	35	11.8	25	9.0	16
11	0.86	87	36.9	63	21.2	35	17.0	35	12.9	25
15	0.86	87	50	80	29	50	23.1	35	17.5	25
18.5	0.86	88	61	100	35	63	28	50	21	35
22	0.87	89	71	100	41	63	33	63	25	35
30	0.87	90	96	125	55	80	44	63	34	50
37	0.87	90	119	200	68	100	55	80	41	63
45	0.88	91	141	225	81	125	65	100	49	63
55	0.88	91	172	250	99	160	79	125	60	100
75	0.88	91	235	350	135	200	108	160	82	125
90	0.88	92	279	355	160	225	128	200	97	125
110	0.88	92	341	425	196	250	157	225	119	160
132	0.88	92	409	600	235	300	188	250	143	200
160	0.88	93	491	600	282	355	226	300	171	224
200	0.88	93	613	800	353	425	282	355	214	300
250	0.88	93	—	—	441	500	353	425	267	355
315	0.88	93	—	—	556	630	444	500	337	400
400	0.89	96	—	—	—	—	541	630	410	500
500	0.89	96	—	—	—	—	—	—	512	630

1) see 7.1.2 for definitions

The motor current ratings relate to normal internally cooled and surface-cooled threephase motors with synchronous speeds of 1500 min^{-1}.

The fuses relate to the stated motor current ratings and to direct starting:
starting current max. 6 × rated motor current,
starting time max. 5 s.

In the case of slipring motors and also squirrel-cage motors with star-delta starting ($t_{start} \leqq 15$ *s*, $I_{start} = 2\, I_r$) it is sufficient to size the fuses for the rated current of the motor concerned.

Motor relay in phase current: set to 0.58 × motor rated current.

With higher rated current, starting current and/or longer starting time, use larger fuses. Note comments on protection of lines and cables against overcurrents (Section 13.2.3).

2.6 Attenuation constant *a* of transmission systems

The transmission properties of transmission systems, e. g. of lines and two-terminal pair networks, are denoted in logarithmic terms for the ratio of the output quantity to the input quantity of the same dimension. When several transmission elements are arranged in series the total attenuation or gain is then obtained, again in logarithmic terms, by simply adding together the individual partial quantities.

The natural logarithm for the ratio of two quantities, e. g. two voltages, yields the voltage gain in Neper (Np):

$$a = ln\left|U_2/U_1\right| \text{Np}$$

The utilisation of base ten logarithmus results in an increase in dB

$$a = lg\left|U_2/U_1\right| dB$$

If $P = U^2/R$, the power gain, provided $R_1 = R_2$ is

$$a = 0{,}5 \cdot ln\left|P_2/P_1\right| \text{Np bzw.}$$

$$a = 10 \cdot lg\left|P_2/P_1\right| dB$$

The conversion between logarithmic ratios of voltage, current and power when $R_1 \neq R_2$ is

$$\ln U_2/U_1 = \ln I_2/I_1 + \ln R_2/R_1 = \frac{1}{2} \ln P_2/P_1 + \frac{1}{2} \ln R_2/R_1. \text{ bzw.}$$

$$10 \lg P_2/P_1 = 20 \lg U_2/U_1, - 10 \lg R_2/R_1, = 20 \lg I_2/I_1, + 10 \lg R_2/R_1.$$

Relationship between Neper and decibel:

1 dB = 0.115129... Np
1 Np = 8.685889... dB

In the case of absolute levels one refers to the internationally specified values P_0 = 1 mW at 600 Ω, equivalent to $U_0 \cdot$ 0.7746 V, $I_0 \cdot$ 1.291 mA (0 Np or 0 dB).

For example, 0.35 Np signifies a voltage ratio of $U/U_0 = e^{0.35} = 1.419$.

This corresponds to an absolute voltage level of U = 0.7746 V · 1.419 = 1.099 V.

Also 0.35 Np = 0.35 · 8.68859 = 3.04 dB.

3 Calculation of Short-Circuit Currents in Three-Phase Systems

3.1 Terms and definitions

3.1.1 Terms as per IEC 60909

3

Short circuit: the accidental or deliberate connection across a comparatively low resistance or impedance between two or more points of a circuit which usually have differing voltage.

Short-circuit current: the current in an electrical circuit in which a short circuit occurs.

Prospective (available) short-circuit current: the short-circuit current which would arise if the short circuit were replaced by an ideal connection having negligible impedance without alteration of the incoming supply.

Symmetrical short-circuit current: root-mean-square (r.m.s.) value of the symmetrical alternating-current (a.c.) component of a prospective short-circuit current, taking no account of the direct-current (d.c.) component, if any.

Initial symmetrical short-circuit current I_k'': the r.m.s. value of the symmetrical a.c. component of a prospective short-circuit current at the instant the short circuit occurs if the short-circuit impedance retains its value at time zero.

Initial symmetrical (apparent) short-circuit power S_k'': a fictitious quantity calculated as the product of initial symmetrical short-circuit current I_k'', nominal system voltage U_n and the factor $\sqrt{3}$.

D.C. (aperiodic) component $i_{d.c.}$ of short-circuit current: the mean value between the upper and lower envelope curve of a short-circuit current decaying from an initial value to zero.

Peak short-circuit current i_p: the maximum possible instantaneous value of a prospective short-circuit current.

Symmetrical short-circuit breaking current I_b: the r.m.s. value of the symmetrical a.c. component of a prospective short-circuit current at the instant of contact separation by the first phase to clear of a switching device.

Steady-state short-circuit current I_k: the r.m.s. value of the symmetrical a.c. component of a prospective short-circuit current persisting after all transient phenomena have died away.

(Independent) Voltage source: an active element which can be simulated by an ideal voltage source in series with a passive element independently of currents and other voltages in the network.

Nominal system voltage U_n: the (line-to-line) voltage by which a system is specified and to which certain operating characteristics are referred.

Equivalent voltage source $cU_n / \sqrt{3}$: the voltage of an ideal source applied at the short-circuit location in the positive-sequence system as the network's only effective voltage in order to calculate the short-circuit currents by the equivalent voltage source method.

Voltage factor c: the relationship between the voltage of the equivalent voltage source and $U_n / \sqrt{3}$.

Subtransient voltage E" of a synchronous machine: the r.m.s. value of the symmetrical interior voltages of a synchronous machine which is effective behind the subtransient reactance X_d'' at the instant the short circuit occurs.

Far-from-generator short circuit: a short circuit whereupon the magnitude of the symmetrical component of the prospective short-circuit current remains essentially constant.

Near-to-generator short circuit: a short circuit whereupon at least one synchronous machine delivers an initial symmetrical short-circuit current greater than twice the synchronous machine's rated current, or a short circuit where synchronous or induction motors contribute more than 5 % of the initial symmetrical short-circuit current I_k'' without motors.

Positive-sequence short-circuit impedance $\underline{Z}_{(1)}$ of a three-phase a.c. system: the impedance in the positive-phase-sequence system as viewed from the fault location.

Negative-sequence short-circuit impedance $\underline{Z}_{(2)}$ of a three-phase a.c. system: the impedance in the negative-phase-sequence system as viewed from the fault location.

Zero-sequence short-circuit impedance $\underline{Z}_{(0)}$ of a three-phase a.c. system: the impedance in the zero-phase-sequence system as viewed from the fault location. It includes the threefold value of the neutral-to-earth impedance.

Subtransient reactance X_d'' of a synchronous machine: the reactance effective at the instant of the short circuit. For calculating short-circuit currents, use the saturated value X_d''.

Minimum time delay t_{min} of a circuit-breaker: the shortest possible time from commencement of the short-circuit current until the first contacts separate in one pole of a switching device.

3.1.2 Symmetrical components of asymmetrical three-phase systems

In three-phase networks a distinction is made between the following kinds of fault:

a) three-phase fault (I_{k3}'')
b) phase-to-phase fault clear of ground (I_{k2}'')
c) two-phase-to-earth fault (I_{k2E}''; I_{kE2E}'')
d) phase-to-earth fault (I_{k1}'')
e) double earth fault (I_{kEE}'')

A suitable method to calculate the short circuit is to split the system in symmetrical components.

With a symmetrical voltage system the currents produced by an asymmetrical loading (I_1, I_2 and I_3) can be determined with the aid of the symmetrical components (positive-, negative- and zero-sequence system).

The symmetrical components can be found with the aid of complex calculation or by graphical means.

We have:

Current in pos.-sequence system $\underline{I}_m = \frac{1}{3}(\underline{I}_1 + \underline{a}\, I_2 + \underline{a}^2 \underline{I}_3)$

Current in neg.-sequence system $\underline{I}_g = \frac{1}{3}(\underline{I}_1 + \underline{a}^2 \underline{I}_2 + \underline{a}\, \underline{I}_3)$

Current in zero-sequence system $\underline{I}_o = \frac{1}{3}(\underline{I}_1 + \underline{I}_2 + \underline{I}_3)$

For the rotational operators of value 1:

$\underline{a} = e^{j120°}$; $\underline{a}^2 = e^{j240°}$; $1 + \underline{a} + \underline{a}^2 = 0$

If the current vector leading the current in the reference conductor is rotated 120° *backwards,* and the lagging current vector 120 ° *forwards,* the resultant is equal to three times the vector $\underline{I}_m$ in the reference conductor. The negative-sequence components are apparent.

If one turns in the other direction, the positive-sequence system is evident and the resultant is three times the vector $\underline{I}_g$ in the reference conductor.

Geometrical addition of all three current vectors ($\underline{I}_1$, $\underline{I}_2$ and $\underline{I}_3$) yields three times the vector $\underline{I}_0$ in the reference conductor.

If the neutral conductor is unaffected, there is no zero-sequence system.

3.2 Fundamentals of calculation according to IEC 60909-0

In order to select and determine the characteristics of equipment for electrical networks it is necessary to know the magnitudes of the short-circuit currents.

The short-circuit current at first runs asymmetrically to the zero line, Fig. 3-1. It contains an alternating-current component and a direct-current component.

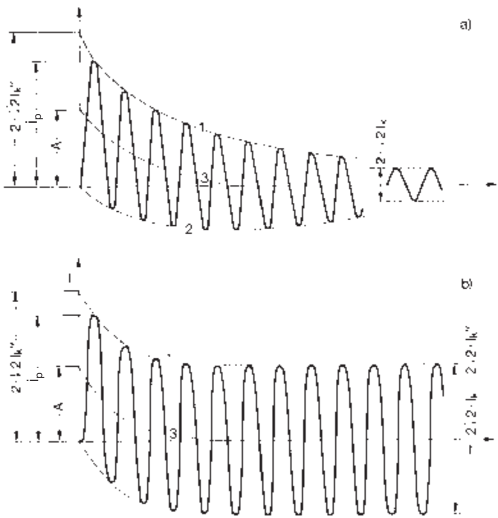


Fig. 3-1

Curve of short-circuit current: a) near-to-generator fault, b) far-from-generator fault I''_k initial symmetrical short-circuit current, i_p peak short-circuit current, I_k steady state short-circuit current, A initial value of direct current, 1 upper envelope, 2 lower envelope, 3 decaying direct current.

Calculatlon of initial symmetrical short-circuit current I_k''

The calculation of short-circuit currents is always based on the assumption of a dead short circuit. Other influences, especially arc resistances, contact resistances, conductor temperatures, inductances of current transformers and the like, can have the effect of lowering the short-circuit currents. Since they are not amenable to calculation, they are accounted for in Table 3-1 by the factor c.

Initial symmetrical short-circuit currents are calculated with the equations in Table 3-2.

Table 3-1

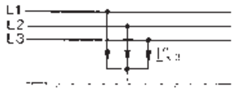
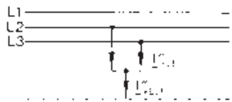
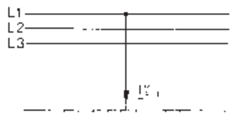
Voltage factor *c*

Nominal voltage	Voltage factor c for calculating the greatest short-circuit current c_{max}	the smallest short-circuit current c_{min}
Low voltage		
100 V to 1000 V		
(see IEC 60038, Table I)		
a) voltage tolerance +6%	1.05	0.95
b) voltage tolerance +10%	1.10	0.95
Medium voltage		
>1 kV to 35 kV	1.10	1.00
(see IEC 60038, Table III)		
High-voltage		
> 35 kV	1.10	1.00
(see IEC 60038, Table IV)		

Note: $c\ U_n$ should not exceed the highest voltage U_m for power system equipment.

Table 3-2

Formulas to calculate initial short-circuit currents network-fed short circuits

Kind of fault		Dimension equations (IEC 60909)
Three-phase fault with or without earth fault		$I''_{k3} = \dfrac{1{,}1 \cdot U_n}{\sqrt{3}\,\lvert \underline{\underline{Z}}_1 \rvert}$
Phase-to-phase fault clear of ground		$I''_{k2} = \dfrac{1{,}1 \cdot U_n}{\lvert \underline{\underline{Z}}_1 + \underline{\underline{Z}}_2 \rvert}$
Two-phase-to-earth fault		$I''_{kE2E} = \dfrac{\sqrt{3} \cdot 1{,}1\, U_n}{\left\lvert \underline{\underline{Z}}_1 + \underline{\underline{Z}}_0 + \underline{\underline{Z}}_0 \dfrac{\underline{\underline{Z}}_1}{\underline{\underline{Z}}_2} \right\rvert}$
Phase-to-earth fault		$I''_{k1} = \dfrac{\sqrt{3} \cdot 1{,}1 \cdot U_n}{\lvert \underline{\underline{Z}}_1 + \underline{\underline{Z}}_2 + \underline{\underline{Z}}_0 \rvert}$

The directions of the arrows shown here are chosen arbitrarily.

Calculation of peak short-circuit current i_p

When calculating the peak short-circuit current i_p, sequential faults are disregarded. Three-phase short circuits are treated as though the short circuit occurs in all three conductors simultaneously. We have:

$$i_p = \kappa \cdot \sqrt{2} \cdot I''_k.$$

The factor κ takes into account the decay of the d. c. component. It can be calculated as

$\kappa = 1.02 + 0.98\ e^{-3\ R/X}$ or taken from Fig. 3-2.

Exact calculation of i_p with factor κ is possible only in networks with branches having the same ratios R/X. If a network includes parallel branches with widely different ratios R/X, the following methods of approximation can be applied:

a) Factor κ is determined uniformly for the smallest ratio R/X. One need only consider the branches which are contained in the faulted network and carry partial short-circuit currents.

b) The factor is found for the ratio R/X from the resulting system impedance $Z_k = R_k + jX_k$ at the fault location, using $1.15 \cdot \kappa_k$ for calculating i_p. In low-voltage networks the product $1.15 \cdot \kappa$ is limited to 1.8, and in high-voltage networks to 2.0. If the ratio of all network branches is $R/\kappa \leq 0{,}3$, the factor of 1.15 does not need to betaken into account.

c) Factor κ can also be calculated by the method of the equivalent frequency as in IEC 60909, para. 4.3.1.2.

The maximum value of $\kappa = 2$ is attained only in the theoretical limiting case with an active resistance of $R = 0$ in the short-circuit path. Experience shows that with a short-circuit at the generator terminals a value of $\kappa = 1.8$ is not exceeded with machines < 100 MVA.

With a unit-connected generator and high-power transformer, however, a value of $\kappa = 1.9$ can be reached in unfavourable circumstances in the event of a short circuit near the transformer on its high-voltage side, owing to the transformer's very small ratio R/X. The same applies to networks with high short circuit currents if a short circuit occurs after a reactor.

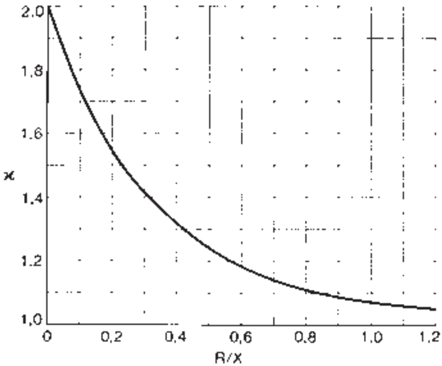


Fig. 3-2

Factor κ

Calculation of steady-state short-circuit current I_k

Three-phase fault with single supply

$I_k = I''_{kQ}$	network
$I_k = \lambda \cdot I_{rG}$	synchronous machine

Three-phase fault with single supply from more than one side

$I_k = \lambda \cdot I_{rG} + I''_{kQ}$

$\lambda \cdot I_{rG}$	contribution of a generator in relation to the high voltage side of a power plant
I''_{kQ}	initial symmetrical short-circuit current of network

Three-phase fault in a meshed network

$I_k = I''_{koM}$

I''_{koM}	initial symmetrical short-circuit current without motors

I_k depends on the excitation of the generators, on saturation effects and on changes in switching conditions in the network during the short circuit. An adequate approximation for the upper and lower limit values can be obtained with the factors λ_{max} and λ_{min}, Fig. 3-3 and 3-4. I_{rG} is the rated current of the synchronous machine.

For X_{dsat} one uses the reciprocal of the no-load/short-circuit ratio I_{k0}/I_{rG}.

The 1st series of curves of λ_{max} applies when the maximum excitation voltage reaches 1.3 times the excitation voltage for rated load operation and rated power factor in the case of turbogenerators, or 1.6 times the excitation for rated load operation in the case of salient-pole machines.

The 2nd series of curves of λ_{max} applies when the maximum excitation voltage reaches 1.6 times the excitation for rated load operation in the case of turbogenerators, or 2.0 times the excitation for rated load operation in the case of salient-pole machines.

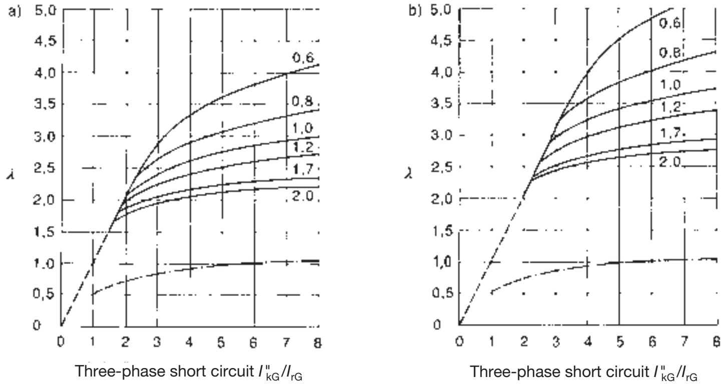


Fig. 3-3

Factors λ for salient-pole machines in relation to ratio I''_{kG}/I_{rG} and saturated synchronous reactance X_d of 0.6 to 2.0, —— λ_{max}, – · – λ_{min};
a) Series 1 U_{fmax} / U_{fr} = 1.6; b) Series 2 U_{fmax} / U_{fr} = 2.0.

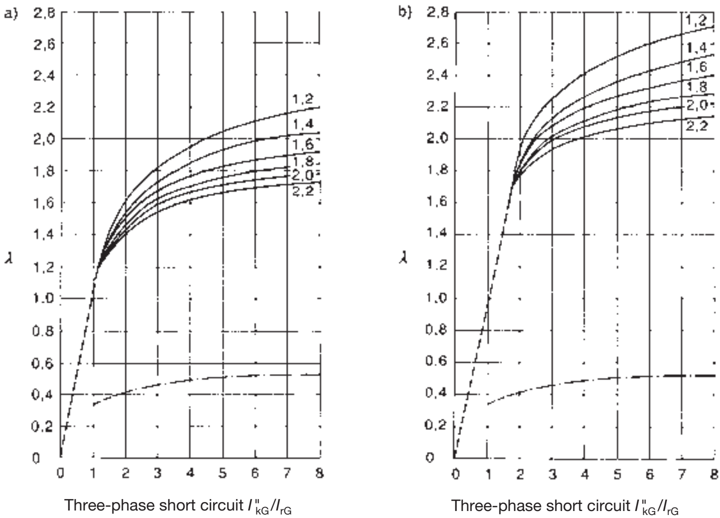


Fig. 3-4

Factors λ for turbogenerators in relation to ratio I''_{kG}/I_{rG} and saturated synchronous reactance X_d of 1.2 to 2.2, —— λ_{max}, – · – λ_{min};
a) Series 1 U_{fmax} / U_{fr} = 1.3; b) Series 2 U_{fmax} / U_{fr} = 1.6.

Calculation of symmetrical breaking current I_b

Three-phase fault with single supply

$I_b = \mu \cdot I''_{kG}$	synchronous machine
$I_b = \mu \cdot q \cdot I''_{kM}$	induction machine
$I_b = I''_{kQ}$	network

Three-phase fault with single supply from more than one side

$$I_b = I_{bs} + I''_{kQ} + I_{bM}$$

I_{bs}	symmetrical short-circuit breaking current of a power plant
I_{kQ}	initial symmetrical short-circuit current of a network
I_{bM}	symmetrical short-circuit breaking current of an induction machine

Three-phase fault in a meshed network

$$I_a = I''_k$$

A more exact result for the symmetrical short-circuit breaking current is obtained with IEC 60909.

The factor μ denotes the decay of the symmetrical short-circuit current during the switching delay time. It can be taken from Fig. 3-5 or the equations.

$$\mu = 0.84 + 0.26\, e^{-0.26\, I''_{kG}/I_{rG}} \text{ for } t_{min} = 0.02 \text{ s}$$

$$\mu = 0.71 + 0.51\, e^{-0.30\, I''_{kG}/I_{rG}} \text{ for } t_{min} = 0.05 \text{ s}$$

$$\mu = 0.62 + 0.72\, e^{-0.32\, I''_{kG}/I_{rG}} \text{ for } t_{min} = 0.10 \text{ s}$$

$$\mu = 0.56 + 0.94\, e^{-0.38\, I''_{kG}/I_{rG}} \text{ for } t_{min} = 0.25 \text{ s}$$

$$\mu_{max} = 1$$

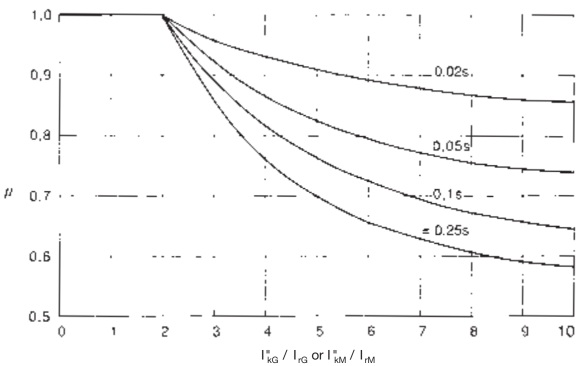


Fig. 3-5

Factor μ for calculating the symmetrical short-circuit breaking current I_b as a function of ratio I''_{kG}/I_{rG} or I''_{kM}/I_{rM}, and of switching delay time t_{min} of 0.02 to 0.25 s.

If the short circuit is fed by a number of independent voltage sources, the symmetrical breaking currents may be added.

With compound excitation or converter excitation one can put $\mu = 1$ if the exact value is not known. With converter excitation Fig. 3-5 applies only if $t_v \leq 0.25$ s and the maximum excitation voltage does not exceed 1.6 times the value at nominal excitation. In all other cases put $\mu = 1$.

The factor q applies to induction motors and takes account of the rapid decay of the motor's short-circuit current owing to the absence of an excitation field. It can be taken from Fig. 3-6 or the equations.

$q = 1.03 + 0.12 \ln m$ for $t_{min} = 0.02$ s

$q = 0.79 + 0.12 \ln m$ for $t_{min} = 0.05$ s

$q = 0.57 + 0.12 \ln m$ for $t_{min} = 0.10$ s

$q = 0.26 + 0.10 \ln m$ for $t_{min} = 0.25$ s

$q_{max} = 1$

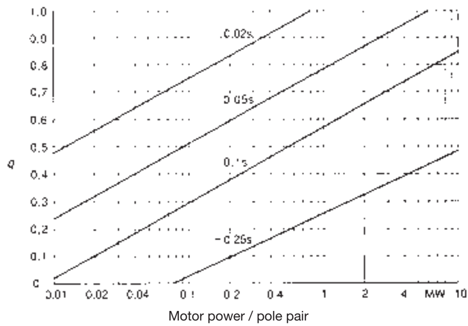


Fig. 3-6

Factor q for calculating the symmetrical short-circuit breaking current of induction motors as a function of the ratio motor power / pole pair and of switching delay time t_{min} *of 0.02 to 0.25 s.*

The equations for calculating initial short-circuit currents I''_k are given in Table 3-2.

The kind of fault which produces the highest short-circuit currents at the fault site can be determined with Fig. 3-7. The double earth fault is not included in Fig. 3-7; it results in smaller currents than a two-phase short-circuit. For the case of a two-phase-to-earth fault, the short-circuit current flowing via earth and earthed conductors I''_{kE2E} is not considered in Fig. 3-7.

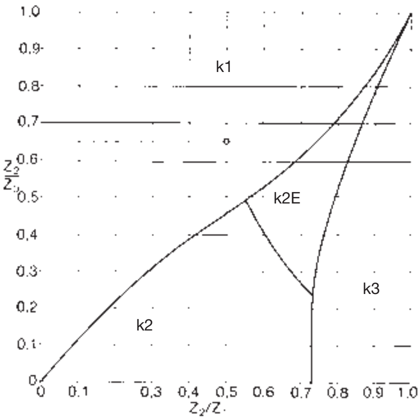


Fig. 3-7

Diagram for determining the fault with the highest short-circuit current

Example: Z_2/Z_1 = 0.5; Z_2/Z_0 = 0.65, the greatest short-circuit current occurs with a phase – to-earth fault.

Table 3-3

Reference values for Z_2/Z_1 and Z_2/Z_0

Impedance ratio		Z_2/Z_1	Z_2/Z_0
to calculate			
I''_k	near to generator	1	–
	far from generator	1	–
I_k	near to generator	0.05…0.25	–
	far from generator	0.25…1	–
Networks	with isolated neutral	–	0
	with earth compensation	–	0
	with neutral earthed via impedances	–	0…0.25
Networks with effectively earthed neutral		–	> 0.25

The data in Fig. 3-7 are true provided that the impedance angles of $\underline{Z}_2/\underline{Z}_1$ and $\underline{Z}_0$ do not differ from each other by more than 15 °. Reference values for Z_2/Z_1 and Z_2/Z_0 are given in Table 3-3.

i_p and I_k are:

for phase-to-phase fault clear of ground: $i_{p2} = \kappa \cdot \sqrt{2} \cdot I''_{k2}$,
$I_{k2} = I_{b2} = I''_{k2}$;

for two-phase-to-earth fault: no calculation necessary;

for phase-to-earth fault: $i_{p1} = \kappa \cdot \sqrt{2} \cdot I''_{k1}$,
$I_{k1} = I_{b1} = I''_{k1}$.

Maximum short-circuit currents

When calculating the maximum short-circuit currents, the following conditions are to be assumed:

- maximum voltage factor
- the network's topology is to be chosen in such a way that the maximum short-circuit currents are expected
- motors are to be taken into account
- the resistances of lines are to be determined at a temperature of 20 °C

Minimum short-circuit currents

When calculating minimum short-circuit currents one has to make the following changes:

- Reduced voltage factor *c*
- The network's topology must be chosen so as to yield the minimum short-circuit currents.
- Motors are to be disregarded
- The resistances R_L of the lines must be determined for the conductor temperature t_e at the end of the short circuit (R_{L20} conductor temperature at 20 °C):

  $R_L = [1 + 0.004\,(t_e - 20\,°C)/°C] \cdot R_{L20}$

3.3 Impedances of electrical equipment

The impedances of electrical equipment are generally stated by the manufacturer. The values given here are for guidance only.

3.3.1 System infeed

The effective impedance of the system infeed, of which one knows only the initial symmetrical short-circuit current I''_{kQ} at junction point Q, is calculated as:

$$Z_Q = \frac{c \cdot U_{nQ}}{\sqrt{3} \cdot I''_{kQ}}$$

Here U_{nQ} Nominal system voltage

I''_{kQ} Initial symmetrical short-circuit current

$\underline{Z}_Q$ $= R_Q + jX_Q$, effective impedance of system infeed for short-circuit current calculation

X_Q $= \sqrt{Z_Q^2 - R_Q^2}$.

If no precise value is known for the equivalent active resistance R_Q of the system infeed, one can put $R_Q = 0.1\ X_Q$ *with* $X_Q = 0.995\ Z_Q$. The effect of temperature can be disregarded.

If the impedance is referred to the low-voltage side of the transformer, we have

$$Z_Q = \frac{c \cdot U_{nQ}}{\sqrt{3} \cdot I''_{kQ}} \cdot \frac{1}{t_r^2}.$$

3.3.2 Electrical machines

Synchronous generators with direct system connection

For calculating short-circuit currents the positive- and negative-sequence impedances of the generators are taken as

$$\underline{Z}_{GK} = K_G \cdot \underline{Z}_G = K_G\,(R_G + jX''_d)$$

with the correction factor

$$K_G = \frac{U_n}{U_{rG}} \cdot \frac{c_{max}}{1 + X''_d \cdot \sin \varphi_{rg}}$$

Here:

c_{max} Voltage factor

U_n Nominal system voltage

U_{rG} Rated voltage of generator

$\underline{Z}_{GK}$ Corrected impedance of generator

$\underline{Z}_G$ Impedance of generator ($\underline{Z}_G = R_G + jX''_d$)

X''_d Subtransient reactance of generator referred to impedance

$$x''_d = X''_d / Z_{rG} \qquad \underline{Z}_{rG} = U^2_{rG}/S_{rG}$$

R_G Resistance of a generator

The peak short-circuit current can be calculatet with sufficient accuracy if R_G is replaced bei R_{Gf}:

$R_{Gf} = 0.05 \cdot X''_d$ for rated powers ≧ 100 MVA } with high-voltage
$R_{Gf} = 0.07 \cdot X''_d$ for rated powers < 100 MVA } generators
$R_{Gf} = 0.15 \cdot X''_d$ for low-voltage generators.

The factors 0.05, 0.07 and 0.15 also take account of the decay of the symmetrical short-circuit current during the first half-cycle.
Guide values for reactances are shown in Table 3-4.

Table 3-4

Reactances of synchronous machines

Generator type	Turbogenerators	Salient-pole generators with damper winding[1]	Salient-pole generators without damper winding
Subtransient reactance (saturated) x''_d in %	9…22[2]	12…30[3]	20…40[3]
Transient reactance (saturated) x''_d in %	14…35[4]	20…45	20…40
Synchronous reactance (unsaturated)[5] x''_d in %	140…300	80…180	80…180
Negative-sequence reactance[6] x_2 in %	9…22	10…25	30…50
Zero-sequence reactance[7] x_0 in %	3…10	5…20	5…25

1) Valid for laminated pole shoes and complete damper winding and also for solid pole shoes with strap connections.
2) Values increase with machine rating. Low values for low-voltage generators.
3) The higher values are for low-speed rotors (n < 375 min^{-1}).
4) For very large machines (above 1000 MVA) as much as 40 to 45 %.
5) Saturated values are 5 to 20 % lower.
6) In general $x_2 = 0.5\,(x''_d + x''_q)$. Also valid for transients.
7) Depending on winding pitch.

Power units with tap-changer

For the impedances, use

$$\underline{Z}_S = K_S\,(t_r^2\,\underline{Z}_G + \underline{Z}_{TOS})$$

with the correction factor

$$K_S = \frac{U_{nQ}^2}{U_{rG}^2} \cdot \frac{U_{rTUS}^2}{U_{rTOS}^2} \cdot \frac{c_{max}}{1 + (X''_d - X''_T)\sin\varphi_{rG}}$$

Here:

$\underline{Z}_{KW}$ Corrected impedance of power plant unit, referred to high-voltage side

$\underline{Z}_G$ Subtransient Impedance of generator

$\underline{Z}_{TOS}$ Impedance of unit transformer, referred to high-voltage side

U_{nQ} Nominal system voltage at main connecting point Q of power unit

U_{rG} Rated voltage of generator

X_T Referred reactance of unit transformer at principal tapping

U_{rT} Rated voltage of transformer

For application of the correction factor it is assumed that the service voltage at the generator terminals is equal to U_{rG}.

Power units without tap-changer

For the impendance, use:

$$\underline{Z}_{SO} = K_{SO}\,(t_r^2\,\underline{Z}_G + \underline{Z}_{TOS})$$

with the correction factor

$$K_{SO} = \frac{U_{na}}{U_{rG}\,(1 + P_G)} \cdot \frac{U_{rTUS}}{U_{rTOS}} \cdot (1 \pm P_r) \cdot \frac{c_{max}}{1 + X''_d\,\sin\varphi_{rG}}$$

Here:

$\underline{Z}_{SO}$ Corrected impendance of the power plant unit, referred to the high voltage side

$\underline{Z}_G$ Subtransient impedance of the generator

$\underline{Z}_{TOS}$ Impedance of the unit transformer, referred to the high voltage side

U_{na} Network voltage at the termination point Q of the power plant unit

U_{rG} rated voltage of the generator

X''_d Per unit subtransient reactance of the generator

P_T Tap position of the transformer

Synchronous motors

The values for synchronous generators are also valid for synchronous motors and synchronous condensers.

Induction motors

Induction motors contribute values to I''_k, i_p and I_b and in the case of a asymmetrical short circuit, to I_k as well.

The short-circuit reactance Z_M of induction motors is calculated from the ratio I_{an}/I_{rM}:

$$Z_M = \frac{1}{I_{start}/I_{rM}} \cdot \frac{U_{rM}}{\sqrt{3} \cdot I_{rM}} = \frac{U^2_{rM}}{I_{start}/I_{rM} \cdot S_{rM}}$$

where I_{start} Motor starting current, the rms value of the highest current the motor draws with the rotor locked at rated voltage and rated frequency after transients have decayed,

U_{rM} Rated voltage of motor

I_{rM} Rated current of motor

S_{rM} Apparent power of motor ($\sqrt{3} \cdot U_{rM} \cdot I_{rM}$).

The heaviest short-circuit currents I''_k, i_p, I_b and I_k in the event of three-phase, two-phase and single-phase short circuits are calculated as shown in Table 3-5.

For calculating the peak short-circuit current:
κ_m = 1.65 for HV motors, motor power per pole pair < 1MW
κ_m = 1.75 for HV motors, motor power per pole pair ≥ 1MW
κ_m = 1.3 for LV motors

Table 3-5

To calculate short-circuit currents of induction motors with terminal short circuit
(The single-phase short-circuit is determined by the network configuration)

type of error	three-phase	two-phase	single-phase
Initial symmetrical short-circuit current	$I''_{k3M} = \frac{c \cdot U_n}{\sqrt{3} \cdot Z_M}$	$I''_{k2M} = \frac{\sqrt{3}}{2} I''_{k3M}$	pls refer to legend
Peak short-circuit current	$i_{p3M} = \kappa_m \sqrt{2} I''_{k3M}$	$i_{p2M} = \frac{\sqrt{3}}{2} i_{p3M}$	$i_{p1M} = \kappa_m \sqrt{2} \cdot I''_{k1M}$
Symmetrical short-circuit breaking current	$I_{b3M} = I''_{k3M}$	$I_{b2M} \sim \frac{\sqrt{3}}{2} I''_{k3M}$	$I_{b1M} \approx I''_{k1M}$
Steady-state short-circuit current	$I_{k3M} = 0$	$I_{k2M} \sim \frac{1}{2} I''_{k3M}$	$I_{k1M} \approx I''_{k1M}$

The influence of induction motors connected to the faulty network by way of transformers can be disregarded if

$$\frac{\Sigma P_{rM}}{\Sigma S_{rT}} \leq \frac{0,8}{\frac{c \cdot 100\, \Sigma S_{rT}}{\sqrt{3} \cdot U_{na} \cdot I''_{ka}} - 0,3}.$$

Here,

ΣP_{rM} is the sum of the ratings of all high-voltage and such low-voltage motors as need to be considered,

ΣS_{rT} is the sum of the ratings of all transformers feeding these motors and

S''_k is the initial fault power of the network (without the contribution represented by the motors).

I''_{ka} Initial symmetrical short-circuit current a the termination point without motors

U_{na} System nominal voltage at termination point.

To simplify calculation, the rated current I_{rM} of the low-voltage motor group can be taken as the transformer current on the low-voltage side.

3

3.3.3 Transformers and reactors

Transformers

The positive- and negative-sequence transformer impedances are equal. The zero-sequence impedance may differ from this.

The positive-sequence impedances of the transformers $\underline{Z}_1 = \underline{Z}_T = R_T + jX_T$ are calculated as follows:

$$Z_T = \frac{U_{kr}}{100\ \%} \frac{U^2_{rT}}{S_{rT}} \qquad R_T = \frac{u_{Rr}}{100\ \%} \frac{U^2_{rT}}{S_{rT}} \qquad X_T = \sqrt{Z^2_T - R^2_T}$$

Table 3-6

Typical values of impedance voltage drop u_k of three-phase transformers

Rated primary voltage in kV	5…20	30	60	110	220	400
u_k in %	3.5…8	6…9	7…10	9…12	10…14	10…16

Table 3-7

Typical values for ohmic voltage drop u_R of three-phase transformers

Power rating in MVA	0.25	0.63	2.5	6.3	12.5	31.5
u_R in %	1.4…1.7	1.2…1.5	0.9…1.1	0.7… 0.85	0.6…0.7	0.5…0.6

For transformers with ratings over 31.5 MVA, u_R < 0 5 %.

An impendance correction factor is to be introduced for two-winding transformers with and without tap changers

$$\underline{Z}_{TK} = K_T \cdot \underline{Z}_T$$

with correction factor

$$K_T = 0{,}95 \cdot \frac{c_{max}}{1 + 0{,}6 \cdot X_T}$$

C_{max} Voltage factor of the low voltage side

X_T per unit rectance of the transformer

When the long-term service conditions of the network transformers are reliably known, the following factor can be used.

$$K_T = \frac{U_n}{U_b} \cdot \frac{c_{max}}{1 + |X_T^b - X_{rT}| \cdot \sin \varphi_T^b}$$

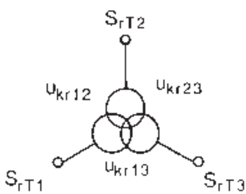
U_b maximum service voltage in front of the short circuit

I_T^b maximum service current in front of the short circuit

φ_T^b angle of the power factor in front of the short circuit

With three-winding transformers, the positive-sequence impedances for the corresponding rated throughput capacities referred to voltage U_{rT} are:

a)



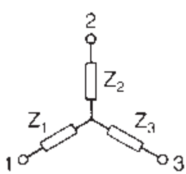
$$|\underline{Z}_{12}| = |\underline{Z}_1| + |\underline{Z}_2| = u_{kr12} \frac{U_{rT}^2}{S_{rT12}}$$

$$|\underline{Z}_{13}| = |\underline{Z}_1| + |\underline{Z}_2| = u_{kr13} \frac{U_{rT}^2}{S_{rT13}}$$

$$|\underline{Z}_{23}| = |\underline{Z}_2| + |\underline{Z}_3| = u_{kr23} \frac{U_{rT}^2}{S_{rT23}}$$

and the impedances of each winding are

b)



$$\underline{Z}_1 = \frac{1}{2}(\underline{Z}_{12} + \underline{Z}_{13} - \underline{Z}_{23})$$

$$\underline{Z}_2 = \frac{1}{2}(\underline{Z}_{12} + \underline{Z}_{23} - \underline{Z}_{13})$$

$$\underline{Z}_3 = \frac{1}{2}(\underline{Z}_{13} + \underline{Z}_{23} - \underline{Z}_{12})$$

Fig. 3-9

Equivalent diagram a) and winding impedance b) of a three-winding transformer
u_{kr12} short-circuit voltage referred to S_{rT12}
u_{kr13} short-circuit voltage referred to S_{rT13}
$u_{kr2}3$ short-circuit voltage referred to S_{rT23}
S_{rT12}, S_{rT13}, S_{rT23} rated throughput capacities of transformer

Three-winding transformers are mostly high-power transformers in which the reactances are much greater than the ohmic resistances. As an approximation, therefore, the impedances can be put equal to the reactances.

A correction factor is to be introduced for three-winding transformers with and without tap changers.

$$K_{T12} = 0{,}95 \cdot \frac{c_{max}}{1 + 0{,}6 \cdot X_{T12}}; \quad K_{T13} = 0{,}95 \cdot \frac{c_{max}}{1 + 0{,}6 \cdot X_{T13}}; \quad K_{T23} = 0{,}95 \cdot \frac{c_{max}}{1 + 0{,}6 \cdot X_{T23}};$$

The zero-sequence impedance varies according to the construction of the core, the kind of connection and the other windings (table 3-7).

Fig. 3-10 shows examples for measuring the zero-sequence impedances of transformers

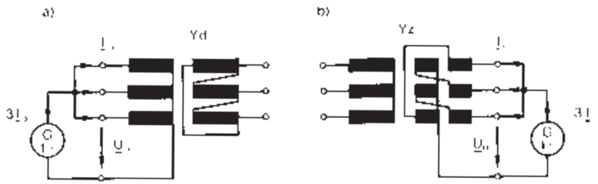
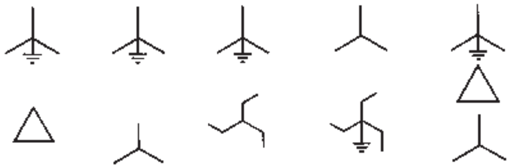


Fig. 3-10

Measurement of the zero-sequence impedances of transformers for purposes of short-circuit current calculation: a) connection Yd, b) connection Yz

Table 3-8

Reference values of X_0/X_1 for three-phase transformers

Connection 					
Three-limb core	0.7…1 ∞	3…10 ∞	3…10 ∞	∞ 0.1…0.15	1…2.4 ∞
Five-limb core	1 ∞	10…100 ∞	10…100 ∞	∞ 0,1…0.15	1…2.4 ∞
3 single-phase transformers	1 ∞	10…100 ∞	10…100 ∞	∞ 0,1…0.15	1…2.4 ∞

Values in the upper line when zero voltage applied to upper winding, values in lower line when zero voltage applied to lower winding (see Fig. 3-10).

For low-voltage transformers one can use:

Connection Dy $R_{0T} \approx R_T \quad X_{0T} \approx 0.95\, X_T$

Connection Dz, Yz $R_{0T} \approx 0.4\, R_T \quad X_{0T} \approx 0.1\, X_T$

Connection Yy[1)] $R_{0T} \approx R_T \quad X_{0T} \approx 7 \ldots 100^{2)}\, X_T$

1) Transformers in Yy are not suitable for multiple-earthing protection.
2) HV star point not earthed.

Current-limiting reactors

The reactor reactance X_D is

$$X_D = \frac{\Delta u_r \cdot U_n}{100\,\% \cdot \sqrt{3} \cdot I_r} = \frac{\Delta u_r \cdot U_n^2}{100\,\% \cdot S_D}$$

where Δu_r Rated percent voltage drop of reactor

U_n Network voltage

I_r Current rating of reactor

S_D Throughput capacity of reactor.

Standard values for the rated voltage drop

Δu_r in %: 3, 5, 6, 8, 10

Further aids to calculation are given in Sections 12.1 and 12.2. The effective resistance is negligibly small. The reactances are of equal value in the positive-, negative- and zero-sequence systems.

3.3.4 Three-phase overhead lines

The usual equivalent circuit of an overhead line for network calculation purposes is the Π circuit, which generally includes resistance, inductance and capacitance, Fig. 3-11.

In the positive phase-sequence system, the effective resistance R_L of high-voltage overhead lines is usually negligible compared with the inductive reactance. Only at the low- and medium-voltage level are the two roughly of the same order.

When calculating short-circuit currents, the positive-sequence capacitance is disregarded. In the zero-sequence system, account normally has to be taken of the conductor-earth capacitance. The leakage resistance R_a need not be considered.

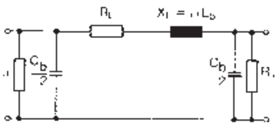


Fig. 3-11

Equivalent circuit of an overhead line

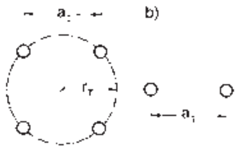


Fig. 3-12

Conductor configurations
a) 4-wire bundle
b) 2-wire bundle

Calculation of positive- and negative-sequence impedance

Symbols used:

a_T Conductor strand spacing,
r Conductor radius,
r_e Equivalent radius for bundle conductors (for single strand $r_e = r$),
n Number of strands in bundle conductor,
r_T Radius of circle passing through midpoints of strands of a bundle (Fig. 3-12),
d Mean geometric distance between the three wires of a three-phase system,
d_{12}, d_{23}, d_{31}, see Fig. 3-13,
r_S Radius of earth wire,
μ_0 Space permeability $4\pi \cdot 10^{-4} \frac{\text{H}}{\text{km}}$,
μ_S Relative permeability of earth wire,
μ_L Relative permeability of conductor (in general $\mu_L = 1$),
ω Angular frequency in s^{-1},
δ Earth current penetration in m,
ρ Specific earth resistance,
R_L Resistance of conductor,
R_S Earth wire resistance (dependent on current for steel wires and wires containing steel),
L_b Inductance per conductor in H/km; $L_b = L_1$.

Calculation

The inductive reactance (X_L) for symmetrically twisted single-circuit and double-circuit lines are:

Single-circuit line: $X_L = \omega \cdot L_b = \omega \cdot \frac{\mu_0}{2\pi} \left(\ln \frac{d}{r_e} + \frac{1}{4n} \right)$ in Ω/km per conductor,

Double-circuit line: $X_L = \omega \cdot L_b = \omega \cdot \frac{\mu_0}{2\pi} \left(ln \frac{d\,d'}{r_e d''} + \frac{1}{4n} \right)$ in Ω/km per conductor;

Mean geometric distances between conductors (see Fig. 3-13): (Symmetric to tower center line)

$$d = \sqrt[3]{d_{12} \cdot d_{23} \cdot d_{31}}$$
$$d' = \sqrt[3]{d_{12'} \cdot d_{23'} \cdot d_{13'}}$$
$$d'' = \sqrt[3]{d_{11'} \cdot d_{22'} \cdot d_{33'}}$$

The equivalent radius r_e is

$$r_e = \sqrt[n]{n \cdot r \cdot r_T^{n-1}}$$

In general, if the strands are arranged at a uniform angle *n:*

$$r_e = \frac{a_T}{2 \cdot \sin \frac{\pi}{n}},$$

e. g. for a 4-wire bundle: $r_e = \frac{a_T}{2 \cdot \sin \frac{\pi}{4}} = \frac{a_T}{\sqrt{2}}$

The positive- and negative-sequence impedance is calculated as:

$$\underline{Z}_1 = \underline{Z}_2 = \frac{R_1}{n} + X_L$$

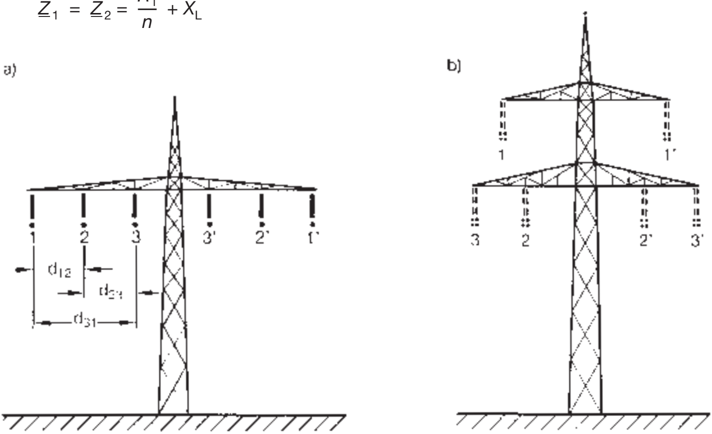


Fig. 3-13

Tower configurations: double-circuit line with one earth wire; a) flat, b) “Danube‘”

Fig. 3-14 and 3-15 show the positive-sequence (and also negative-sequence) reactances of three-phase overhead lines.

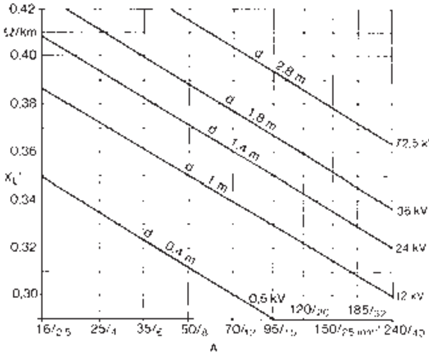


Fig. 3-14

Reactance X'_L (positive phase sequence) of three-phase transmission lines up to 72.5 kV, f = 50 Hz, as a function of conductor cross section A, single-circuit lines with aluminium / steel wires, d = mean geometric distance between the 3 wires.

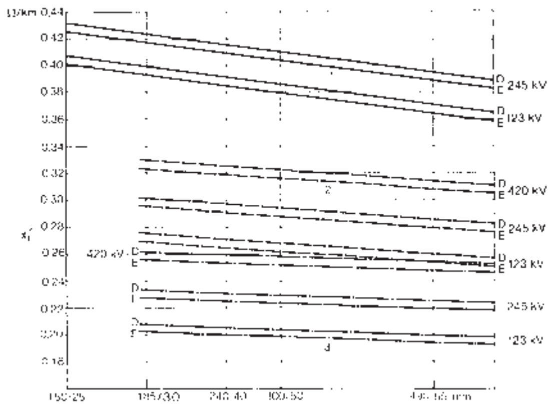


Fig. 3-15

Reactance XL (positive-sequence) of three-phase transmission lines with alumimium / steel wires ("Danube" configuration), f = 50 Hz. Calculated for a mean geometric distance between the three conductors of one system, at 123 kV: d = 4 m, at 245 kV: d = 6 m, at 420 kV: d = 9.4 m;
E denotes operation with one system; D denotes operation with two systems; 1 single wire, 2 two-wire bundle, a = 0.4 m, 3 four-wire bundle, a = 0.4 m.

The following formulae apply:

Single-circuit line without earth wire	$\underline{Z}_0^{\mathrm{I}} = R_0 + \mathrm{j}X_0$
Single-circuit line with earth wire	$\underline{Z}_0^{\mathrm{Is}} = \underline{Z}_0^{\mathrm{I}} - 3\,\dfrac{\underline{Z}_{\mathrm{as}}^2}{\underline{Z}_{\mathrm{s}}}$
Double-circuit line without earth wire	$\underline{Z}_0^{\mathrm{II}} = \underline{Z}_0^{\mathrm{I}} + 3\,\underline{Z}_{\mathrm{ab}}$
Double-circuit line with earth wire	$\underline{Z}_0^{\mathrm{IIs}} = \underline{Z}_0^{\mathrm{II}} - 6\,\dfrac{\underline{Z}_{\mathrm{as}}^2}{\underline{Z}_{\mathrm{s}}}$

For the zero-sequence resistance and zero-sequence reactance included in the formulae, we have:

Zero-sequence resistance

$$R_0 = R_{\mathrm{L}} + 3\,\frac{\mu_0}{8}\omega, \qquad d = \sqrt[3]{d_{12}\,d_{23}\,d_{31}};$$

Zero-sequence reactance

$$X_0 = \omega\,\frac{\mu_0}{2\,\pi}\left(3\,\ln\frac{\delta}{\sqrt[3]{rd^2}} + \frac{\mu_{\mathrm{L}}}{4\,n}\right) \qquad \delta = \frac{1.85}{\sqrt{\mu_0\,\dfrac{1}{\rho}\,\omega}}.$$

Table 3-9

Earth current penetration δ in relation to specific resistance ρ at f = 50 Hz acc. DIN VDE 0228 and CCIT

Nature of soil		marl	clay	porous lime, sandstone, clay schist	Quartz, Impervious limestone	Granite, Clayey slate	Gneiss
ρ	Ωm	20	10	100	300	1 000	2 000
$\kappa = \dfrac{1}{\rho}$	μS/cm	500	1 000	100	33	10	5
δ	m	420	290	930	1 610	2 940	4 160

The earth current penetration δ denotes the depth at which the return current diminishes such that its effect is the same as that of the return current distributed over the earth cross section.

Compared with the single-circuit line without earth wire, the double-circuit line without earth wire also includes the additive term $3 \cdot \underline{Z}_{a\,b}$, where $\underline{Z}_{a\,b}$ is the coupling impedance of the loops system a/earth and system b/earth:

$$\underline{Z}_{a\,b} = \frac{\mu_0}{8}\,\omega + \mathrm{j}\,\omega\,\frac{\mu_0}{2\,\pi}\ln\frac{\delta}{d_{a\,b}},$$

$$d_{a\,b} = \sqrt{d'd''}$$

$$d' = \sqrt[3]{d_{12'} \cdot d_{23'} \cdot d_{13'}}$$

$$d'' = \sqrt[3]{d_{12'} \cdot d_{23'} \cdot d_{33'}}$$

For a double-circuit line with earth wires (Fig. 3-16) account must also be taken of:

1. Alternating impedance of the loops conductor/earth and earth wire/earth:

$$\underline{Z}_{as} = \frac{\mu_0}{8}\,\omega + \mathrm{j}\,\omega\,\frac{\mu_0}{2\,\pi}\ln\frac{\delta}{d_{as}}, \qquad d_{as} = \sqrt[3]{d_{1s}\,d_{2s}\,d_{3s}}$$

for two earth wires:

$$d_{as} = \sqrt[6]{d_{1s1}\,d_{2s1}\,d_{3s1}\,d_{1s2}\,d_{2s2}\,d_{3s2}}$$

2. Impedance of the loop earth wire/earth:

$$\underline{Z}_{s} = R + \frac{\mu_0}{8}\,\omega + \mathrm{j}\,\omega\,\frac{\mu_0}{2\,\pi}\left(\ln\frac{\delta}{r} + \frac{\mu_s}{4\,n}\right).$$

The values used are for one earth wire $n = 1$; $r = r_s$; $R = R_s$;

for two earth wires $n = 2$; $r = \sqrt{r_s\,d_{s1s2}}$; $R = \frac{R_s}{2}$

when d_{s1s2} is the distance between two symmetrically arranged earth wires.

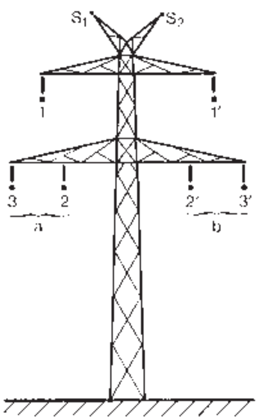


Fig: 3-16

Tower configuration: Double-circuit line with two earth wires, system a and b

Values of the ratio R_s/R_{-} (effective resistance / d. c. resistance) are roughly between 1.4 and 1.6 for steel earth wires, but from 1.05 to 1.0 for well-conducting earth wires of Al/St, Bz or Cu.

For steel earth wires, one can take an average of $\mu_s \approx 25$, while values of about $\mu_s = 5$ to 10 should be used for Al/St wires with one layer of aluminium. For Al/St earth wires with a cross-section ratio of 6:1 or higher and two layers of aluminium, and also for earth wires or ground connections of Cu, $\mu_s \approx 1$.

The operating capacitances C_b of high-voltage lines of 110 kV to 380 kV lie within a range of $9 \cdot 10^{-9}$ to $14 \cdot 10^{-9}$ F/km. The values are higher for higher voltages.

The earth wires must be taken into account when calculating the conductor/earth capacitance. The following values are for guidance only:

Flat tower: $C_E = (0.6 \ldots 0.7) \cdot C_b$.

“Danube” tower: $C_E = (0.5 \ldots 0.55) \cdot C_b$

The higher values of C_E are for lines with earth wire, the lower values for those without earth wire.

The value of C_E for double-circuit lines is lower than for single-circuit lines.

The relationship between conductor/conductor capacitance C_g, conductor/earth capacitance C_E and operating capacitance C_b is

$$C_b = C_E + 3 \cdot C_g.$$

Technical values for transmission wires are given in Section 13.1.4.

Table 3-10

Reference values for the impedances of three-phase overhead lines: “Donau” tower, one earth wire, conductor Al/St 240/40, specific earth resistance ρ = 100 Ω · m, f = 50 Hz

Voltage	d	d_{ab}	d_{as}	Earth wire	Impedance $\underline{Z}_1 = R_1 + \mathrm{j}\,X_1$	Operation with one system zero-sequence impedance $\underline{Z}_0$	$\frac{X_0}{X_1}$	Operation with two systems zero-sequence impedance $\underline{Z}_0$	$\frac{X_0}{X_1}$
	m	m	m		Ω / km per cond.	Ω / km per conductor		Ω / km per cond. and system	
123 kV	4	10	11	St 50	0.12 + j 0.39	0.31 + j 1.38	3.5	0.50 + j 2.20	5.6
				Al/St 44/32		0.32 + j 1.26	3.2	0.52 + j 1.86	4.8
				Al/St 240/40		0.22 + j 1.10	2.8	0.33 + j 1.64	4.2
245 kV	6	15.6	16.5	Al/St 44/32	0.12 + j 0.42	0.30 + j 1.19	2.8	0.49 + j 1.78	4.2
				Al/St 240/40		0.22 + j 1.10	2.6	0.32 + j 1.61	3.8
245 kV 2-wire bundle	6	15.6	16.5	Al/St 240/40	0.06 + j 0.30	0.16 + j 0.98	3.3	0.26 + j 1.49	5.0
420 kV 4-wire bundle	9.4	23	24	Al/St 240/40	0.03 + j 0.26	0.13 + j 0.91	3.5	0.24 + j 1.39	5.3

3.3.5 Three-phase cables

The equivalent diagram of cables can also be represented by Π elements, in the same way as overhead lines (Fig. 3-11). Owing to the smaller spacings, the inductances are smaller, but the capacitances are between one and two orders greater than with overhead lines.

When calculating short-circuit currents the positive-sequence operating capacitance is disregarded. The conductor/earth capacitance is used in the zero phase-sequence system.

Calculation of positive and negative phase-sequence impedance

The a.c. resistance of cables is composed of the d.c. resistance *(R_{-})* and the components due to skin effect and proximity effect. The resistance of metal-clad cables (cable sheath, armour) is further increased by the sheath and armour losses.

The d.c. resistance (R_{-}) at 20 °C and A = conductor cross section in mm^2 is

for copper: $R'_{-} = \frac{18,52}{A}$ in $\frac{\Omega}{km}$,

for aluminium: $R'_{-} = \frac{29,41}{A}$ in $\frac{\Omega}{km}$,

for aluminium alloy: $R'_{-} = \frac{32,26}{A}$ in $\frac{\Omega}{km}$.

The a.c. equivalent resistance at 20 ºC L and inductive reactance X_L at 50 Hz for different types of cable and different voltages are given in Tables 3-11 to 3-14.

For low-voltage cables, the values for positive- and negative-sequence impedances are given in IEC 60909.

Table 3-11

Belted cable [N(A)KBA; NYFGY]: a.c. resistance $R'_{\sim}$ and inductive operation reactance X' at positive-sequence system at $f = 50$ Hz

cores and cross-section	$R'_{\sim}$ Ω / km		X' Ω / km	
	Cu	Al	7,2 kV	12 kV
3 × 25	0.727	–	–	0.123
3 × 35	0.526	–	0.115	0.116
3 × 50	0.389	0.642	0.109	0.110
3 × 70	0.270	0.445	0.104	0.105
3 × 95	0.196	0.323	0.099	0.101
3 × 120	0.156	0.256	0.096	0.097
3 × 150	0.128	0.210	0.094	0.095
3 × 185	0.104	0.168	0.091	0.092
3 × 240	0.081	0.130	0.089	0.090
3 × 300	0.066	0.106	0.087	0.088

Table 3-12

Hochstaedtercable [N(A)EKEBA]: a.c. resistance $R'_{\sim}$ and inductive operation reactance X' at positive-sequence system at $f = 50$ Hz

cores and cross-section	$R'_{\sim}$ Ω / km		X' Ω / km	
	Cu	Al	24 kV	36 kV
3 × 25	0.729	–	0.158	–
3 × 35	0.526	–	0.150	–
3 × 50	0.390	0.644	0.143	0.151
3 × 70	0.271	0.446	0.135	0.141
3 × 95	0.196	0.323	0.128	0.135
3 × 120	0.157	0.256	0.123	0.129
3 × 150	0.128	0.210	0.120	0.126
3 × 185	0.104	0.168	0.116	0.123
3 × 240	0.081	0.129	0.111	0.119
3 × 300	0.066	0.105	0.108	0.116

Table 3-13

XLPE-cable [N2XSY; N(A)2XS2Y]: a.c. resistance $R'_{\sim}$ and inductive operation reactance X' at positive-sequence system at $f = 50$ Hz (delta installation)

cores and cross-section	$R'_{\sim}$ Ω/km		X' Ω/km				
	Cu	Al	12 kV	24 kV	36 kV	72,5 kV	123 kV
3 × 1 × 25	0.730	–	0.148	0.160	–	–	–
3 × 1 × 35	0.528	–	0.141	0.152	0.163	–	–
3 × 1 × 50	0.390	0.644	0.134	0.145	0.155	–	–
3 × 1 × 70	0.271	0.446	0.127	0.137	0.146	–	–
3 × 1 × 95	0.197	0.323	0.121	0.130	0.139	0.148	–
3 × 1 × 120	0.157	0.256	0.117	0.125	0.134	0.145	–
3 × 1 × 150	0.129	0.211	0.113	0.121	0.130	0.138	0.154
3 × 1 × 185	0.105	0.169	0.109	0.117	0.125	0.135	0.151
3 × 1 × 240	0.081	0.130	0.105	0.112	0.120	0.129	0.145
3 × 1 × 300	0.067	0.106	0.102	0.109	0.116	0.126	0.138
3 × 1 × 400	0.056	0.085	0.099	0.106	0.112	0.119	0.132
3 × 1 × 500	0.146	0.069	0.096	0.102	0.108	0.116	0.129
3 × 1 × 630	0.031	0.049	–	–	–	0.110	0.123
3 × 1 × 800	0.026	0.040	–	–	–	0.107	0.119
3 × 1 × 1000	0.023	0.033	–	–	–	0.104	0.116
3 × 1 × 1200	0.017	0.026	–	–	–	0.104	0.113
3 × 1 × 1400	0.016	0.021	–	–	–	0.104	0.113
3 × 1 × 1600	0.015	0.021	–	–	–	0.101	0.110
3 × 1 × 2000	0.013	0.018	–	–	–	0.097	0.107
3 × 1 × 2500	0.013	0.016	–	–	–	–	0.104

Table 3-14

XLPE-cabel [N2XSEY; NA2XS2Y]: a.c. resistance $R'_{\sim}$ and inductive operation reactance X' at positive-sequence system at $f = 50$ Hz, 12 kV

cores and cross-section	N2XSEY		NA2XS2Y	
	$R'_{\sim}$ Ω/km	X' Ω/km	$R'_{\sim}$ Ω/km	X' Ω/km
3 × 35	0.525	0.118	–	–
3 × 50	0.388	0.112	0.642	0.106
3 × 70	0.269	0.106	0.444	0.100
3 × 95	0.194	0.101	0.321	0.095
3 × 120	0.155	0.097	0.254	0.092
3 × 150	0.126	0.095	0.208	0.090
3 × 185	0.102	0.091	0.166	0.087
3 × 240	0.078	0.088	0.127	0.084

Zero-sequence impedance

It is not possible to give a single formula for calculating the zero-sequence impedance of cables. Sheaths, armour, the soil, pipes and metal structures absorb the neutral currents. The construction of the cable and the nature of the outer sheath and of the armour are important. The influence of these on the zero-sequence impedance is best established by asking the cable manufacturer. Dependable values of the zero-sequence impedance can be obtained only by measurement on cables already installed.

The influence of the return line for the neutral currents on the zero-sequence impedance is particularly strong with small cable cross-sections (less than 70 mm²). If the neutral currents return *exclusively* by way of the neutral (4th) conductor, then

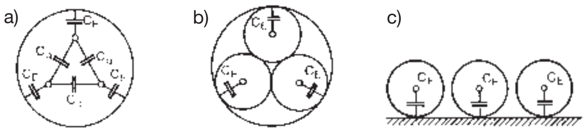
$$R_{0L} = R_L + 3 \cdot R_{neutral}, \qquad X_{0L} \approx (3{,}5 \ldots 4.0) x_L$$

The zero-sequence impedances of low-voltage cables are given in IEC 60909.

Capacitances

The capacitances in cables depend on the type of construction (Fig. 3-17).

With belted cables, the operating capacitance C_b is $C_b = C_E + 3\ C_g$, as for overhead transmission lines. In SL and Hochstädter cables, and with all single-core cables, there is no capacitive coupling between the three conductors; the operating capacitance C_b is thus equal to the conductor/earth capacitance C_E..



$C_b = C_E = 3\ C_g$ $\quad$ $C_g = 0 \longrightarrow C_b = C_E$ $\quad$ $C_g = 0 \longrightarrow C_b = C_E$

$C_E \approx 0{,}6\ C_b$

Fig. 3-17

Partial capacitances for different types of cable:
a) Belted cable, b) SL and H type cables, c) Single-core cable

Conductor to ground capacities are shown in tables 3-15 to 3-18.

Table 3-15

Belted cable [N(A)KBA; NYFGY]: capacitance *C*' at positive-sequence system

cores and cross-section	*C*' µF/km	
	7.2 kV	12 kV
3 × 25	–	0.230
3 × 35	0.480	0.280
3 × 50	0.550	0.300
3 × 70	0.620	0.340
3 × 95	0.690	0.380
3 × 120	0.750	0.410
3 × 150	0.820	0.430
3 × 185	0.880	0.460
3 × 240	0.980	0.510
3 × 300	1.070	0.560

Table 3-16

Hochstaedtercable [N(A)EKEBA: capacitance *C*' at positive-sequence system

cores and cross-section	*C*' µF/km	
	24 kV	36 kV
3 × 25	0.202	–
3 × 35	0.222	–
3 × 50	0.247	0.230
3 × 70	0.279	0.250
3 × 95	0.312	0.280
3 × 120	0.342	0.310
3 × 150	0.369	0.330
3 × 185	0.402	0.360
3 × 240	0.447	0.400
3 × 300	0.489	0.430

Table 3-17

XLPE-cable [N2XSY; N(A)2XS2Y]: capacitance *C'* at positive-sequence system

cores and cross-section	*C'* µF/km				
	12 kV	24 kV	36 kV	72.5 kV	123 kV
3 × 1 × 25	0.198	0.142	–	–	–
3 × 1 × 35	0.219	0.155	0.122	–	–
3 × 1 × 50	0.243	0.171	0.133	–	–
3 × 1 × 70	0.275	0.191	0.148	–	–
3 × 1 × 95	0.309	0.212	0.163	0.15	–
3 × 1 × 120	0.339	0.231	0.176	0.16	–
3 × 1 × 150	0.367	0.249	0.188	0.17	0.12
3 × 1 × 185	0.400	0.270	0.203	0.18	0.13
3 × 1 × 240	0.446	0.298	0.223	0.20	0.14
3 × 1 × 300	0.489	0.325	0.241	0.21	0.15
3 × 1 × 400	0.542	0.358	0.264	0.24	0.16
3 × 1 × 500	0.603	0.396	0.291	0.26	0.18
3 × 1 × 630	–	–	–	0.29	0.20
3 × 1 × 800	–	–	–	0.32	0.22
3 × 1 ×1000	–	–	–	0.35	0.23
3 × 1 ×1200	–	–	–	0.40	0.26
3 × 1 ×1400	–	–	–	0.42	0.27
3 × 1 ×1600	–	–	–	0.45	0.29
3 × 1 ×2000	–	–	–	0.49	0.32
3 × 1 ×2500	–	–	–	–	0.35

Table 3-18

XLPE-cable [N2XSEY, NA2XS2Y]: capacitance *C'* at positive-sequence system for 12 kV

cores and cross-system	*C'* µF/km	
	N2XSEY	NA2XS2Y
3 × 35	0.219	–
3 × 50	0.243	0.239
3 × 70	0.275	0.267
3 × 95	0.309	0.305
3 × 120	0.339	0.333
3 × 150	0.367	0.361
3 × 185	0.400	0.398
3 × 240	0.446	0.436

3.3.6 Conductors in switchgear installations

In the case of large cross-sections the resistance can be disregarded.

Guide values for the inductance per metre of conductors of rectangular section and arranged are shown in Fig. 3-18.

Here:

D Distance between centres of outer main conductor,
b Height of conductor,
B Width of bars of one phase,
L´ Inductance of one conductor in H/m.

Small inductances can be achieved by connecting two or more three-phase systems in parallel. But also conductors in a split phase arrangement yield very small inductances per unit length of less than 20 % of the values obtained with the method described. With the conductors laid flat side by side the inductances per unit length are about 50 % of the values according Fig. 3-18.

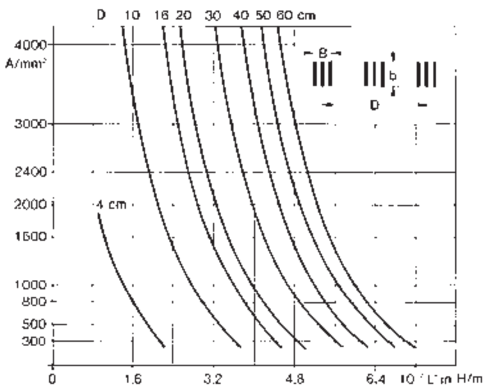


Fig. 3-18

Inductance L´ of busbars of rectangular cross section

3.4 Examples of short-circuit calculations

More complex phase fault calculations are made with computer programs (NEPLAN®). See Section 6.1.5 for examples.

When calculating short-circuit currents in high-voltage installations, it is often sufficient to work with reactances because the reactances are generally much greater in magnitude than the effective resistances. Also, if one works only with reactances, the calculation for the biggest short-circuits is on the safe side. Corrections to the reactances are disregarded.

Example 1 (Fig. 3-19)

Calculation of the single and 3-phase earth fault current I''_{k1}.

Find I''_{k3} and I''_{k1} at the 220 kV busbar of the power station represented by Fig. 3-19.

Calculation is made using the method of symmetrical components. First find the positive-, negative- and zero-sequence reactances X_1, X_2 and X_0 from the network data given in the figure, 3-19.

3

Positive-sequence reactances (index 1)

Overhead line $\quad X_{1L} = 50 \cdot 0.32\ \Omega \cdot \frac{1}{2} = 8\ \Omega$

220 kV network $\quad X_{1Q} = 0.995 \cdot \frac{1.1 \cdot 220\ \text{kV}/\sqrt{3}}{21\ \text{kA}} = 6.620\ \Omega$

Power plant unit $\quad X_{1G} = 0.14 \cdot \frac{(21\ \text{kV})^2}{125\ \text{MVA}} = 0.494\ \Omega$

$$X_{1T} = 0.13 \cdot \frac{(220\ \text{kV})^2}{130\ \text{MVA}} = 48.4\ \Omega$$

$$X_S = K_S\,(t_r^2 \cdot X_{1G} + X_{1T})$$

$$K_S = \left(\frac{220\ \text{kV}}{21\ \text{kV}}\right)^2 \cdot \left(\frac{21\ \text{kV}}{220\ \text{kV}}\right)^2 \cdot \frac{1.1}{1 + |\,0.14 - 0.13\,| \cdot 0.6} = 1.093$$

$$X_S = 1.093 \left[\left(\frac{220}{21}\right)^2 \cdot 0.494 + 48.4\right] \Omega = 112.160\ \Omega$$

At the first instant of the short circuit, $x_1 = x_2$. The negative-sequence reactances are thus the same as the positive-sequence values. For the generator voltage: $U_{rG} = 21$ kV with $\sin \varphi_{rG} = 0.6$, the rated voltages of the transformers are the same as the system nominal voltages.

Zero-sequence reactances (index 0)

A zero-sequence system exists only between earthed points of the network and the fault location. Generators G1 and G 2 and also transformer T1 do not therefore contribute to the reactances of the zero-sequence system.

Overhead line
2 circuits in parallel $\quad X_{0L} = 3.5 \cdot X_{1L} = 28\ \Omega$

220 kV network $\quad X_{0Q} = 2.5 \cdot X_{1Q} = 16.55\ \Omega$

Transformer T 2 $\quad X_{0T_2} = 0.8 \cdot X_{1T} \cdot 1.093 = 42.321\ \Omega$

With the reactances obtained in this way, we can draw the single-phase equivalent diagram to calculate I''_{k1} (Fig. 3-19b).

Since the total positive-sequence reactance at the first instant of the short circuit is the same as the negative-sequence value, it is sufficient to find the total positive and zero sequence reactance.

Calculation of positive-sequence reactance:

$$\frac{1}{x_1} = \frac{1}{56.076\ \Omega} + \frac{1}{14.622\ \Omega} \rightarrow x_1 = 11.598\ \Omega$$

Calculation of zero-sequence reactance:

$$\frac{1}{x_0} = \frac{1}{42.321\ \Omega} + \frac{1}{44.556\ \Omega} \rightarrow x_0 = 21.705\ \Omega$$

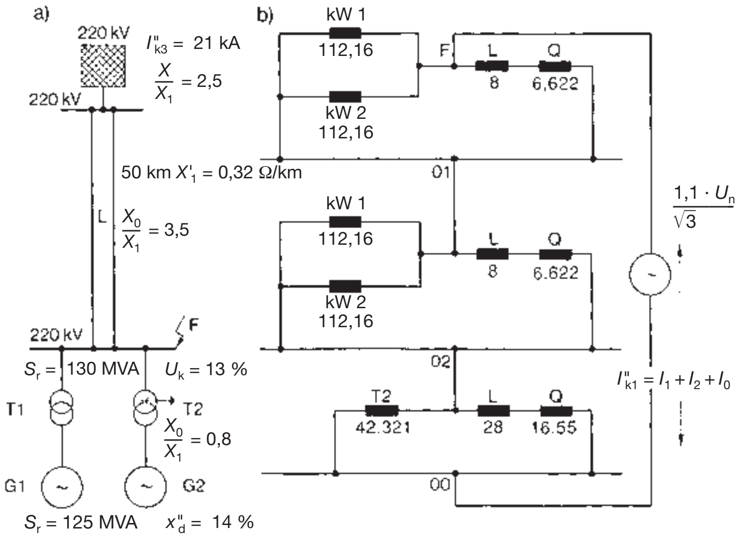


Fig. 3-19

a) Circuit diagram, b) Equivalent circuit diagram in positive phase sequence, negative phase sequence and zero phase sequence with connections and equivalent voltage source at fault location F for I''_{k1}.

With the total positive-, negative- and zero-sequence reactances, we have

$$I''_{k3} = \frac{1.1 \cdot U_n \cdot \sqrt{3}}{x_1} = \frac{1.1 \cdot 220\text{ kV} \cdot \sqrt{3}}{11.597\ \Omega} = 12.05\text{ kA.}$$

$$I''_{k1} = \frac{1.1 \cdot \sqrt{3} \cdot U_n}{x_1 + x_2 + x_0} = \frac{1.1 \cdot \sqrt{3} \cdot 220\text{ kV}}{44.897\ \Omega} = 9.34\text{ kA.}$$

The contributions to I''_{k3} and I''_{k1} represented by the 220 kV network (Q) or power station (S) are obtained on the basis of the relationship

$$I''_{k3} = \underline{I}_1 \text{ with } I_1 = 12{,}05\text{ kA with}$$

$$I''_{k1} = I_1 + I_2 + I_0 = 3\ \underline{I}_1 \text{ mit } I_0 = I_1 = I_2 = 3.11\text{ kA.}$$

from the equations:

$$\underline{I}''_{k3Q} = \underline{I}_{1Q} \text{ and } \underline{I}_{k3S} = \underline{I}_{1S}$$

$$\underline{I}''_{k1Q} = \underline{I}_{1Q} + \underline{I}_{2Q} + \underline{I}_{0Q} \text{ und } \underline{I}''_{k1S} = \underline{I}_{1S} + \underline{I}_{2S} + \underline{I}_{0S}.$$

The partial component currents are obtained from the ratios of the respective impedances.

3-pole-to-earth-fault:

$$I''_{k3Q} = I_{1Q} = 12.05\ \text{kA} \cdot \frac{56.08}{70.7} = 9.56\ \text{kA}$$

$$I''_{k3S} = I_{1S} = 12.05\ \text{kA} \cdot \frac{14.62}{70.7} = 2.49\ \text{kA}$$

single-pole-to-earth-fault:

$$I_{1Q} = I_{2Q} = 3.11\ \text{kA} \cdot \frac{56.08}{70.70} = 2.47\ \text{kA}$$

$$I_{0Q} = 3.11\ \text{kA} \cdot \frac{42.32}{86.87} = 1.52\ \text{kA}$$

$$I_{1S} = 0.64\ \text{kA}$$

$$I_{0S} = 1.59\ \text{kA}$$

$$\underline{I}''_{k1Q} = (2.47 + 2.47 + 1.52)\ \text{kA} = 6.46\ \text{kA}$$

$$\underline{I}''_{k1S} = (0.64 + 0.64 + 1.59)\ \text{kA} = 2.87\ \text{kA}.$$

Example 2 (Fig. 20)

The short-circuit currents are calculated with the aid of Table 3-2 (with $c_{max} = 1.1$ at voltage tolerance ± 10%.

20 kV network:

$$x_{1Q} = 0.995\ \frac{1.1 \cdot (0.4)^2}{250} = 0.0007\ \Omega$$

$$r_{1Q} \approx 0.1\ x_{1Q} = 0.00007\ \Omega$$

Transformer

$$x_{1T} = 0.058\ \frac{(0.4)^2}{0.63} \cdot 0.95 \cdot \frac{1.1}{1 + 0.6 \cdot 0.058} = 0.0149\ \Omega$$

$$r_{1T} = 0.015\ \frac{(0.4)^2}{0.63} \cdot 0.95 \cdot \frac{1.1}{1 + 0.6 \cdot 0.058} = 0.0039\ \Omega$$

$$x_{0T} = 0.95 \cdot x_{1T} = 0.0142\ \Omega$$

$$r_{0T} \approx r_{1T} = 0.0039\ \Omega$$

Cable:

$$x_{1L} = 0.08 \cdot 0.082 = 0.0066\ \Omega$$

$$r_{1L20} = 0.08 \cdot 0.269 = 0.0215\ \Omega$$

$$r_{1L80} = 1.56 \cdot r_{1L20} = 0.0336\ \Omega$$

$$x_{0L} \approx 5.68 \cdot x_{1L} = 0.0373\ \Omega$$

$$r_{0L20} \approx 3.18 \cdot r_{1L20} = 0.0684\ \Omega$$

$$r_{0L80} = 1.56 \cdot r_{0L20} = 0.1068\ \Omega$$

Maximum and minimum short-circuit currents at fault location F 1

a. Maximum short-circuit currents

$$\underline{Z}_1 = \underline{Z}_2 = (0.0039 + j\ 0.0156)\ \Omega; \quad \underline{Z}_0 = (0.0039 + j\ 0.0142)\ \Omega$$

$$I''_{k3} = \frac{1.1 \cdot 0.4}{\sqrt{3} \cdot 0.0161}\ \text{kA} = 15.8\ \text{kA}$$

$$I''_{k2} = \frac{\sqrt{3}}{2} I''_{k3} = 13.7\ \text{kA}$$

$$I''_{k1} = \frac{\sqrt{3} \cdot 1.1 \cdot 0.4}{0.0468}\ \text{kA} = 16.3\ \text{kA}.$$

b. Minimum short-circuit currents

The miminum short-circuit currents are calculated with c = 0.95.

Maximum and minimum short-circuit currents at fault location F 2

a. Maximum short-circuit currents

$$\underline{Z}_1 = \underline{Z}_2 = (0.0254 + \mathrm{j}\,0.0222)\ \Omega; \quad \underline{Z}_0 = (0.0723 + \mathrm{j}\,0.0514)\ \Omega$$

$$I''_{k3} = \frac{1.1 \cdot 0.4}{\sqrt{3} \cdot 0.0337}\ \text{kA} = 7.5\ \text{kA}$$

$$I''_{k2} = \frac{\sqrt{3}}{2} I''_{k3} = 6.5\ \text{kA}$$

$$I''_{k1} = \frac{\sqrt{3} \cdot 1.1 \cdot 0.4}{0.1560}\ \text{kA} = 4.9\ \text{kA.}$$

b. Minimum short-circuit currents

The minimum short-circuit currents are calculated with c = 0.95 and a conductor temperature of 160 °C (max. admissible cable temperature at the end of short circuit).

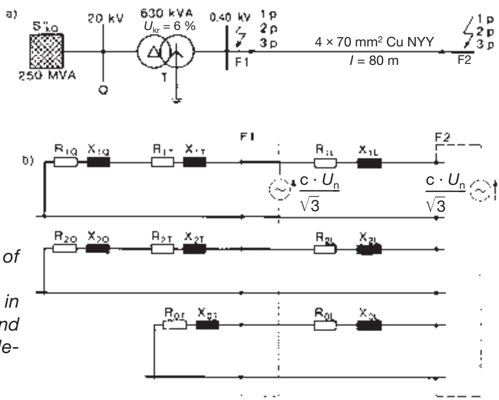


Fig. 3-20

a) Circuit diagram of low-voltage network,
b) Equivalent diagram in component systems and connection for single-phase fault

Table 3-19

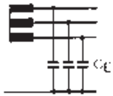
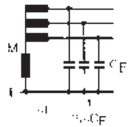
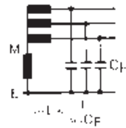
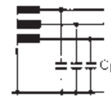
Summary of results

Fault location	Max. short-circuit currents			Min. short-circuit currents		
	3p kA	2p kA	1p kA	3p kA	2p kA	1p kA
Fault location F 1	15.8	13.7	16.3	13.6	11.8	14.1
Fault location F 2	7.5	6.5	4.9	5.0	4.4	3.2

The breaking capacity of the circuit-breakers must be at least 16.0 kA or 7.5 kA. Protective devices must be sure to respond at 11.8 kA or 3.2 kA. These figures relate to fault location F1 or F2.

3.5 Effect of neutral point arrangement on fault behaviour in three-phase high-voltage networks above 1 kV

Table 3-20

Arrangement of neutral point	insulated	with arc suppression coil	current-limiting *R* or *X*	low-resistance earth
				
Examples of use	Networks of limited extent, power plant auxiliaries	Overhead-line networks 10…123 kV	Cable networks 10…230 kV system e. g. in towns	High-voltage networks (123 kV) to 400 kV (protective multiple earthing in l. v. network)
Between system and earth are:	Capacitances, (inst. transformer inductances)	Capacitances, Suppression coils	Capacitances, Neutral reactor	(Capacitances), Earth conductor
$\lvert \underline{Z}_0/\underline{Z}_1 \rvert$	$\left\lvert \dfrac{1/\mathrm{j}\omega C_E}{\underline{Z}_1} \right\rvert$	very high resistance	inductive: 4 to 60 resistive: 30 to 60	2 to 4
Current $\underline{I}_F$ with single-phase fault Calculation (approximate) $E_1 = \dfrac{c \cdot U_n}{\sqrt{3}}$ c voltage factor acc. table 3-1	Ground-fault current $\underline{I}_E$ $\underline{I}_E \approx \mathrm{j}\, 3\, \omega C_E \cdot E_1$	Residual ground-fault current $\underline{I}_R$ $\underline{I}_R \approx 3\, \omega C_E (\delta + \mathrm{j}\nu)\, E_1$ δ loss angle ν interference	Ground-fault current $\underline{I}''_{k1}$ $\underline{I}''_{k1} = \underline{I}_R \approx \dfrac{3\, E_1}{\mathrm{j}\,(X_1 + X_2 + X_0)}$ $\dfrac{\underline{I}''_{k1}}{\underline{I}''_{k3}} = \dfrac{3\, X_1}{2\, X_1 + X_0} = \dfrac{3}{2 + X_0/X_1}$	

(continued)

Table 3-20 (continued)

Method of neutral point connection	insulated	with arc suppression coil	current-limiting R or X	low-resistance earth
I_F / I''_{k3}	$<< 1$	$<< 1$	inductive: 0.05 to 0.5 resistive: 0.1 to 0.05	0.5 to 0.75
U_{LEmax} / U_n	≈ 1	1 to (1.1)	inductive: 0.8 to 0.95 resistive: 0.1 to 0.05	0.75 to ≦ 0.80
U_{0max} / U_n	≈ 0.6	0.6 to 0.66	inductive: 0.42 to 0.56 resistive: 0.58 to 0.60	0.3 to 0.42
Voltage rise in whole network	yes	yes	no	no
Duration of fault	10 to 60 min Possible short-time earthing with subsequent selective disconnection by neutral current (< 1 s)	10 to 60 min	< 1 s	< 1 s
Ground-fault arc	Self-quenching up to several A	Self-quenching	Partly self-quenching usually sustained	Sustained
Detection	transient earth-fault relay, wattmetrical earth-fault relay. (With short-time earthing: disconnection by connection by neutral current)		Selective disconnection by neutral current (or short-circuit protection)	Short-circuit protection
Risk of double earth fault	yes	yes	slight	no
earthing procedure DIN VDE 0101	Earth electrode voltage $U_E \leq 150$ V Touch voltage ≦ 75 V if duraction of current flow $t_F < 10$ s		Earth electrode voltage $U_E > 150$ V Touch voltages ≧ 75V if duraction of current flow $t_F < 10$ s	
Measures against interference with communication circuits DIN VDE 0228	Generally not necessary needed only with railway block lines	Not necessary	Overhead lines: possibly required if approaching over a considerable distance Cables: generally not necessary	

4 Dimensioning switchgear installations

4.1 Insulation rating

Rating the dielectric withstand of equipment is based on the expected dielectric stresses. This is a combination of the stress caused by the power-frequency voltage and the stress caused by the mostly short-term overvoltages. The insulation coordination for power-frequency systems with voltages ≤ 1000 V is based on IEC 60664-1 (VDE 0110 Part 1) and IEC/TR 60664-2 (VDE 0110 Part 1, Supplements), in force since a few years only. For systems with power-frequency voltages > 1 kV the specifications in IEC 60071-1 (VDE 0111 Part l) and the application guide in IEC 60071-2 (VDE 0111 Part 2) apply.

4

4.1.1 Insulation coordination in high voltage systems

The *insulation coordination* is defined in IEC 60071-1 (VDE 0111 Part l) as the selection of the dielectric withstand required for equipment that is to be used at a specific site in a network. This process requires knowledge of the operational conditions in the network and the planned overvoltage protection devices, and the probability of an insulation fault on equipment which can be accepted under economic and operational aspects.

The *“dielectric withstand”* can be defined here by a *rated insulation level* or by a *standard insulation level*. A rated insulation level is considered any combination of standard withstand voltages, a standard insulation level is considered a rated insulation level whose standard withstand voltages in combination with an associated highest voltage for equipment U_m are recommended in selection tables (Tables 4-1 and 4-2). These combinations are based on operational experience with networks that meet the IEC standard. However, they are not associated with specific operational or system conditions. It is frequent practicial use to determine the dielectric withstand requirements on electrical high voltage equipment by selecting a standard insulation level from these tables. If however extreme operational or system conditions are to be taken into account, proceeding step by step according Fig. 4-1 is the right way.

When discussing insulation, a distinction is made between external and internal insulation. *External insulation* consists of clearances in air and the dielectrically stressed surfaces of solid insulation. It is exposed to atmospheric and other effects such as pollution, moisture, animals etc. It can be either protected (indoor) or unprotected (outdoor). The *internal insulation* can be solid, fluid or gaseous insulation material. It is protected against atmospheric and other external effects.

There is also a distinction between *self-restoring and non-self-restoring insulation,* but only with reference to the response of the insulation under dielectric tests. Insulation is considered self-restoring if its insulation properties are restored after a breakdown during the test.

The power frequency voltages and the overvoltages acting on an insulation or an overvoltage protection device can be classified by causes and processes into the following categories:

– power frequency continuous voltages resulting from normal system operation
– temporary overvoltages (power frequency) resulting from earth faults, switching operations (e.g. load shedding, resonances, ferroresonance or similar)

– slow-front overvoltages resulting from switching operations or direct lightning strikes at great distance, with rise times between 20 μs and 5000 μs and times to half-value up to 20 ms
– fast-front overvoltages resulting from switching operations or lightning strikes with rise times between 0.1 μs and 20 μs and times to half-value up to 300 μs
– very fast-front overvoltages resulting from faults or switching operations in gas-insulated switchgear with rise times below 0.1 μs and superimposed oscillations in the frequency range of 30 kHz to 100 MHz with a total duration of 3 ms
– combined overvoltages, primarily between conductors and at open breaker gaps.

It is assumed that within one of these categories the different voltage characteristics will have the same dielectric effects on the insulation and can be converted by calculation to a specified characteristic representative for the category. The following standardized voltage shapes are defined as representative voltage characteristics for the above categories – except for the very fast-front overvoltages:
– standard short-duration power-frequency voltage with a frequency between 48 Hz and 62 Hz and a duration of 60 s
– standard switching impulse voltage; a voltage pulse with a rise time of 250 μs and a time to half-value of 2500 μs
– standard lightning impulse voltage; a voltage pulse with a rise time of 1.2 μs and a time to half-value of 50 μs
– combined standard switching impulse voltage; two simultaneous voltage impulses of opposite polarity

Insulation coordination procedure

The procedure in accordance with IEC 60071-1 (VDE 0111 Part l) in its current form requires basic knowledge of the physical processes, the operating conditions and the dielectric response of the equipment with its application. Fig. 4-1 shows the predicted process sequence as a flow chart.

Step 1:

The starting point of the coordination procedure is the system analysis, which should determine what voltage stresses can be expected under operational conditions, possibly with the aid of switching tests in the system. This should also include overvoltage protection devices. The investigations for both ranges of highest voltages for equipment (ranges I and II) must include the stress on the conductor-earth insulation, the stress between the conductors and the longitudinal stress on the switching apparatus. The overvoltages must be assessed by peak value, curve and rate of occurrence and classified under the corresponding (curve) categories. The results of the system analysis will include peak values and rate of occurrence of voltage stress in the following categories: temporary power-frequency voltage, switching impulse voltage, lightning impulse voltage etc. They are shown in the flow chart (Fig. 4-1) as U_{rp}, *representative voltages and overvoltages*.

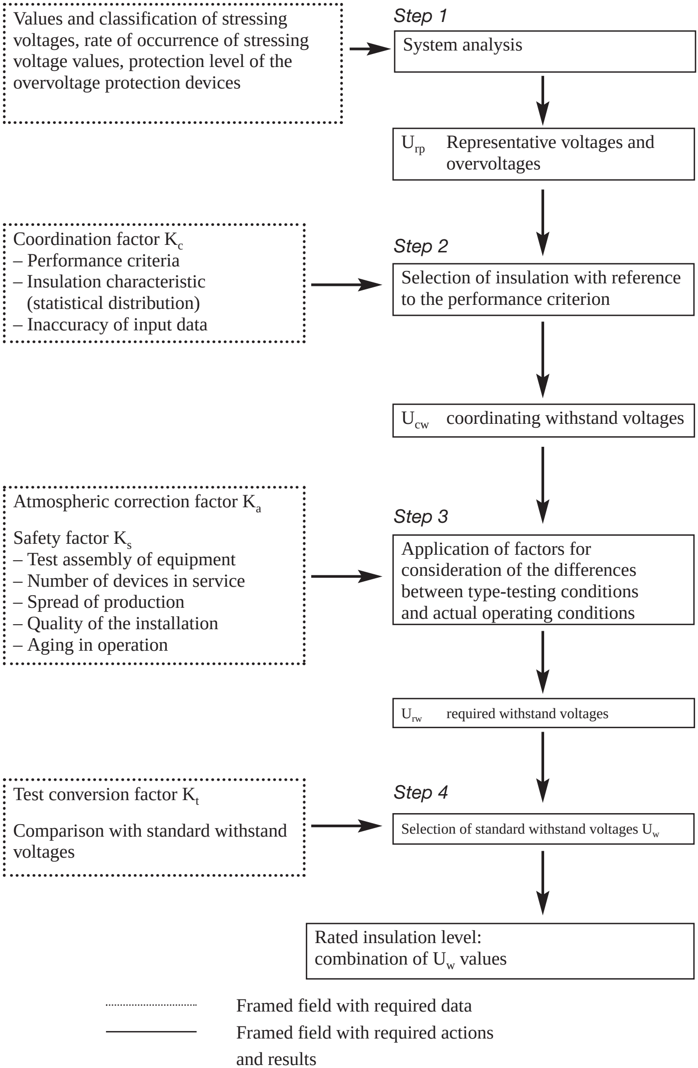


Fig. 4-1

Flow chart for determining the rated insulation level or the standard insulation level

Step 2:

The *performance criteria* are of fundamental importance for the next step. These are given in the form of permissible fault rates, how often a device at that specific point on the system may be subject to insulation faults caused by the representative voltages and overvoltages (U_{rp}). The next step is to determine the lowest values of the withstand voltages, the equipment must satisfy to meet the performance criteria. They are referred to as *coordinating withstand voltages* (U_{cw}). The difference between the value of a representative overvoltage and that of the associated coordinating withstand voltage is characterized by the coordination factor K_c, which must be multiplied by the representative overvoltage to derive the coordinating withstand voltage.

To determine the coordination factor K_c with transient overvoltages, a deterministic procedure, a statistical procedure or a combination of the two may be selected. Input quantities are the probability function of the overvoltages (U_{rp}), as the result of the system analysis on one hand and on the other hand, the disruptive discharge probability distribution of the insulation in question. The coordination factor should also include an allowance for any inaccuracies in the input quantities.

The deterministic procedure is used in cases where, for example, with an internal insulation only a conventional withstand voltage ($P_w = 100\%$) can be assumed and this is also protected by a surge arrester. The deterministic layout is also used in the case of overvoltage protection of equipment linked to overhead lines, when the difference between an existing statistical withstand-voltage characteristic ($P_w = 90\%$) and the assumed conventional withstand voltage of the same insulation configuration is taken into consideration by the coordination factor K_c. The deterministic procedure does not leave a defined fault rate for the equipment during operation.

In the statistical procedure, the overvoltage and disruptive discharge probability are available as statistical data and can be combined simultaneously, e.g. with the Monte Carlo method. This calculation must be done for the different kinds of insulation concerned and for different system configurations to determine the total non-availability of a device or an installation.

An insulation can therefore only be economically optimized by statistical designing when the downtime expenses are defined for specific fault types. Therefore, the more complex statistical procedure can only be applied in very specific cases, such as the design of switchgear installations for the maximum transmission voltages.

Step 3:

The next step leads from the coordinating withstand voltages (U_{cw}) to the *required withstand voltages* (U_{rw}). Two correction factors are used here. The atmospheric correction factor K_a primarily corrects for the air pressure at the set-up area of the equipment with external insulation, i.e. primarily the altitude. Ambient temperature and humidity have the tendency of acting against each other in their influence on the withstand voltage. The atmospheric conditions generally do not influence the internal insulation.

The atmospheric correction factor is calculated as follows:

$$K_a = e^{m \frac{H}{8150}}$$

H: altitude in metres

m: an exponent that for clean insulators is different from 1 only with switching impulses and that depending on the voltage and geometry of the insulation is to be taken as a guidance value from characteristics (cf. IEC 60071-2, Fig. 9!). In the case of contaminated insulators, m is in the range between 0.5 and 0.8 for the power-frequency withstand voltage test.

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The safety factor K_s considers the number of all other influences that could result in a difference between the equipment in operation and the test object in the type test.

These are:
– aging caused by thermal, dielectric, chemical and mechanical stresses,
– spread caused by manufacturing conditions,
– spread caused by installation, such as changes in the connection technology, parallel loading or a large number of devices in operation in comparison to type-testing one single specimen only, etc.

Recommended safety factors are:
– for internal insulation: K_s = 1.15,
– for external insulation: K_s = 1.05.

If the safety factor of 1.15 applicable for internal insulation is also used for external insulation, the atmospheric correction is also covered to an operational altitude of 1000 m.

The required withstand voltages (U_{rw}) determined to this point are the minimum withstand voltages that must be verified for a device by type tests to ensure that the failure rate predicted in the performance criterion is not exceeded at the operational site in the system. The required withstand voltages can basically be discarded for each of the (curve) categories described above.

Step 4:

The selection tables (Tables 4-1 and 4-2) show standard withstand voltages for the testing of equipment. They show standard voltages for the voltage range I (≤ 245 kV) for testing with short-time power-frequency withstand voltage and with lightning impulse withstand voltage. Voltage range II (> 245 kV) lists standard voltages for testing with lightning impulse withstand voltage and switching impulse withstand voltage.

If the system analysis shows required withstand voltages (U_{rw}) in categories for which the selection tables do not have standard values, conversion to one of the categories listed there is recommended by using corresponding *test conversion factors*. Test conversion factors are listed for the two voltage ranges for internal and external insulation in the application guide IEC 60071-2 (VDE 0111 Part 2) in Tables 2 and 3.

Table 4-1

Standardized insulation levels in voltage range I (1 kV < U_m ≤ 245 kV) as per IEC 60071-1 (VDE 0111 Part 1)

Highest voltage for equipment U_m kV rms value	Standard short-time power-frequency withstand voltage kV rms value	Standard lightning impulse withstand voltage kV peak value
3.6	10	20 40
7.2	20	40 60
12	28	60 75 95
17.5	38	75 95
24	50	95 125 145
36	70	145 170
52	95	250
72.5	140	325
123	(185) 230	450 550
145	(185) 230 275	(450) 550 650
170	(230) 275 325	(550) 650 750
245	(275) (325) 360 395 460	(650) (750) 850 950 1050

Note: if the values in parentheses are not sufficient to verify that the required conductor-conductor withstand voltages are met, additional conductor-conductor withstand voltage tests will be required.

A standardized insulation level from Tables 4-1 and 4-2 must be selected to ensure that in all test voltage categories the values of the required withstand voltages (U_{rw}) are reached or exceeded. At least two combinations of rated voltage values are assigned to almost every value for the maximum equipment voltage U_m. The result of the procedure for the insulation coordination determines whether the higher or lower values are required, or whether the insulation level of another equipment voltage is to be used.

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Table 4-2

Standardized insulation levels in range II: U_m > 245 kV
as per IEC 60071-1 (VDE 0111 Part 1)

Highest voltage for equipment U_m kV rms value	Standard switching-impulse withstand voltage			Standard lightning impulse withstand voltage kV peak value
	Longitudinal insulation (note 1) kV peak value	Conductor-earth kV peak value	Ratio conductor-conductor to conductor-earth peak value	
300	750	750	1.50	850 950
	750	850	1.50	950 1 050
362	850	850	1.50	950 1 050
	850	950	1.50	1 050 1 175
420	850	850	1.60	1 050 1 175
	950	950	1.50	1 175 1 300
	950	1 050	1.50	1 300 1 425
525	950	950	1.70	1 175 1 300
	950	1 050	1.60	1 300 1 425
	950	1 175	1.50	1 425 1 550
765	1 175	1 300	1.70	1 675 1 800
	1 175	1 425	1.70	1 800 1 950
	1 175	1 550	1.60	1 950 2 100

Note 1: Value of the impulse voltage in combined test.

Note 2: The introduction of U_m = 550 kV (instead of 525 kV), 800 kV (instead of 765 kV), 1050 kV and 1200 kV and the associated standard withstand voltages is being considered.

4.1.2 Insulation coordination in low voltage systems

For insulation coordination in low voltage systems no international guides or specifications were available before 1998. In the following years however a series of IEC-publications (or specifications) on this matter were published. Of basic importance are IEC 60664-1 (VDE 0110 Part 1) and IEC 60364-5-53 (DIN V VDE V 0100-534). Overvoltages in low voltage systems may result from lightning strokes or from switching operations. The basic target of insulation coordination is to avoide damages by lightning overvoltages. Requirements for switching overvoltages are generally covered without further measures.

Lightning overvoltages may be created

- by direct lightning strokes to overhead lines
- as induced overvoltages in case of strokes in the vicinity of lines or
- due to lightning currents in various conductors transfered via ohmic, inductive or capacitive coupling or through transformers into low voltage circuits.

Low voltage insulation coordination is based on four overvoltage categories into which the equipment components are divided according to their rated lightning stroke withstand voltages (Table 4-7):

- Highly protected equipment (Overvoltage category I)
- Equipment to be connected to fixed installations (Overvoltage category II)
- Equipment components for use in fixed installations (Overvoltage categorie III)
- Equipment at the entrance to the fixed installation (Overvoltage category IV).

Table 4 -3

Standard insulation levels of equipment for rated voltages < 1000V according to IEC 60664-1 (VDE 0110 Part 1)

Highest voltage for equipment U_m V rms value	Rated lightning impulse withstand voltage (1,2/50 μs) Overvoltage category IV kV peak value	Overvoltage categorie III kV peak value	Overvoltage category II kV peak value	Overvoltage category I kV peak value
Single phase systems with neutral 120 to 240	4	2.5	1.5	0.8
Three phase systems 230/400 277/480	6	4	2,5	1.5
400/690 1000	8	6	4	2.5

The rated lightning impulse withstand voltage values are valid for the whole operating range of the equipment up to 2000 m height. When used at sea level the equipment will offer a relevant margin in insulating capability. Under proving tests in a laboratory situated in a location of low height a relevant increase of test voltages is requested. The optional way of dimensioning equipment on the basis of assigned (non-homogeneous) gap widths takes already into account the conditions at 80 kPa air pressure at 2000 m height.

The data given in table 4-3 are in strict accordance only with the specifications valid for equipment in installations behind the transfer box. For installations and equipment between the secondary terminals of the distribution transformer and the transfer box it is urgently recommended to apply category IV equipment.

The fields of application associated with the different overvoltage categories may not to be understood as a hint that a decay of overvoltage waves along the conductors of a system will occur of itself as a natural effect. On contrary the sequence of the fields of application stands for the different degrees of availability that can be accepted in different ranges of low voltage supply systems. The risk of a damage is clearly taken into account and an overvoltage damage caused at a terminal device is more acceptable than a failure on the entrance installation.

To make sure that the voltage stress on the equipment will not exceed the permissible values with the specified probability appropriate surge arresters must be selected. Arresters are classified in three categories with respect to their energy absorption capability. Characteristic features are the test conditions for the prove of the energy absorbtion capability according IEC 61643-11 (VDE 0675 Part 11).

Type 1 includes arresters with the highest energy absorbtion capability. These arresters also called lightning arresters are generally used in combination with lightning protection systems(LPS).This type of arrester is installed between neutral and potential equalization conductor of a building. It must be able to conduct a significant part of the lightning current.

Type 2 is applied as arrester to limit lightning and switching overvoltages.

Type 3 is preferably applicable for the protection of terminal devices.

For the systematic selection of overvoltage arresters for installation in an extended installation of a building this installation is divided in lightning protection zones (LPZ). The LPZ concept must take into account the travelling wave character of the overvoltage energy rushing in from outside. The selection of arresters based on this concept has to make sure that arresters will be capable of the stresses to be expected (energy absorbtion). It also has to make sure that for the installed electrical and electronical equipment according to number, type and insulation level an assigned overvoltage damage probability is not exceeded. Guidance to estimate the probability of damages is given in the provisional specification DIN V VDE V 0185-2 (VDE 0185 Part 2) in combination with its amendment 1.

In addition to the aspect of damages due to failures on installations and to fire, also the possibilities of damage and interference on electrical and electronical systems due to lightning overvoltages, but also due to switching operations, must be taken into account. Therefore the lightning protective zones concept must also take care of EMC requirements. LPZ-concept and EMC-concept cannot be regarded separately.

Lightning protective zone 0 is called the outside area (including the lightning protecting system) of the building, in which the installations to be protected are installed. Depending on the ambient conditions (exposed location, frequent thunderstorms etc.) the lightning protective system has to meet the requirements of one of the four classes of lightning protective systems according DIN V VDE 0185-4. In lightning protective class I. lightning stroke currents up to 200kA, in class II up to 150kA and in classes III and IV up to 100kA are expected.

Lightning protective zone 1 includes generally the entrance area from the entrance of the feeder line or cable into the building, the main distribution panel and the cable connections to the subdistribution boards. The latter may form an other zone together with the equipment they are feeding. A building area with motors, welding transformers and contactors is to be associated to an other lightning protective zone (protective zone 2) than an area with interconnected computers (protective zone 3), each of them with relevant insulation levels.

At the transition of a conductor from one lightning protective zone to the next a set of surge arresters is to be installed. Since also between neutral and protective conductor an arrester may be necessary their number and rated voltage depends also on the type of low voltage system (TN-S, TN-C, TT etc.). At the entrance of a line into a building, i.e. at the transition from protective zone 0 to protective zone 1, arresters of type 1 are to be installed. They must have an energy absorbing capability for the highest lightning energy to be expected. Arresters following then may have energy absorbing capabilities decaying in steps. Along the conductor normally different types of arresters will be installed.

It must be taken into account, that also in underground cables overvoltages may occur due to indirect lightning strokes. Overvoltage protection by arrester is therefore to be applied at both ends. Overhead lines between transformer and building are also to be protected with arresters at both ends.

When selecting arresters not only the energy absorption capability must be taken into account but also the protective level Up, which is decisive for the dielectric stress of the equipment. Guidance for selection and application is given in IEC 61643-12 (VDE 0675 Part 12) and in DIN V VDE V 0100-534. See also Section 7.1!

Additional measures to avoid damages on low voltage installations due to lightning overvoltages are

- lightning protection systems and external shielding with earthing systems,
- potential equalization conductors of small inductance,
- internal shielding against electro-magnetic fields, and
- wiring with shielded cables and in small conductor loops.

4.2 Dimensioning of power installations for mechanical and thermal short-circuit strength as per IEC 60865-1 (VDE 0103)

Symbols used

A_s	Cross-section of one sub-conductor
a	Centre-line distance between conductors
a_m	Effective distance between neighbouring main conductors
a_{min}	Minimum air clearance
a_s	Effective distance between sub-conductors
a_{1n}	Centre-line distance between sub-conductor 1 and sub-conductor n
a_{1s}	Centre-line distance between sub-conductors
a_{sw}	Effective centre-line distance between the sub-conductors in the bundle
b	Dimension of a sub-conductor perpendicular to the direction of the force
b_c	Equivalent static conductor sag at midspan
b_h	Maximum horizontal displacement
b_m	Dimension of a main conductor perpendicular to the direction of the force
c	Factor for the influence of connecting pieces
c_{th}	Material constant
C_D	Dilatation factor
C_F	Form factor
D	Outer diameter of a tubular conductor
d	Dimension of a sub-conductor in the direction of the force
d_m	Dimension of a main conductor in the direction of the force
d_s	Diameter of a flexible conductor
E	Young's modules
E_s	Actual Young's modules
F	Force acting between two parallel long conductors during a short circuit
F_d	Force on support of rigid conductors (peak value)
F_f	Drop force
F_m	Force between main conductors during a short circuit
F_{m2}	Force between main conductors during a line-to-line short circuit
F_{m3}	Force on the central main conductor during a balanced three-phase short circuit
F_s	Force between sub-conductors during a short circuit
F_{st}	Static tensile force in flexible main conductor
F_t	Short-circuit tensile force
F_{pi}	Pinch force

F'	Characteristic electromagnetic force per unit lenght on flexible main conductors
f	System frequency
f_c	Relevant natural frequency of a main conductor
f_{cs}	Relevant natural frequency of a sub conductor
f_η	Factor characterising the contraction of the bundle
g_n	Conventional value of acceleration of gravity
I''_{k1}	Three-phase initial symmetricial short-circuit current (r.m.s.)
I''_{k2}	Line-to-line initial symmetrical short-circuit current (r.m.s.)
I''_{k3}	Line-to-earth initial short-circuit current (r.m.s.)
i_p	Peak short-circuit current
i_{p2}	Peak short-circuit current in case of a line-to-line short circuit
i_{p3}	Peak short-circuit current in case of a balanced three-phase short circuit
i_1, i_2, i_3	Instantaneous values of the currents in the conductors
J	Second moment of main conductor area
J_s	Second moment of sub-conductor area
j	Parameter determining the bundle configuration during short-circuit current flow
k	Number of sets of spacers or stiffening elements
k_{1n}	Factor for the effective distance between sub-conductor 1 and sub-conductor n
k_{1s}	Factor for effective conductor distance
l	Centre-line distance between supports
l_c	Cord lenght of a flexible main conductor in the span
l_i	Lenght of one insulator chain
l_s	Centre-line distance between connecting pieces or between one connecting piece and the adjacent support
m'	Mass per unit lenght of main conductor
m'_s	Mass per unit lenght of one sub-conductor
m_z	Total mass of one set of connecting pieces
N	Stiffness norm of an installation with flexible conductors
n	Number of sub-conductors of a main conductor
q	Factor of plasticity
$R_{p0.2}$	Stress corresponding to the yield point
r	The ratio of electromechanical force one a conductor under short-circuit conditions to gravity
S	Resultant spring constant of both supports of one span
s	Wall thickness of tubes
T	Period of conductor oscillation

T_k, T_{k1}	Duration of short-circuit current
T_{res}	Resulting period of the conductor oscillation during the short-circuit current flow
V_F	Ratio of dynamic and static force on supports
V_r	Ratio of stress for a main conductor with and without three-phase automatic reclosing
V_{rs}	Ratio of stress for a sub-conductor with and without three-phase automatic reclosing
V_σ	Ratio of dynamic and static main conductor stress
$V_{\sigma s}$	Ratio of dynamic and static sub-conductor stress
y_a	Centre-line distance between non-clashing sub-conductors during short-circuit current flow
Z	Section modulus of main conductor
Z_s	Section modulus of sub-conductor
α	Factor for force on support
β	Factor for main conductor stress
γ	Factor for relevant natural frequency estimation
δ_1	Angular direction of the force
δ_k	Swing-out angle at the end of the short-circuit current flow
δ_m	Maximum swing-out angle
ε_{ela}	Elastic expansion
$\varepsilon_{pi}, \varepsilon_{st}$	Strain factor of the bundle contraction
ε_{th}	Thermal expansion
ζ	Stress factor of the flexible main conductor
η	Factors for calculating F_{pi} in case of non-clashing sub-conductors
κ	Factor for the calulation of the peak short-circuit current
μ_0	Magnetic constant, permeability of vacuum
$v_e, v_{1...4}$	Factors for calculating F_{pi}
ξ	Factor for calculating F_{pi} in the case of cleashing sub-conductors
σ_m	Bending stress caused by the forces between main conductors
σ_s	Bending stress caused by the forces between sub-conductors
σ_{tot}	Resulting conductor stress
σ_{fin}	Lowest value of σ when Young's modulus becomes constant
x	Quantity for the maximum swing-out-angle
φ, ψ	Factor for the tensile force in a flexible conductor

Note 1: When using the following equations the dimension units of quantities must be observed carefully. The application of units of the SI-system is not universal particularly in the tables with the moments of inertia and of restistance and in the calculating examples.

Note 2: For arithmetic calculations Supplementary Sheet 1 of IEC 60865-1 is recommended to occasional users.

4.2.1 Dimensioning of bar conductors for mechanical short-circuit strength

Parallel conductors whose length l is high in comparison to their distance a from one another are subjected to forces evenly distributed along the length of the conductor when current flows. In the event of a short circuit, these forces are particularly high and stress the conductors by bending and the means of fixing by cantilever, pressure or tensile force. This is why busbars must not be designed for the load current only but also to resist the maximum occurring short-circuit current. The load on the busbars and supports to be expected in the event of a short circuit must therefore be calculated. The mechanical short-circuit strength of power installations can be calculated or also determined by testing.

The following information is not only applicable to busbars but also to tubular conductors, or very generally to rigid conductors. It is also applicable to two- and three-phase short circuits in a.c. and three-phase systems.

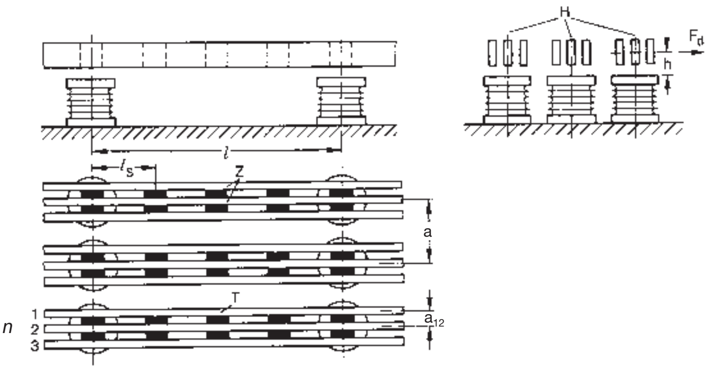


Fig. 4-2

Busbar configuration with three main conductors H with three sub-conductors T each, with spacers Z: a main conductor centre-line spacing, a_{1n} geometrical sub-conductor centre-line spacing (e.g. between the 1st and 2nd sub-conductor a_{12}), F_d support load, h distance between point of application of force and the upper edge of the support, l support distance, l_s maximum distance of a spacer from the support or the adjacent spacer.

IEC 61660-2 applies to calculations in d.c. systems.

When calculating F with three-phase short-circuits for i_p the value $0.93 \cdot i_{p3}$ can be used. The factor 0.93 considers (incl. phase shift) the greatest possible shock load that can be experienced by the middle conductor of a single-plane configuration in three-phase systems.

The highest electrodynamic force between the main conductors through which the same current flows is

$$F_m = \frac{\mu_0}{2\pi} \cdot i_p^2 \cdot \frac{l}{a}$$

If the main conductor consists of n single conductors, the electrodynamic force F_s between the sub-conductors is

$$F_s = \frac{\mu_0}{2\pi} \cdot \left(\frac{i_p}{n}\right)^2 \cdot \frac{l_s}{a_s}$$

Effective conductor spacing

These equations are valid strictly speaking only for line-shaped conductors and in the first approximation for conductors of any cross section, so long as their distance from one another is significantly greater than the greatest conductor dimension. If this condition is not met, e.g. with busbar packets comprising a number of rectangular bar conductors, the individual bars must be regarded as individual line-shaped conductors and the forces between them calculated. In this case, the actual effective main conductor spacing $a_m = a / k_{1s}$ must be used as the main conductor spacing.

Here, k_{1s} must be taken from Fig. 4-3 where $a_{1s} = a$ and d the total width of the busbar packet in the direction of the short-circuit force. b – as shown in Fig. 4-3 – is the height of the busbars perpendicular to the direction of the short-circuit force.

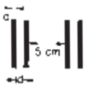
The actual effective sub-conductor distance is

$$\frac{1}{a_s} = \frac{k_{12}}{a_{12}} + \frac{k_{13}}{a_{13}} + \dots + \frac{k_{1n}}{a_{1n}}$$

For the most frequently used conductor cross sections, a_s is listed in Table 4-3.

Table 4-3

Effective sub-conductor spacing a_s for rectangular cross sections of bars and U-sections (all quantities in cm) as per IEC 60865-1 (VDE 0103)

Configuration of bars	Bar thickness *d* cm	Bar width *b* 4 cm	5 cm	6 cm	8 cm	10 cm	12 cm	16 cm	20 cm
	0.5 1	2.0 2.8	2.4 3.1	2.7 3.4	3.3 4.1	4.0 4.7	— 5.4	— 6.7	— 8.0
	0.5 1	— 1.7	1.3 1.9	1.5 2.0	1.8 2.3	2.2 2.7	— 3.0	— 3.7	— 4.3
	1	1.4	1.5	1.6	1.8	2.0	2.2	2.6	3.1
	0.5 1	— 1.7	1.4 1.8	1.5 2.0	1.8 2.2	2.0 2.5	— 2.7	— 3.2	— —

		U 60	U 80	U100	U120	U140	U160	U180	U 200
	h_s =	6	8	10	12	14	16	18	20
	e_s =	8.5	10	10	12	14	16	18	20
	a_s =	7.9	9.4	10	12	14	16	18	20

Stresses on conductors and forces on supports

The bending stress σ of a busbar must not exceed a specified limit in the event of a short circuit to avoid excessive stress on the material. In specifying this limit a sustained bending of the busbar of up to 1 % of the support length has been accepted, because a deformation of this magnitude is of no influence on the mechanical performance of the system.

The stress on rigid conductors (busbars) and the forces on the supports are influenced by the oscillation response of the conductors. This in return is dependent on the clamping conditions and the permissible plastic deformation or the natural frequency of the conductor. First the upper limit values of the stress are given with consideration to the plastic deformation, while the following section shows the stresses arising from consideration of the oscillation response.

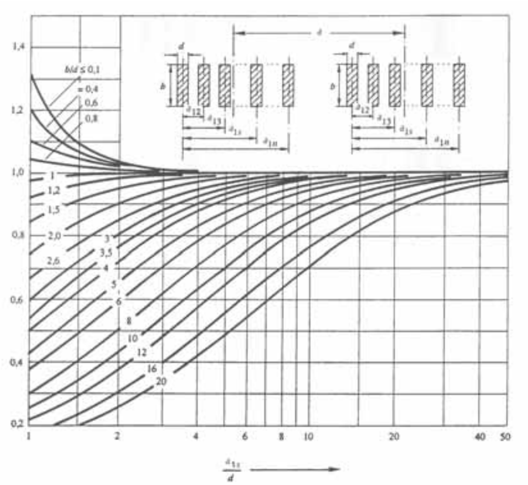


Fig. 4-3

Correction factor k_{1s} for calculating the effective conductor spacing

Main conductor stress: $$\sigma_m = V_\sigma \cdot V_r \cdot \beta \cdot \frac{F_m \cdot l}{8 \cdot Z}$$

Sub-conductor stress: $$\sigma_s = V_{\sigma s} \cdot V_r \cdot \frac{F_s \cdot l_s}{16 \cdot Z_s}$$

When considering the plastic deformation

$V_\sigma \cdot V_r = V_{\sigma s} \cdot V_r = 1$ in two-phase a.c. systems

$V_\sigma \cdot V_r = V_{\sigma s} \cdot V_r = 1$ in three-phase systems without three-phase auto-reclosure

$V_\sigma \cdot V_r = V_{\sigma s} \cdot V_r = 1.8$ in three-phase systems with three-phase auto-reclosure

The resulting conductor stress is a combination of the main and sub-conductor stress:

$$\sigma_{tot} = \sigma_m + \sigma_s$$

The force F_d on each support:

$$F_d = V_F \cdot V_r \cdot \alpha \cdot F_m$$

with

$V_F \cdot V_r = 1$ for $\sigma_{tot} \geq 0.8 \cdot R'_{p0.2}$

$V_F \cdot V_r = \dfrac{0.8 \cdot R'_{p0.2}}{\sigma_{tot}}$ for $\sigma_{tot} < 0.8 \cdot R'_{p0.2}$

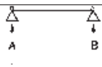
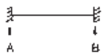
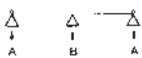
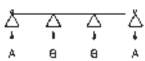
However, in two-phase a.c. systems $V_F \cdot V_r$ does not require a value greater than 2 and in three-phase systems no greater than 2.7.

If it is unclear whether a busbar can be considered supported or fixed at any specific support point, the least suitable case must be taken for rating the busbar and the support.

If the condition $\sigma_{tot} \geq 0.8 \cdot R'_{p0.2}$ is met, the busbar cannot transfer any forces greater than the static forces to the supports without permanent deformation ($V_F \cdot V_r = 1$). However, if σ_{tot} is well below $0.8 \cdot R'_{p0.2}$, it is recommended that conductor and support loads be determined according Table 4-4 taking into consideration the relevant characteristic frequency of the conductor.

Table 4-4

Factors α, β and γ as per IEC 60865-1 (VDE 0103)

Type of busbar and its clamping condition			Force on support Factor α	Main conductor stress Factor β	Relevant charcteristic frequency Factor γ
Single-span beam	both sides supported		*A*: 0.5 *B*: 0,5	1.0	1.57
	fixed, supported		*A*: 0.625 *B*: 0.375	0.73	2.45
	both sides fixed		*A*: 0.5 *B*: 0.5	0.50	3.56
Continuous beam with multiple supprts and *N* equal or approximately equal support distances	$N = 2$		*A*: 0.375 *B*: 1.25	0.73	2.45
	$N \geqq 3$		*A*: 0.4 *B*: 1.1	0.73	3.56

Note to Table 4-4

Continuous beams with multiple supports are continuous stiff bars or tubular conductors that have one or more supports along their length. They are secured against horizontal displacement at one of the supports. The length to be used in the calculation l is the distance between the supports, i.e. the length of the spans, not the length of the continuous beam.

The factors α and β apply for equal support distances. Support distances are still considered equal when the smallest support distance is at least 0.2 times the value of the largest. In this case, end supports are not subject to a higher force than the inner supports. Use the largest support distance for l in the formula.

Stresses on conductors and forces on supports with respect to conductor oscillation

If the characteristic frequency f_c of a conductor is taken into account, lower values for stresses on conductors and forces on supports may be derived than if the characteristic frequency is not considered. If higher values are found here, they are not relevant.

The characteristic frequency of a conductor is

$$f_c = \frac{\gamma}{l^2}\sqrt{\frac{E \cdot J}{m'}}$$

For determining the characteristic frequency of a main conductor, the factor γ is used depending on the clamping conditions in Table 4-4. If the main conductor consists of several sub-conductors, *J* and *m'* refer to the main conductor. The data of a sub-conductor should be used for *J* and *m'* if there are no stiffening elements along the length of the support distance. In the event that stiffening elements, with or without stiffening effect, are present, see IEC 60865-1 (VDE 0103) for additional information. This applies also to main conductors consitsing of U- and I-sections.The installation position of the bar conductor with reference to the direction of the short-circuit force (Fig. 4-7) must be considered for the axial planar moment of inertia. $\gamma = 3.56$ and l for the distance between two stiffening elements must be used for calculating the sub-conductor stresses.

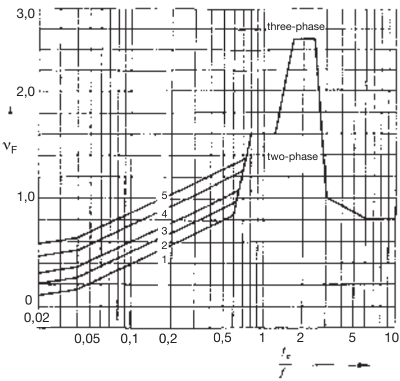


Fig. 4-4
Factor V_F to determine the forces on supports

1: κ ≥ 1.60
2: κ = 1.40
3: κ = 1.25
4: κ = 1.10
5: κ = 1.00

κ *values for Fig. 4-4 and 4-5*

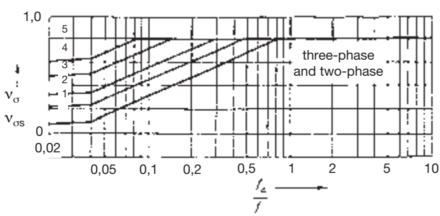


Fig. 4-5

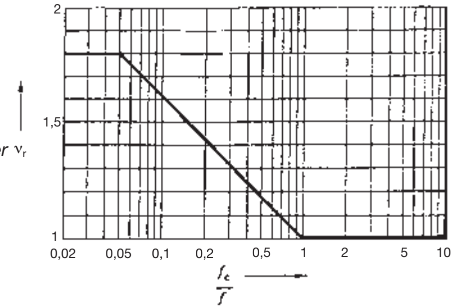
Factors V_σ and $V_{\sigma s}$ to determine the conductor stresses

When the characteristic frequencies are considered, the values for V_σ, $V_{\sigma s}$, V_F and V_r to calculate the main conductor and sub-conductor stresses and the forces on supports using the formulae given above may be taken from Fig. 4-4, 4-5 and 4-6. Algorithmus and ranges of these curves are given in IEC 60865-1 (VDE 0103)

At short-circuit durations T_k or T_{k1} of 0.1 s or less the actual stresses and forces may be considerably less than the calculated values with $f_c \leq f$. With elastic supports the actual value of f_c is less than the calculated value. This needs to be taken into account for $f_c > 2.4\, f$.

Fig. 4-6

Factor V_r, to be used with three-phase auto-reclosing in three-phase systems; in all other cases $V_r = 1$.



Maximum permissible stresses

Conductors are considered short-circuit proof when

$\sigma_{tot} \leq q \cdot R_{p0.2}$ and

$\sigma_s \leq R_{p0.2}$

The plasticity factor q for rectangular busbars is 1.5, for U and I busbars 1.19 or 1.83. Here $q = 1.19$ applies with U busbars with bending around the axis of symmetry of the U, otherwise 1.83. With I busbars $q = 1.83$ applies for bending around the vertical axis of the I, otherwise 1.19. For tubular conductors (with D = external diameter and s = wall thickness) calculate as follows

$$q = 1.7 \cdot \frac{1 - (1 - 2\frac{s}{D})^3}{1 - (1 - 2\frac{s}{D})^4}.$$

The force F_d on the supports must not exceed the minimum breaking force guaranteed by the manufacturer F_r (IEC 60168 (VDE 0674 Part 1)) of the insulators. The comparison value for the devices is the rated mechanical terminal load for static + dynamic load. Because this value is not defined in the device standards, it must be obtained from the manufacturer of the devices.

In the case of post insulators that are stressed by cantilever force the distance h of the point of application of force (Fig. 4-2) must be considered.

$F_{red} = k_{red} \cdot F_r$ = reduced rated full load of support.

The reduction factor k_{red} for the approved cantilever force is calculated with the bending moment at the foot of the insulator.

Moments of resistance (section moduli) of composite main conductors

If a stress as in Fig. 4-7a is applied, the main conductor moment of resistance is the sum of the sub-conductor moments of resistance. The same applies for a stress applied as in Fig. 4-7b when there is no or only one stiffening element per span.

If there are two or more stiffeners, the calculation can be made with higher values for the main conductor moment of resistance. The following percentages of the ideal moments of resistance of composite main conductors (Table 4-5) may be used:

- two or three sub-conductors of rectangular cross section 60%
- more sub-conductors of rectangular cross section 50%
- two or more sub-conductors of U-shaped cross section 50%

If four rectangular sub-conductors are connected in pairs by two or more stiffening elements but there are no stiffening elements between the pairs with the 5 cm spacing, only 14 % of the ideal values given in Table 4-5, i.e. $Z_y = 1.73\ b\ d^2$, may be used. The stiffening elements must be installed so that the sub-conductors are prevented from being displaced in a longitudinal direction. The plasticity factor q is exactly as large as that for non-combined main conductors.

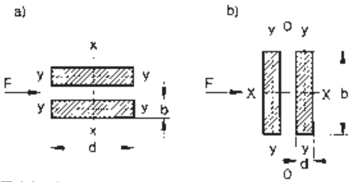
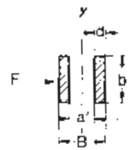


Fig. 4-7

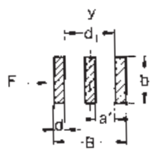
Direction of force and bending axes with conductor packets

Table 4-5

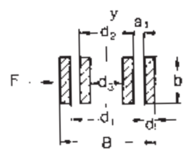
Formulae for calculating the ideal moments of inertia and resistance of composite main conductors with stiffening elements (100 % values).



$$J_y = \frac{b}{12}(B^3 - a'^3) \qquad Z_y = \frac{b}{6B}(B^3 - a'^3)$$



$$J_y = \frac{b}{12}(B^3 - d_1^3 + d^3) \qquad Z_y = \frac{b}{6B}(B^3 - d_1^3 + d^3)$$

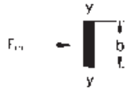


$$J_y = \frac{b}{12}(B^3 - d_1^3 + d_2^3 - d_3^3) \qquad Z_y = \frac{b}{6B}(B^3 - d_1^3 + d_2^3 - d_3^3)$$

Cross section mm	J_y cm⁴	Z_y cm³	J_y cm⁴	Z_y cm³	J_y cm⁴	Z_y cm³
Calculated values for J_y in cm⁴ and Z_y in cm³, if $a' = d$ and $d_3 = 5$ cm						
50/5	1.355	1.80	5.15	4.125	—	—
50/10	10.830	7.20	41.25	16.5	341.65	62.10
60/5	1.626	2.16	6.18	4.95	—	—
60/10	12.996	8.64	49.50	19.8	409.98	74.52
80/5	2.168	2.88	8.24	6.60	—	—
80/10	17.328	11.52	66.00	26.4	546.64	99.36
100/5	2.71	3.6	10.3	8.25	—	—
100/10	21.66	14.4	82.5	33	683.3	124.2
120/10	26	17.28	99.00	39.6	819.96	149.04

Table 4-6

Moments of resistance and of inertia for flat bars

Configuration	flat		upright	
Busbar dimensions				
mm	Z_x cm³	J_x cm⁴	Z_y cm³	J_y cm⁴
12 × 2	0.048	0.0288	0.008	0.0008
15 × 2	0.075	0.0562	0.010	0.001
15 × 3	0.112	0.084	0.022	0.003
20 × 2	0.133	0.133	0.0133	0.00133
20 × 3	0.200	0.200	0.030	0.0045
20 × 5	0.333	0.333	0.083	0.0208
25 × 3	0.312	0.390	0.037	0.005
25 × 5	0.521	0.651	0.104	0.026
30 × 3	0.450	0.675	0.045	0.007
30 × 5	0.750	1.125	0.125	0.031
40 × 3	0.800	1.600	0.060	0.009
40 × 5	1.333	2.666	0.166	0.042
40 × 10	2.666	5.333	0.666	0.333
50 × 5	2.080	5.200	0.208	0.052
50 × 10	4.160	10.400	0.833	0.416
60 × 5	3.000	9.000	0.250	0.063
60 × 10	6.000	18.000	1.000	0.500
80 × 5	5.333	21.330	0.333	0.0833
80 × 10	10.660	42.600	1.333	0.666
100 × 5	8.333	41.660	0.4166	0.104
100 × 10	16.660	83.300	1.666	0.833
120 × 10	24.000	144.000	2.000	1.000
160 × 10	42.600	341.300	2.666	1.333
200 × 10	66.600	666.000	3.333	1.660

Calculation example

Busbar configuration as shown in Fig. 4-2 with three main conductors of three sub-conductors each with rectangular cross section 80 mm × 10 mm of 3.2 m length from

ENAW-1601B-T7.

$R_{p0.2}$ = 12 000 N/cm² = 120 MPa (Table 13-1)

$R'_{p0.2}$ = 18 000 N/cm² (Table 13-1)

Stiffeners for each main conductor consist of the tee-off bars and one extra stiffening element in each of the conductors (phases) L1 and L3.

l_s = 40 cm
l = 80 cm
a = 12 cm
a_m = 12.4 cm with k_{1s} = 0.97 as shown in Fig. 4-3 where a_{1s} = a, d = 5 cm, b = 8 cm
a_s = 2.3 cm (Table 4-3)
Z_s = 1.333 cm³ (Table 4-6)
Z_y = 26.4 cm³ (Table 4-5)
Z = $0.6 \cdot Z_y = 0.6 \cdot 26.4\ \text{cm}^3 = 15.84\ \text{cm}^3$
$v_\sigma \cdot v_r = v_{\sigma s} \cdot v_r = 1$
α = 1.1 (Table 4-4 for continuous beam with N ≧ 3, end bay supports α = 0.4)
β = 0.73 (Table 4-4)

4

The prospective peak short-circuit current without auto-reclosing is i_{p3} = 90 kA.

$$F_m = 0.173 \cdot i_{p3}^2 \cdot \frac{l}{a_m} = 0.173 \cdot 90^2 \cdot \frac{80}{12.4} = 9041\ \text{N}$$

$$\sigma_m = V_\sigma \cdot V_r \cdot \beta \cdot \frac{F_m \cdot l}{8 \cdot Z} = 1.0 \cdot 0.73\ \frac{9041\ \text{N} \cdot 80\ \text{cm}}{8 \cdot 15.84\ \text{cm}^3} = 4167\ \text{N/cm}^2$$

$$F_s = 0.2 \left(\frac{i_{p3}}{t}\right)^2 \cdot \frac{l_s}{a_s} = 0.2 \left(\frac{90}{3}\right)^2 \cdot \frac{40}{2.3} = 3130\ \text{N}$$

$$\sigma_s = V_{\sigma s} \cdot V_r \cdot \frac{F_s \cdot l_s}{16 \cdot Z_s} = 1.0 \cdot \frac{3130\ \text{N} \cdot 40\ \text{cm}}{16 \cdot 1.333\ \text{cm}^3} = 5870\ \text{N/cm}^2$$

$$\sigma_{tot} = \sigma_m + \sigma_s = 4\,167\ \text{N/cm}^2 + 5\,870\ \text{N/cm}^2 = 10\,037\ \text{N/cm}^2$$

$$\sigma_{tot} = 10\,037\ \text{N/cm}^2 < 0.8 \cdot R'_{p0.2}$$

$$V_F \cdot V_r = \frac{0.8 \cdot R'_{p0.2}}{\sigma_{tot}} = \frac{0.8 \cdot 18\,000}{10\,037} = 1.44$$

$$F_d = V_F \cdot V_r \cdot \alpha \cdot F_m = 1.44 \cdot 1.1 \cdot 9\,041 = 14\,321\ \text{N}$$

Conductor stresses

$$\sigma_{tot} = 10\,037\ \text{N/cm}^2 < 1.5 \cdot R_{p0,2} = 18000\ \text{N/cm}^2$$

$$\sigma_s = 5\,870\ \text{N/cm}^2 < R_{p0,2} = 12\,000\ \text{N/cm}^2$$

The busbars can be manufactured in accordance with the planned design.

Force on support

If the height of the point of application of force in Fig. 4-2 h ≤ 50 mm, a post insulator of form C as in Table 13-34 at a rated force F = 16 000 N may be used. If the point of application of the force F is higher than shown in the table, the forces must be converted to take the maximum bending moment at the foot of the insulator into account.

Assessment with respect to the conductor oscillations

Main conductor:
γ = 3.56 (Table 4-4)
l = 80 cm
E = 70 000 N/mm^2 (Table 13-1)
J = $b\, d^{3}/12$ = 0.67 cm^4 (for single conductors, Table 1-21)
m' = 2.16 kg/m (per sub-conductor, cf. Table 13-7)
f_c = 82.4 Hz (where 1 N = 1 kg m/s^2), valid without stiffening elements
f_c = 144 Hz with stiffening elements (see IEC 60865-1)
V_r = 1 (as in Fig. 4-6 where f = 50 Hz and f_c/f = 2.88)
V_σ = 1, V_F = 1.5 (as in Fig. 4-4 and 4-5)
(Regarding the elasticity of the supports, smaller values for f_c must be used, i.e. for V_F with values up to 2.7.)

Sub-conductors:
γ = 3.56, l = 40 cm, f_{cs} = 330 Hz, V_r = 1, $V_{\sigma s}$ = 1

In this case the short, rigid busbars, taking conductor vibrations into account, do not yield smaller values for products $V_\sigma V_r$, $V_{\sigma s} V_r$, $V_F V_r$, i.e. lower stresses than when the plastic deformation is taken into account. This makes the above results determining.

4.2.2 Dimensioning of stranded conductors for mechanical short-circuit strength

To apply the following calculation procedure is highly demanding, in particular when used only now and then. It is recommented to use in addition to this manual also the standard itself (IEC 60865-1) and if possible, to apply a calculating program, as for instance KURWIN by ABB. Curves in this section are based on algorithms and validity ranges also from IEC 60865-1.

The additional electrodynamic force density per unit length *F'* that a conductor is subjected to with a short circuit is

$$F' = \frac{\mu_0}{2.\pi} \cdot \frac{(I''_{k2})^2}{a} \cdot \frac{l_c}{l}$$

where

$$\frac{\mu_0}{2 \cdot \pi} = 0.2 \frac{\text{N}}{(\text{kA})^2} \quad .$$

In three-phase systems $I''^2_{k2} = 0{,}75 \cdot I''^2_{k3}$ must be used.

The length of the span must be used for l and the current-carrying length of the conductor for l_c , i.e. with strained conductors (between portals) the length of the conductor without the length of the string insulators. In the case of slack conductors (inter-equipment connections), $l = l_c$ is the length of the conductor between the equipment terminals.

I''_{k2} and I''_{k3} are the rms values of the initial symmetrical short-circuit current in a two-phase or three-phase short circuit. *a* is the distance between centres of the main conductors.

Based on this electrodynamic force, the conductors and supports are stressed by the dynamic forces, i.e. by the short-circuit tensile force F_t, the drop force F_f and with bundle conductors by the bundle contraction force (pinch force) F_{pi}. The horizontal span displacement as in Section 4.2.3 must also be considered.

The resulting short-circuit tensile force F_t during the swing out is

with single conductors: $F_t = F_{st} \cdot (1 + \varphi \cdot \psi)$ 1)

with bundle conductors: $F_t = 1{,}1\, F_{st} \cdot (1 + \varphi \cdot \psi)$ 1), 2)

After the short circuit has been tripped, the conductor will oscillate or fall back to its initial state. The maximum value of the conductor pull occurring at the end of the fall, referred to as the drop force F_f, must only be considered at a force ratio $r > 0.6$ if the maximum swing-out angle is $\delta_m \geq 70°$.

In all other cases the following applies for the drop force

$$F_f = 1{,}2\, F_{st} \sqrt{1 + 8\zeta \frac{\delta_m}{180°}} \quad \text{1), 2), 3)}$$

In the case of bundle conductors, if the sub-conductors contract under the influence of the short-circuit current, the tensile force of the bundle conductor will be the bundle contraction force F_{pi}. If the sub-conductors contact one another[4)], i.e. if the parameter $j \geq 1$, F_{pi} is calculated from

$$F_{pi} = F_{st} \left(1 + \frac{\nu_e}{\varepsilon_{st}} \xi \right) \quad \text{1), 2), 4)}$$

If the sub-conductors do not come into contact during contraction ($j < 1$) F_{pi} is

$$F_{pi} = F_{st} \left(1 + \frac{\nu_e}{\varepsilon_{st}} \eta^2 \right) \quad \text{1), 2)}$$

See page 134 for footnotes

F_{st}[2)], the horizontal component of the static conductor pull, must be taken into account for these calculations[5)], both for the local minimum winter temperature (in Germany usually –20°C) and for the maximum (practical) operating temperature (usually +60°C). The resulting higher values of both tensile forces and and displacement are to be taken into account for the dimensioning. The calculation of the equivalent static sag from the conductor pull is demonstrated in Sec. 4.3.1. The dependence of the static conductor pull or the conductor tension $\sigma = F_{st}/A$[2)] on the temperature ϑ is derived from

$$\sigma^3 + \left[E \cdot \varepsilon \left(\vartheta - \vartheta_0 \right) - \sigma_0 + \frac{E^2\, l^2 . \rho_0^2}{24 . \sigma_0^2} \right] \sigma^2 - \frac{E . l^2}{24} \rho^2 = 0$$

Here σ_0 and ρ_0 values at reference temperature ϑ_0 must be used. ρ_0 is the specific weight, E the practical module of elasticity (Young's modulus) and ε the thermal coefficient of linear expansion of the conductor (see Tables 13-22 ff).

To calculate the short-circuit tensile force:

The load parameter φ is derived from:

$$\varphi = \begin{cases} 3\left(\sqrt{1+r^2} - 1\right) & \text{for } T_{k11} \geq T_{res}/4 \\ 3\left(r \sin\delta_k + \cos\delta_k - 1\right) & \text{for } T_{k11} < T_{res}/4 \end{cases}$$

T_{k11} = relevant short-circuit duration

T_{k11} = T_{k1} up to a maximum value of 0.4 T

T_{k1} = duration of the first current flow

$$r = \frac{F'}{g_n\, m'} \qquad \text{force ratio}^{2)}$$

$$\delta_k = \begin{cases} \delta_1 \left[1 - \cos\left(360° \frac{T_{K11}}{T_{res}} \right) \right] & \text{for } 0 \leq \frac{T_{k11}}{T_{res}} \leq 0{,}5 \\ 2\delta_1 & \text{for } \frac{T_{k11}}{T_{res}} > 0{,}5 \end{cases}$$

Swing-out angle at the end of the short-circuit current period

1) applicable for horizontal span and horizontal position of wire conductors beside one another, spans to 60 m and sags to 8% of the span length. In the case of larger spans the tensile forces will be calculated as excessive. The calculated tensile force is the horizontal component of the conductor pull and includes the static component.
2) in the case of bundle conductors the values for the complete bundle must be used .
3) in the case of short spans whose length is less than 100 times the diameter of a single conductor, the drop force is calculated too large with this formula because of the stiffness of the conductor.
4) if the sub-conductors are effectively struck together, i.e. clash effectively, it is not necessary to consider F_{pi}. The effective clashing together of the sub-conductors is considered fulfilled if the centre-line distance a_s between two adjacent sub-conductors is equal to or less than x times the conductor diameter d_s and in addition if the distance l_s between two adjacent spacers is at least y times the sub-conductor centre-line distance. x, y can be used as a value pair:
   $x = 2.5$ with $y = 70$
   $x = 2.0$ with $y = 50$
5) With calculating programs, e.g. KURWIN of ABB, taking these details into account.

$\delta_1 = \arctan r$ — Direction of the resultant force on the conductor (expressed in degrees)

$$T_{res} = \frac{T}{\sqrt[4]{1+r^2}\left[1-\frac{\pi^2}{64}\left(\frac{\delta_1}{90°}\right)^2\right]}$$

Resultant period of the conductor oscillation

$$T = 2\pi\sqrt{0{,}8\,\frac{b_c}{g_n}}$$

Period of the conductor oscillation

$$b_c = \frac{m' g_n l^2}{8\,F_{st}}$$

Equivalent static conductor sag in the middle of the span2)

Where:

m' mass of a main conductor per unit length2), 6)

g_n gravity constant (9.80665 m/s² = 9.80665 N/kg)

The span reaction factor ψ is a function of the stress factor ζ of a main conductor and of the load parameter φ, calculated above, as in Fig. 4-8. It is

$$\zeta = \frac{(g_n m' l)^2}{24 F_{st}^3 N} \quad \text{with} \quad N = \frac{1}{S\,l} + \frac{1}{E_S A_S}$$

Stiffness norm2)

Where:

$$E_S = \begin{cases} E\left[0{,}3 + 0{,}7\sin\left(\frac{F_{st}}{A_S\,\sigma_{fin}}\,90°\right)\right] & \text{for } \frac{F_{st}}{A_S} \le \sigma_{fin} \\ E & \text{for } \frac{F_{st}}{A_S} > \sigma_{fin} \end{cases}$$

Effective modulus of elasticity2)

σ_{fin} 50 N/mm² (Above σ_{fin} the modulus of elasticity is constant .)

E modulus of elasticity (i.e. Young's modulus) of the wire (see Tables 13-22 ff)

S spring constant of the span resulting from elasticity of the supports in the event of short circuit. (For equipment connections S = 100 N/mm, if not otherwise known. In the case of strained conductors between portals, the spring constant must be determined separately. A common value is S = 500 N/mm)

A_S conductor cross section (actual value or nominal cross section as in Tables 13-23 ff)2)

2) See footnote 2) page 134.

6) When calculating F_t, F_f and b_h (Sec. 4.2.3) the mass-per-unit length of the main conductor including the distributed single loads must be used.

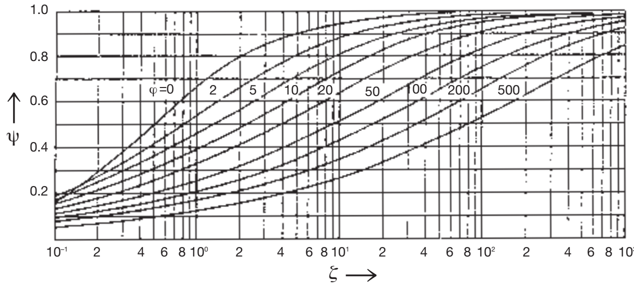


Fig. 4-8

Span reaction factor ψ depending on stress factor ζ and the load parameter φ

Calculating the drop force:

The drop force is particularly dependent on the angle δ_m (see Fig. 4-9) to which the conductor swings out during the short-circuit current flow. Here, for the relevant short-circuit duration T_{k11} must be used as the duration of the short-circuit current T_{k1} (in case of auto-reclosing this is the duration of the first current flow), where the value 0.4 T must be taken as the maximum value for T_{k1} (F_{st} and ζ are given above).

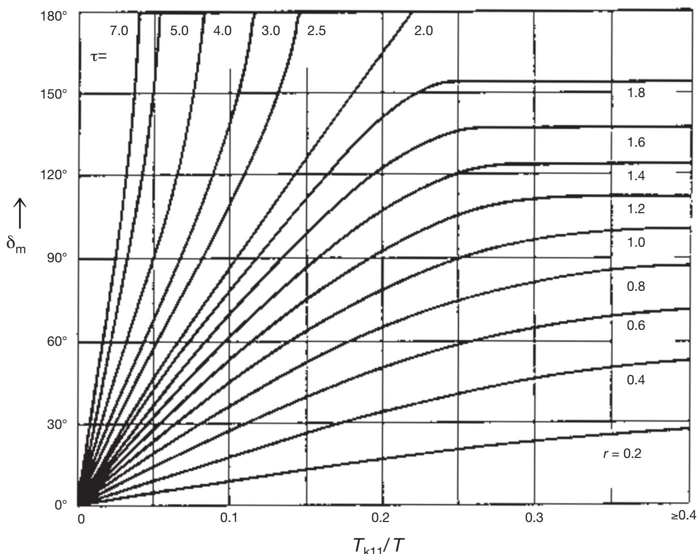


Fig. 4-9

Maximum swing out angle δ_m as function of the relevant short-circuit duration T_{k11} based on the period of the conductor oscillation T

Calculation of the bundle contraction force:

$$j = \sqrt{\frac{\varepsilon_{pi}}{1+\varepsilon_{st}}}$$

Parameter for determining the position of the bundle conductor during the short-circuit current flow

$$\varepsilon_{st} = 1{,}5 \frac{F_{st}\, l_s^2\, N}{(a_s - d_s)^2} \left(\sin\frac{180°}{n}\right)^2 \mathrm{k}$$

Strain factors with bundle conductors

$$\varepsilon_{pi} = 0{,}375 n \frac{F_v\, l_s^3\, N}{(a_s - d_s)^3} \left(\sin\frac{180°}{n}\right)^3$$

$$F_v = (n-1)\frac{\mu_0}{2\pi}\left(\frac{I''_k}{n}\right)^2 \frac{l_s}{a_s}\frac{\nu_2}{\nu_3}$$

Short-circuit current force between the sub-conductors

I''_k current in the bundle conductor: Maximum value from I''_{k2}, I''_{k3} or I''_{k1}

I''_{k1} rms value of the initial symmetrical short-circuit current with single-phase short circuit

n number of sub-conductors of a bundle conductor

ν_2 see Fig. 4-10 as function of ν_1 and the factor κ

κ Factor for calculating the peak short-circuit current i_p as in Fig. 3-2

ν_3 see Fig. 4-11 as function of n, a_s and d_s

a_s centre-line distance between two adjacent sub-conductors

d_s conductor diameter

l_s average distance between two adjacent spacers in a span

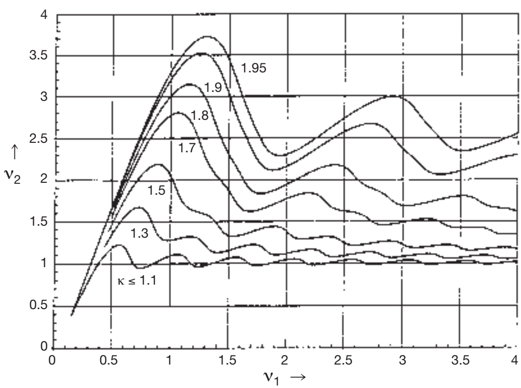


Fig. 4-10

Factor ν_2 as function of ν_1 and κ

$$\nu_1 = f \frac{1}{\sin\frac{180°}{n}} \sqrt{\frac{(a_s - d_s)\, m'_s}{\frac{\mu_0}{2\pi}\left(\frac{I''_k}{n}\right)^2 \frac{n-1}{a_s}}}$$

m'_s = mass-per-unit length of a sub-conductor

f = frequency of the current circuit

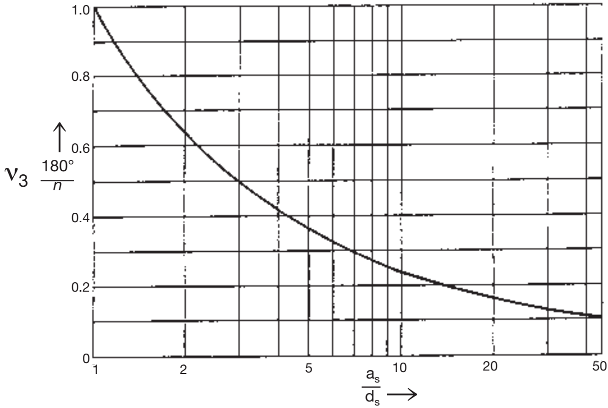


Fig. 4-11

Factor ν_3 as function of the number of sub-conductors n and the bundle dimensions a_s and d_s

Bundle contraction force with sub-conductors in contact, i.e. clashing sub-conductors ($j \geq 1$):

$$\nu_e = \frac{1}{2} + \sqrt{\frac{9}{8}n(n-1)\frac{\mu_0}{2\pi}\left(\frac{I''_k}{n}\right)N\nu_2\left(\frac{l_s}{a_s-d_s}\right)^4\frac{\left(\sin\frac{180°}{n}\right)^4}{\xi^3}\left(1-\frac{\arctan\sqrt{\nu_4}}{\sqrt{\nu_4}}\right)-\frac{1}{4}}$$

$$\nu_4 = \frac{a_s-d_s}{d_s}$$

ξ as in Fig. 4-12

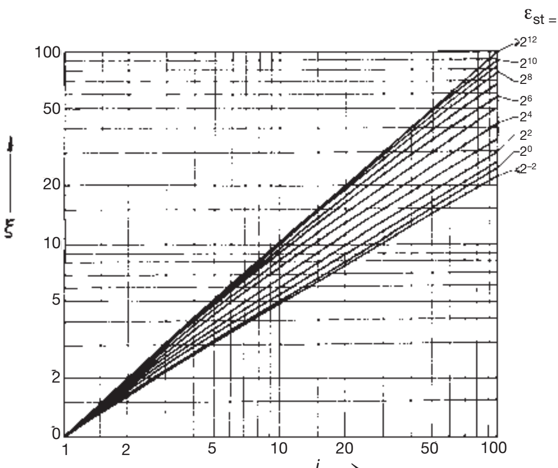


Fig. 4-12

Factor ξ as function of j and ε_{st}

Bundle contraction force with sub-conductors not in contact, i.e. non-clashing sub-conductors ($j < 1$):

$$\nu_e = \frac{1}{2} + \sqrt{\frac{9}{8}n(n-1)\frac{\mu_0}{2\pi}\left(\frac{I''_k}{n}\right)N\nu_2\left(\frac{l_s}{a_s-d_s}\right)^4 \frac{\left(\sin\frac{180°}{n}\right)^4}{\eta^4}\left(1-\frac{\arctan\sqrt{\nu_4}}{\sqrt{\nu_4}}\right)-\frac{1}{4}}$$

$$\nu_4 = \frac{a_s - d_s}{a_s - \eta(a_s - d_s)}$$

η as in Figs. 4-13a to 4-13c

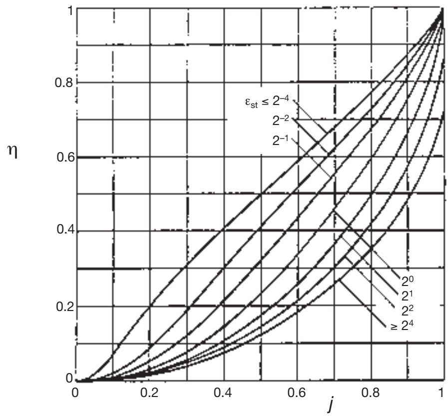


Fig. 4-13a

η as function of j and ε_{st} for $2.5 < a_s / d_s \leq 5.0$

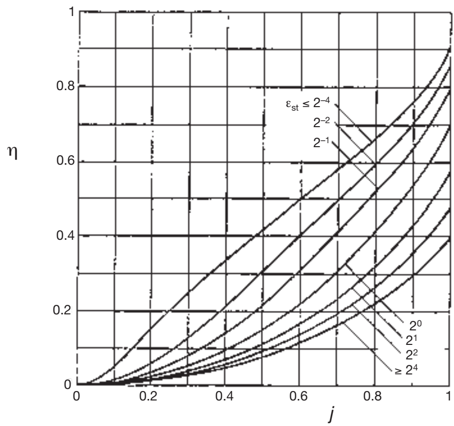


Fig. 4-13b

η as function of j and ε_{st} for $5.0 < a_s / d_s \leq 10.0$

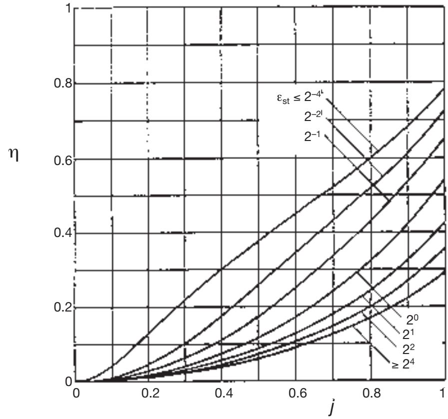


Fig. 4-13c

η as function of j and ε_{st} for $10.0 < a_s / d_s \leq 15.0$

Permissible loads

For post insulators the maximum value from F_f, F_t and F_{pi} must not exceed the rated mechanical withstand values Fr stated by the manufacturers of insulators and mounting structures. With post type insulators with bending forces applied in a distance above the insulator top the additional mechanical stress must be taken into account. See also Section 4.2.1. For the static load, $F_{st} \leq 0.4\ F_r$ must apply.

For apparatus the maximum value from F_f, F_t and F_{pi} must not exceed the resultant (static + dynamic) rated mechanical terminal load. F_{st} may not exceed the (static) rated mechanical terminal load. The fixing devices must be rated for the maximum value of 1.5 F_t, 1.0 F_f and 1.0 F_{pi}. Factor 1.5 takes into account that the energy of the oscillation is absorbed by the insulator mass.

For strained conductors, the connectors and supports/portals must be based on the maximum value from F_f, F_t and F_{pi} as a quasi-static exceptional load. Because the loads do not occur at the same time in three-phase configurations, the dynamic force must be assumed as effective in 2 conductors and the static force as effective in the third conductor.

Guidelines for the dimensioning of foundations should be requested from the design offices of the manufacturers.

Calculation example

Strained conductors between portals in a 420-kV three-phase switchgear installation with current feeder jumpers at the ends and a down-dropper in the middle[7)].

Bundle conductor 2 x Al 1000 mm^2 as in Tables 13-24 and 13-25
Additional load of the current feeder jumpers and of the down droppers is distributed over the length of the span to the sub-conductors: m'_L = 1.431 kg/m
Centre-line distance of sub-conductors: a_s = 0.2 m
Average distance of spacers: l_s = 6.5 m
Span length: l = 42.5 m
Length of bundle conductor between the current feeder jumpers: l_c = 32.5 m
Centre-line distance of main conductors: a = 5 m
Spring constant of the span with static load: S_s = 320.3 N/mm
Spring constant of the span with load caused by short circuit: S_d = 480.5 N/mm
Horizontal static main conductor pull at –20°/60°C: F_{st-20} = 12126.4 N, F_{st+60} = 11370.4 N
Relevant short-circuit current: I''_{k3}= 50 kA, i_p = 125 kA, f = 50 Hz
Short-circuit duration: T_{k1} = 1 s

Calculation of short-circuit tensile force F_t and drop force F_f at –20°C and +60°C

Electrodynamic force density: F' = (0.2 x 0.75 x 50^2 / 5) (32.5 / 42.5) N/m = 57.35 N/m
Relevant mass of conductor per unit length incl. individual loads:
m' = 2 (2.767 + 1.431) kg/m = 8.396 kg/m
Force ratio: r = 57.35 / (9.80665 x 8.396) = 0.697
Direction of resultant force on the conductor: δ_1 = arctan 0.697 = 34.9°

	–20°C	60°C	
Equivalent static conductor sag b_c	1.53	1.63	m
Period of conductor oscillation T	2.22	2.29	s
Resultant period of oscillation T_{res}	2.06	2.13	s
Relevant short-circuit duration T_{k11}	0.89	0.92	s
Swing-out angle δ_k (with $T_{k11} \le 0.5\, T_{res}$)	66.5	66.5	°
Load parameter φ (with $T_{k11} \ge T_{res}/4$)	0.656	0.656	
Effective modulus of elasticity E_s (with $F_{st}/A \le \sigma_{fin}$)	23791	23342	N/mm^2
Stiffness norm N	70	70	10^{-9}/N
Stress factor ζ	4.1	4.9	
Span reaction factor ψ (as in Fig. 4-8)	0.845	0.866	
Short-circuit tensile force F_t (with bundle conductors)	20730	19614	N
Maximum swing-out angle δ_m (as in Fig. 4-9)	79	79	°
Drop force F_f (because r > 0.6 and $\delta_m \ge 70°$)	56961	58326	N

The maximum value of the short-circuit tensile force is derived at the lower temperature and is F_t = 20730 N. The maximum value of the drop force is derived at the higher temperature and is F_f = 58623 N.

7) The calculation was conducted with the KURWIN calculation program of ABB. This yields more accurate figures than would be possible with manual calculation and would be required with regard to the general accuracy of the procedure.

Calculation of the bundle contraction force F_{pi} at –20°C and +60°C

The contraction force must be calculated because the sub-conductors do not clash effectively. It is $x = a_s/d_s$ = 200 mm / 41.1 mm = 4.87 and $y = l_s / a_s$ = 6.5 m / 0.2 m = 32.5. The condition $y \geq 50$ and $x \leq 2.0$ is not met.

The question whether the sub-conductors come into contact with one another during the contraction is decided at the parameter j as follows:

The relevant short-circuit current is the three-phase short-circuit current (50 kA). The relevant weight of the bundle conductor is only the weight of the two conductors of m' = 2 x 2.767 kg/m = 5.534 kg/m. At a circuit frequency of 50 Hz, this yields the determining parameter ν_1 to 1.33.

With factor $\kappa = i_p / \sqrt{2}\, I''_{k3}$ = 125 / (1.41 x 50) = 1.77 factor ν_2 = 2.64 is derived from Fig. 4-10. Fig. 4-11 yields ν_3 = 0.37. These factors yield the short-circuit force between the sub-conductors as F_ν = 0.2 25² (6.5 / 0.2) (2.64 / 0.37) N = 29205 N. This gives the following for the two relevant temperatures:

	–20°C	60°C
Strain factor ε_{st}	2.13	2.01
Strain factor ε_{pi}	104.9	105.5
Parameter j	5.79	5.92

Therefore, the sub-conductors do come into contact with one another. This continues as follows:

	–20°C	60°C	
Parameter ξ (as in Fig. 4-12)	4.10	4.14	
Parameter ν_e (at j ≥ 1)	1.32	1.31	
Bundle contraction force F_{pi}	43032	42092	N

The maximum value of the contraction force occurs at the lower temperature and is F_{pi} = 43032 N.

4.2.3 Horizontal span displacement

The RMS-value of the electrodynamic force occurring with short circuits drives the conductors apart. Depending on the interplay of conductor mass and duration and magnitude of the short-circuit current, a conductor can oscillate completely upwards, then to the other side and again to the bottom of the oscillation, in other words travelling in a complete circle. Furthermore, due to the electrodynamic force per unit lenght the conductor is stretched (factor C_D) and the conductor curve is deformed (factor C_F), with the result that a conductor can swing further outwards than would be predicted from its static sag.

The maximum horizontal span displacement b_h (outwards and inwards) in the middle of the span is calculated with slack conductors ($l_c = l$)

$$b_h = \begin{cases} C_F C_D b_C & \text{for} \quad \delta_m \geq 90° \\ C_F C_D b_C \sin\delta_m & \text{for} \quad \delta_m \leq 90° \end{cases} \quad \text{for} \quad l_C = l$$

and with strained conductors, which are attached to support structures by insulator strings (length l_i).

$$b_h = \begin{cases} C_F C_D b_C \sin\delta_1 & \text{for} \quad \delta_m \geq \delta_1 \\ C_F C_D b_C \sin\delta_m & \text{for} \quad \delta_m \leq \delta_1 \end{cases} \quad \text{for} \quad l_C = l - 2\, l_i$$

Here, δ_1, b_c and δ_m have the same values, as calculated in Sec. 4.2.2 or as in Fig. 4-9. In three-phase systems the three-phase short-circuit current as in Sec. 4.2.2 must also be used. In addition, the following applies:

$$C_F = \begin{cases} 1{,}05 & \text{for} \quad r \le 0{,}8 \\ 0{,}97 + 0{,}1r & \text{for} \quad 0{,}8 \le r \le 1{,}8 \\ 1{,}15 & \text{for} \quad r \ge 1{,}8 \end{cases}$$

with the force ratio r as in Sec. 4.2.2

$$C_D = \sqrt{1 + \frac{3}{8}\left(\frac{l}{b_c}\right)^2 \left(\varepsilon_{ela} + \varepsilon_{th}\right)}$$

$$\varepsilon_{ela} = N\left(F_t - F_{st}\right)$$

Elastic conductor expansion

$$\varepsilon_{th} = \begin{cases} c_{th}\left(\dfrac{I''_k}{A_s}\right)^2 \dfrac{T_{res}}{4} & \text{for} \quad T_{k11} \ge \dfrac{T_{res}}{4} \\ c_{th}\left(\dfrac{I''_k}{A_s}\right)^2 T_{K1} & \text{for} \quad T_{k11} \le \dfrac{T_{res}}{4} \end{cases}$$

Thermal conductor expansion

$$c_{th} = \begin{cases} 0{,}27.10^{-18}\ \dfrac{m^4}{A^2 s} & \text{with conductor of Al, AlMgSi, Al/St with cross section-ratio} < 6 \text{ (see Table 13-26)} \\ 0{,}17.10^{-18}\ \dfrac{m^4}{A^2 s} & \text{with conductors of Al/St with cross-section ratio} \ge 6 \\ 0{,}088.10^{-18}\ \dfrac{m^4}{A^2 s} & \text{with conductors of copper} \end{cases}$$

$I''_k = I''_{k3}$ in three-phase systems or $I''_k = I''_{k2}$ in two-phase a.c. systems

Permissible displacement

In the most unsuitable case two adjacent conductors approach each other by the horizontal span displacement b_h. This leaves a minimum distance $a_{min} = a - 2\,b_h$ between them. This minimum distance is reached only briefly during the conductor oscillations. If a subsequent flashover, e.g. at the busbar, is not to occur in the case of a short circuit at some other place, e.g. at a feeder of the switchgear installation, then a_{min} - of the busbar - must not be less than 50% of the minimum clearance of conductor-conductor parallel as requested according VDE 0101 or else in Table 4-10.

Calculation example

Strained conductors between portals as in Sec. 4.2.2

To determine the elastic conductor expansion, the short-circuit tensile force also at the upper temperature (60°C) must be known. It was calculated in Sec. 4.2.2. Then

	–20°C	60°C	
Factor for the elastic conductor expansion ε_{ela}	0.00060	0.00058	
Material factor for Al conductors c_{th}	0.27	$0.27 \cdot 10^{-18}$	$m^4 / (A^2 \cdot s)$
Factor for the thermal conductor expansion ε_{th}	0.000087	0.000090	
Factor for the elast. and therm. cond. expansion C_D	1.095	1.082	
Factor for dynam. deformation of the cond. curve C_F	1.05	1.05	
Horizontal span displacement b_h	1.01	1.06	m

The maximum value of the horizontal span displacement is found at the upper temperature and is 1.06 m. A centre-line distance of main conductors of a = 5 m means that the main conductors can approach to a minimum distance of 2.88 m in the most unfavourable case. As in Table 4-10, the required minimum conductor-conductor distance for the static case in a 420-kV system is 3.1 m. The permissible minimum distance in the event of a short circuit is therefore 1.55 m. Therefore, the strained conductors are short-circuit proof with reference to the horizontal span displacement, because 1.55 m ≤ 2.88 m.

4.2.4 Mechanical stress on cables and cable fittings in the event of short circuit

The electromagnetic forces occurring with short circuit currents are determining for the mechanical withstand ratings of cable accessories. Within multicore cables these forces are still higher because of the close proximity of the conductors. However, the structure of the cable will take up the forces because they mostly act radially. A cable properly dimensioned thermally for short circuits is in general also suitable for withstanding the relevant mechanical short circuit stresses.

For cable accessories the mechanical withstand at rated short circuit peak current i_p must be proven according DIN VDE 0278-629-1 (HD629.1 S1), DIN VDE 0278-620-2 (HD629.2 S1), DIN VDE 0276-632 (HD632.S1) or IEC 60840.

Particularly high mechanical stresses occur with short circuit currents on parallel single-conductor cables (Fig. 4-14).

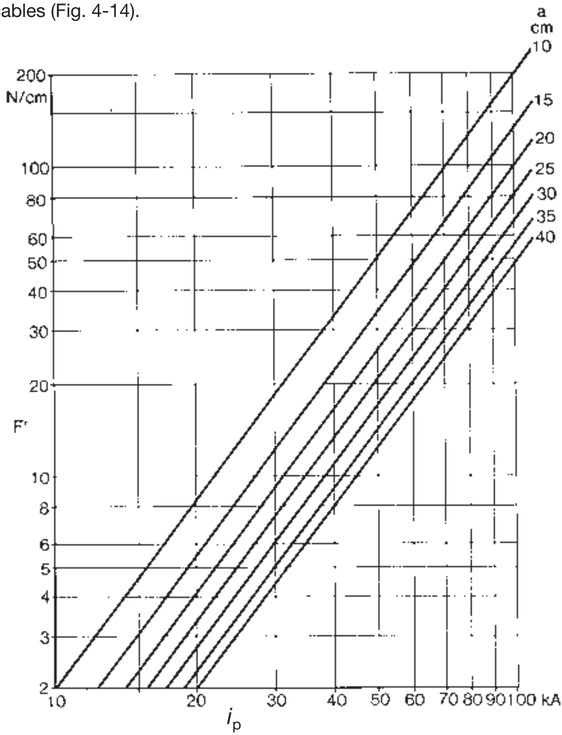


Fig. 4-14

Electrodynamic force density F' on two parallel single-conductor cables depending on the axis distance a of the cables and on the peak short-circuit current i_p.

With a three-phase short circuit, the effective forces are about 10 % lower than with a two-phase short circuit of the same current.

4.2.5 Rating the thermal short-circuit current capability of stranded conductors

Busbars, including their feeders with the installed equipment (switches, current transformers, bushings), are also subject to thermal stress in the event of a short circuit. Verification is always required to ensure that they are sufficiently rated not only mechanically but also thermally for the short-circuit current.

The thermal stress depends on the quantity, the temporal sequence and the duration of the short-circuit current. A thermally equivalent *short-time current* I_{th} is defined as a current whose rms value generates the same heating effect as another short-circuit current which may vary during the short-circuit duration T_k in its d.c. and a.c. components. For simplifying the mathematical solution it is assumed that

- the Skin effect may be neglected,
- the resistance to temperature ratio is linear,
- the specific heat of the conductor material is constant within the temperature range and
- the heating up runs as a diabatic process, i.e. without heat transfer to the ambient atmosphere.

The short-time current is calculated as follows for a single short-circuit event of the short-circuit duration T_k:

$$I_{th} = I''_k \cdot \sqrt{(m + n)}.$$

The factors m and n are determined as in Fig. 4-15. The effect of current limiting equipment can be taken into account. The individual values as in the above equation must be calculated for several sequential short-circuit durations with short intervals (e.g. auto-reclosing). The resulting thermally equivalent phase fault current is then:

$$I_{th} = \sqrt{\frac{1}{T_k} \sum_{i=1}^{n} I_{thl}^2 \cdot T_{ki}} \text{ with } T_k = \sum_{i=1}^{n} T_{ki}.$$

For calculating the thermally equivalent short-time current in a three-phase system normally the case of the three-phase fault is taken into account.

The manufacturer provides the approved *rated short-time withstand current* I_{thr} and the rated duration of short circuit T_{kr} for electrical apparatus (also for current-limiting ones). This is the rms value of the current whose effect the equipment withstands during time T_{kr}.

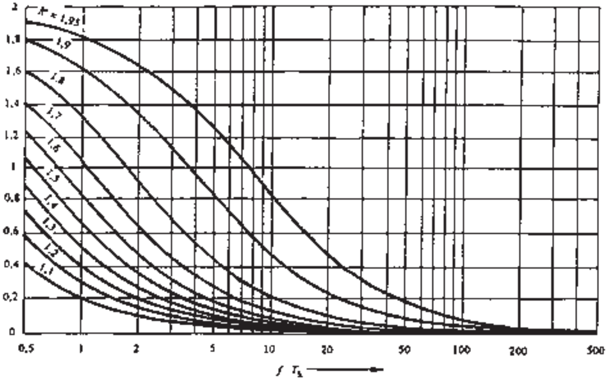
Electrical apparatus have sufficient thermal resistance if:

$$I_{th} \leqq I_{thr} \text{ for } T_k \leqq T_{kr}$$

$$I_{th} \leqq I_{thr} \cdot \sqrt{\frac{T_{kr}}{T_k}} \text{ for } T_k \geqq T_{kr}.$$

T_k is the sum of the relay operating times and the switch total break time. Set grading times must be taken into account.

a)



b)

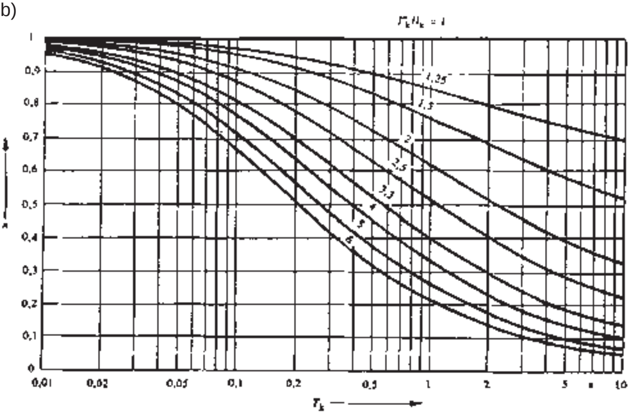


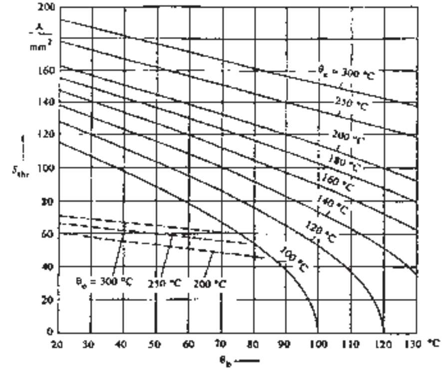
Fig. 4-15

Factors m and n for short-time current: a) factor m for the DC-component with three-phase and single-phase alternating current switchgear at 50 Hz. Parameter: factor κ for calculating the peak short-circuit current i_p as in Fig. 3-2. b) factor n for the thermal effect of the AC-component in three-phase and approximately in single-phase alternating current switchgear, parameter I''_k/I_k (see Fig. 3-1).

The equations of the curves for m and n are given in IEC 60865-1 (VDE 0103).

For conductors, the thermally equivalent short-time current density S_{th} is calculated. It should be less than the rated short-time current density S_{thr}, which can be determined with Fig. 4-16.

a)



b)

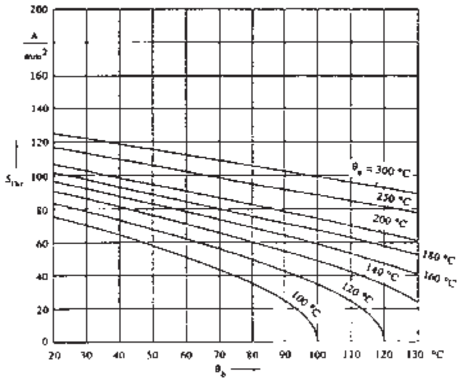


Fig. 4-16

Rated short-time current density S_{thr} as a function of the initial conductor temperatur ϑ_b for T_{kr} = 1 s: a) for copper (continuous curves) and unalloyed steel and steel cable (broken curves); b) for aluminium, Aldrey and Al/St.

The maximum continuous permissible operating temperature must be set as the initial temperature ϑ_b of a conductor, unless otherwise known (see Table 13-31 and 13-32). The end temperature ϑ_e of a conductor is the permissible conductor temperature in the event of a short circuit (see Tables 13-2, 13-3 and 13-32).

Bare conductors have sufficient thermal resistance when the thermally equivalent short-circuit current density conforms to the following equation:

$$S_{th} \leqq S_{thr} \cdot \sqrt{\frac{T_{kr}}{T_k}} \text{ for all } T_k.$$

In some countries instead of the equation above the Joule-integral is used as given in IEC 60865-1 (VDE 0103).
The steel component of Al/St-conductors is not taken into account for the conductor cross section relevant for calculating the current density.

Calculation example

The feeder to the auxiliary transformer of a generator bus must be checked for whether the cross section at 100 mm × 10 mm Cu and the current transformer are sufficient for the thermal stress occurring with a short circuit when the total breaking time $T_k = 1$ s. The installation must be rated for the following values:

$I''_k = 174.2$ kA, $\kappa = 1.8$, $I_k = 48{,}5$ kA, $f = 50$ Hz.

For $\kappa = 1.8$ results $m = 0.04$ and for $\frac{I''_k}{I_k} = 3.6$ is $n = 0.37$.

This yields

$$I_{th} = 174.2 \text{ kA} \sqrt{0.04 + 0.37} = 112 \text{ kA}.$$

According to the manufacturers, the rated short-time withstand current of the instrument transformer $I_{thr} = 125$ kA for $T_{kr} = 1$ s. The instrument transformers therefore have sufficient thermal strength.

The cross section of the feeder conductor is $A = 1000 \text{ mm}^2$.

Therefore, the current density is

$$S_{th} = \frac{112\,000 \text{ A}}{1000 \text{ mm}^2} = 112 \text{ A/mm}^2.$$

The permissible rated short-time current density at the beginning of a short circuit at a temperature $\vartheta_b = 80$ °C and an end temperature $\vartheta_e = 200$ °C as in Fig. 4-16:

$$S_{thr} = 125 \text{ A/mm}^2.$$

The feeder conductor therefore also has sufficient thermal strength.

The rated short-time current densities S_{thr} are given in Table 4-8 for the most commonly used plastic insulated cables.

The permissible rated short-time current (1 s) for the specific cable type and cross section is calculated by multiplication with the conductor nominal cross section. The conversion is done with the following formula up to a short-circuit duration (T_k) of max. 5 seconds:

$$I_{th}(T_k) = I_{thr} / \sqrt{T_k} \qquad T_k \text{ in seconds.}$$

Example

Permissible short-time current (break time 0.5 s) of cable N2XSY 1 × 240 RM/25, 12/20 kV:

$$I_{thr} = 240 \text{ mm}^2 \cdot 143 \text{ A/mm}^2 = 34.3 \text{ kA}$$

$$I_{th}(0.5 \text{ s}) = \frac{34.3 \text{ KA}}{\sqrt{0.5}} = 48.5 \text{ kA}$$

Note:

Short-time current densities for lower conductor temperatures at the beginning of the short circuit (cable only partially loaded) and values for mass-impregnated cables can be taken from DIN VDE 0276-620 and 0276-621.

Table 4-8

Permissible short-circuit conductor temperatures and rated short-time current densities for plastic-insulated cables

Insulation material	Nominal voltage U_0/U kV	Conductor temperature at beginning of the short circuit	Permissible end temperature	Conductor material	Rated short-time current density (1 s) A /mm²
PVC	0.6/1…6/10	70 °C	160 °C[1)]	Cu	115
				Al	76
			140 °C[2)]	Cu	103
				Al	68
XLPE	all ranges LV and HV	90 °C	250 °C[3)]	Cu	143
				Al	94

1) for cross sections ≤ 300 mm²
2) for cross sections > 300 mm²
3) not permitted for soldered connections

For extremely short break times with short circuits (T_k < 15 ms), current limiting comes into play and the thermal short-circuit current capability of cables and conductors can only be assessed by comparison of the Joule integrals $\int i^2\, d\, t = f\,(\hat{I}''_k)$. The let-through energy of the overcurrent protection device must be less than the still available heat absorbtion capability of the conductor.

Permissible Joule integrals for plastic-insulated conductors:

A	= 1.5	2.5	4	10	25	50	mm²
$\int i^2\, d\, t$	= $2.9 \cdot 10^4$	$7.8 \cdot 10^4$	$2.2 \cdot 10^5$	$1.3 \cdot 10^6$	$7.6 \cdot 10^6$	$3.3 \cdot 10^7$	A^2s

Current limiting overcurrent protection devices such as fuses or current limiting breakers are particularly advantageous for short-circuit protection of cables and conductors. Their let-through energy in the event of a short circuit is small. As a result the Joule heat input into a conductor $\int i^2\, d\, t$ dt increases with increasing prospective short-circuit current I''_k many times faster when a current-zero interrupter is used than with a current limiting switching device.

4.3 Dimensioning of wire and tubular conductors for static loads and electrical surface field strength

4.3.1 Calculation of the sag of wire conductors in outdoor installations

Busbars and tee-offs must be rated for normal service current and for short circuit in accordance with IEC 60865-1 (VDE 0103), see Sec. 4.2.

Al/St wire conductors are primarily used for the tensioned busbars, for connecting apparatus and for tee-off conductors also Al wire conductors with a similar cross section are used.

For wire conductor data, see Sections 13.1.4, Tables 13-22 to 13-33.

Wire conductor sag is determined by the dead-end strings, the weight of the wire, the anticipated ice load, the supplementary load of tee-offs or fixed contacts for single-column disconnectors, by the wire-pulling force, by built-in springs or the spring stiffness of the supports and the wire temperature.

The greatest wire conductor sag occurring in the installation is calculated either at a conductor temperature of + 80 °C or, with very short span lengths, at – 5 °C plus ice load.

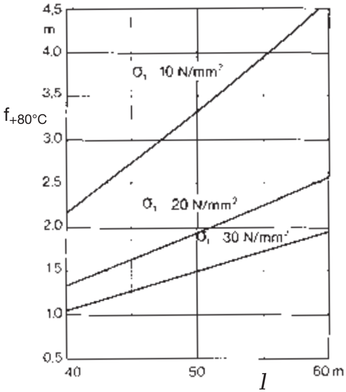


Fig. 4-17

Sag f in m for two-conductor bundles Al/St 240/40 mm², with 123-kV double endstrings, for spans of l = 40…60 m at conductor temperature +80°C. The following are included: two dead-end strings each 2.0 m in length, weight 80 kg (≙ 900 N weight force, incl. ice load) and a tee-off of 10 kg in weight every 10 m. (Parameters of the family of curves: initial wire tension σ_1 at – 5 °C and about 10 mm ice coating).

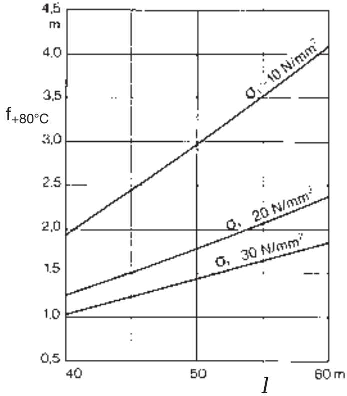


Fig. 4-18

Sag f in m for two-conductor bundles Al/St 300/50 mm², with 123-kV double endstrings, for spans of l = 40…60 m at conductor temperature +80°C. The following are included: two dead-end strings, each 2.0 m in length, weight 80 kg (≙ 900 N weight force, incl. ice load) and a tee-off of 10 kg in weight every 10 m. (Parameters of the family of curves: initial wire tension σ_1 at – 5 °C and about 10 mm ice coating).

According to DIN VDE 0101(VDE 0101) the ice coating on the conductors of outdoor installations shall be (in line with IEC 60694 (VDE 0670 Part 100)) assumed to have a thickness of 1mm, of 10mm or of 20mm, as far as no other local experience or statistic records are available. The density of the ice coating is 900kg/m³ according to IEC/TR 60826.

Typical values for a rough determination of the sags of tensioned busbars, tensioned and suspended wire links and lightning protection wires are given in Fig. 4-17 to 4-25.

Further details about the wire conductor sag of overhead lines are also in EN 50341-1 (DIN VDE 0210-1, Overhead lines > 45 kV AC).

Sag of the tensioned busbars with loads, dead-end strings and tee-offs at every 10 m (width of bay) with a weight of 10 kg each

The sags and tensions of the busbar wires are influenced by their dead-end strings and tee-offs (point loads).

The busbar sags in a 123-kV outdoor installation with a bay width of 10.0 m can be roughly determined using the diagrams in Figs. 4-17 to 4-20. These give for the most common types of wire conductors like two-conductor bundle 240/40 mm², two-conductor bundle 300/50 mm², single-conductor wire 380/50 mm² and single-conductor wire 435/55 mm², for spans of 40…60 m and initial wire tensions σ_1 = 10.0…30.0 N/mm² with ice load, values for the sags occuring at + 80 °C conductor temperature.

At 245- and 420-kV outdoor installations in diagonal arrangement with single-column disconnectors the busbars take the weight of the disconnector fixed contacts instead of the tee-off wires. To limit the temperature-dependent change in sag, spring elements are frequently included in the span to maintain the suspended contacts within the reach of the disconnector scissors.

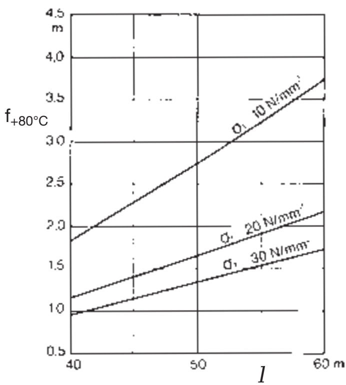


Fig. 4-19

Sag f in m for single-conductor wires Al/St 380/50 mm², with 123-kV double-end strings, for spans of l = 40…60 m at conductor temperature + 80°C. The following are included: two dead-end strings, each 2.0 m in length, weight 80 kg (≙ 900 N weight force, incl. ice load) and a tee-off every 10 m of 10 kg in weight. (Parameters of the family of curves: initial wire tension σ_1 at – 5 °C and about 10 mm ice coating).

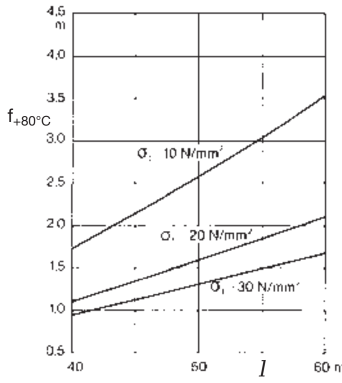


Fig. 4-20

Sag f in m for single-conductor wires Al/St 435/55 mm², with 123-kV double-end strings, for spans of l = 40…60 m at conductor temperature + 80°C. The following are included: two dead-end strings, each 2.0 m in length, weight 80 kg (≙ 900 N weight force, incl. ice load) and a tee-off every 10 m of 10 kg in weight. (Parameters of the family of curves: initial wire tension σ_1 at – 5 °C and about 10 mm ice coating).

Sag of the spanned wire conductors

In many outdoor installations spanned wire conductors with dead-end strings are required.

The sag can be calculated as follows when σ_x is known:

$$f_x = \frac{g_n}{2 \cdot \sigma_x \cdot A} [m' \cdot (0.25\, l^2 - l_k^2) + m_k \cdot l_k]$$

f_x sag m, σ_x horizontal component of the cable tension N/mm², m' mass per unit length of wire kg/m, with ice load if applicable, m_K mass of insulator string in kg, A conductor cross section in mm², l span including insulator strings in m, l_k length of the insulator string in m, g_n gravity constant 9,81 m/s². The sags of some wire conductor spanned with double-end strings in 123 and 245-kV switchgear installations can be taken from the curves in Fig. 4-21 as a function of the span.

Fig. 4-21

Sag $f_{80\,°C}$ for spanned wire connections for spans up to 150 m with conductor temperature + 80 °C:

1 two-conductor bundle Al /St 560 /50 mm², 245-kV-double-end strings, σ_1 20,0 N /mm² at – 5 °C and about 10 mm ice coating

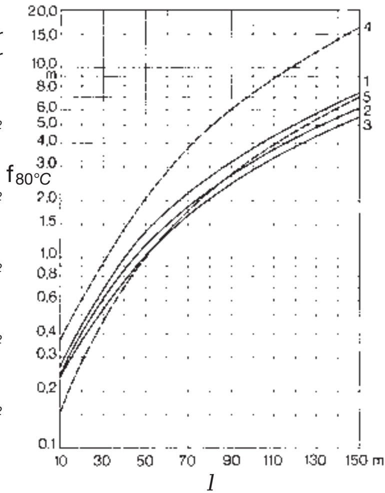
2 two-conductor bundles Al /St 380 /50 mm², 245-kV-double-end strings, σ_1 30.0 N /mm² at – 5 °C and about 10 mm ice coating

3 two-conductor bundles Al /St 240 /40 mm², 245-kV-double-end strings, σ_1 40.0 N /mm² at – 5 °C and about 10 mm ice coating

4 two-conductor bundles Al /St 240 /40 mm², 123-kV-double-end strings, σ_1 10.0 N /mm² at – 5 °C and about 10 mm ice coating

5 two-conductor bundles Al /St 435 /50 mm², 123-kV-double-end strings, σ_1 20.0 N /mm² at – 5 °C and about 10 mm ice coating

(sag in logarithmic scale)



Fracture of an insulator of a double dead-end string

For safety reasons the wire connections in switchgear installations have double dead-end strings. The fracture of an insulator results in an increase in the sag in the middle of the span.

The greatest sag after the fracture of a string f_k is roughly calculated as follows

$$f_k = \sqrt{f_\vartheta^2 + \frac{3}{8} \cdot 0{,}5\, y \cdot l}$$

f_ϑ = sag at ϑ °C before the fracture of a string
l = span length
y = length of yoke of double-end string

The curves in Fig. 4-22 can be used to make an approximate determination for $y = 0.4$ m of the greatest occurring sags.

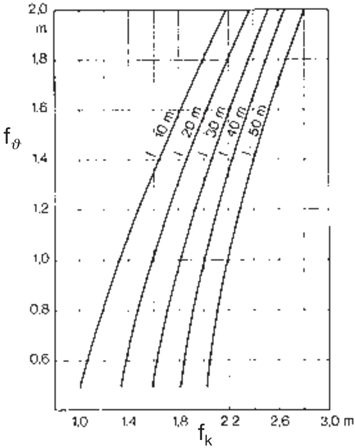


Fig. 4-22

General determination of changes in sag in the event of a fracture of an insulator of the double-end spring. Length of yoke between two insulators $y = 0.4$ m, f_k maximum sag in m, f_ϑ sag at ϑ °C in m, parameter l length of span.

Sag of the earth wire

Outdoor installations are protected against lightning strokes by earth wires. Al/St wires are generally used. Section 5.4 shows the configuration and the protection range of the earth wires in detail. They are placed along the busbar and at right-angles to the overhead line and transformer feeder bays.

The ice load on the wires must also be considered here. For Al/St 44/32 and Al/St 50/30 earth wires in Fig. 4-25, the sags can be determined at conductor temperature + 40 °C (because there is no current heat loss) and for span lengths to 60 m at initial wire tensions σ_1 = 10.0 to 30.0 N/mm^2 with ice load. In practice, the earth wires are generally spanned so their sag is identical to that of the busbars.

Wire connections of equipment

In outdoor installations the high-voltage equipment is generally connected with wire conductors. The applicable wire pull depends on the approved pull (static + dynamic) of the apparatus terminals. The minimum clearances and conductor heights over walkways in switchgear installations are specified in Section 4.6. These are minimum dimensions. For rating for mechanical short-circuit current capability, see Section 4.2.

The sags and conductor tensions can be calculated with standard formulae used in designing overhead lines. The sag in midspan is calculated with the parabolic equation:

$$f_x = \frac{(m' g_n + F_z)\, l^2}{8 \cdot \sigma_x \cdot A}$$

f_x	sag in m	σ_x	horizontal component of the cond. tension N/mm²
A	cond. cross section mm²	m'	conductor mass per unit length in kg/m
l	span in m	F_z	normal ice load in N/m

Values for DIN wire conductors, see Section 13.1.4, Tables 13.22 to 13.29.

Tensions in wire connections

For the conductor sag of 0.5 m accepted in practice at + 80 °C conductor temperature, the required tensions depending on the span for the Al wire conductor cross sections 240, 300, 400, 500, 625 and 800 mm² can be taken from the curves in Figs. 4-23 and 4-24. The permissible mechanical terminal load of the installed devices and apparatus must be observed.

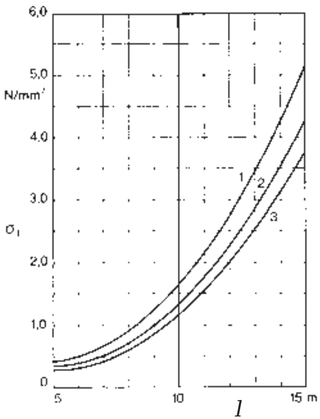


Fig. 4-23

Tensions σ_1 for suspended wire connections at –5 °C and about 10 mm ice coating: 1 conductor Al 240 mm²; 2 conductor Al 400 mm², 3 conductor Al 625 mm²

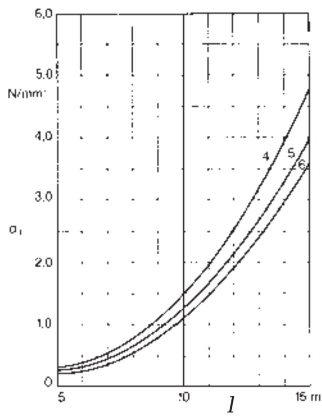


Fig. 4-24

Tensions σ_1 for suspended wire connections at –5 °C and about 10 mm ice coating: 4 conductor Al 300 mm²; 5 conductor Al 500 mm², 6 conductor Al 800 mm²

Sag in proximity to terminal points

When connecting the rotary disconnector, ensure that the cable sag does not affect the functioning of the disconnector arm. As shown in Fig. 4-26, the sag determines the minimum height of the conductor at the distance *c* from the terminal point *A*. The sag at distance *c* is calculated as follows:

$$f_c = \frac{4 \cdot f_{max} \cdot c \cdot (l - c)}{l^2}$$

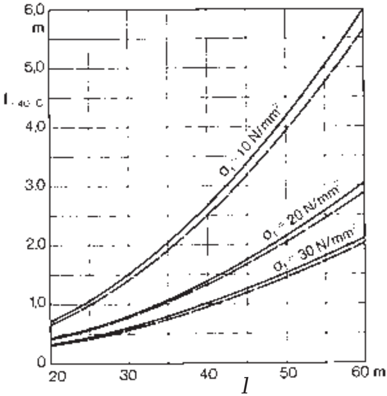


Fig. 4-25

Sag f in m for earth wire Al/St 44/32 mm² — and Al/St 50/30 mm² – – for spans of 20 to 60 m at conductor temperature + 40 °C (no Joule heat). (Parameters of the family of curves: initial tension σ_1 at –5 °C and about 10 mm ice coating.

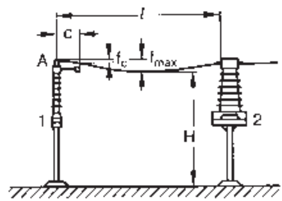


Fig. 4-26

Sag of a connection of equipment at distance c from terminal point A.
1 rotary disconnector, 2 current transformer, A terminal point, l length of device connection, f_{max} sag in midspan, f_c sag at distance c, H height above ground (see Fig. 4-37).

4.3.2 Calculation of deflection and stress of tubular busbars

In general, the deflection *f* and the stress σ of a tube is the result of its own weight

$$f = \frac{1}{i} \cdot \frac{Q \cdot l^3}{E \cdot J} \text{ and } \sigma = \frac{k \cdot Q \cdot l}{W}$$

Where:

$Q = m' \cdot g_n \cdot l$	load by weight of the tube between the support points
l	span (between the support points)
E	module of elasticity (See Table 1-17 and Table 13-1)

J	moment of inertia (for tubes $J = 0.049\ [D^4 - d^4]$) as in Table 1-22
W	moment of resistance for bending (for tubes $W = 0.098\ [D^4 - d^4]/D$) as in Table 1-22
m'	mass of tube per unit of length (without supplementary load) in kg/m (see Tables 13-5, 13-9 and 13-10)
g_n	gravity constant 9.81 m/s^2
i, k	factors (see Table 4-9)

Table 4-9

Factors for calculating the deflection of tubular busbars

Type of support	*i*	*k*
Tube supported at both ends	*77*	*0.125*
Tube one end fixed, one freely supported	*185*	*0.125*
Tube fixed at both ends	*384*	*0.0834*
Tube on three support points	*185*	*0.125*
Tube on four support points	*145*	*0.1*
Tube on more than four support points	*130*	*0.11*

As per DIN VDE 0101 an ice coating with a density of 900 kg/m^3 must be taken into account. The thickness of the ice shall be assumed as 1mm, 10mm or 20mm according to IEC 60694 (VDE 0670 Part 1000).

When doing the calculation with ice, the load Q (due to the mass of the tube) must be increased by adding the ice load.

A permissible value for the deflection is only available as a typical value for optical reasons. For the deflection under own weight, this is l /150 or D and for the deflection under own weight and ice l / 80.

Permissible value for the stress under own weight plus ice is $R_{p0.2}/1.7$ with $R_{p0.2}$ as in Table 13-1. Permissible value with simultaneous wind load is $R_{p0.2}/1.5$.

Example:

Given an aluminium tube E-AlMgSi 0.5 F 22 as in Table 13-10, with external diameter 80 mm, wall thickness 5 mm, span 8 m, supported at both ends. Then

$$Q = m' \cdot g_n \cdot l = 3.18\ \frac{\text{kg}}{\text{m}} \cdot 9.81\ \frac{\text{m}}{s^2} \cdot 8\ \text{m} = 250\ \text{N}$$

$$J = 0.049\ (8^4 - 7^4)\ \text{cm}^4 = 83\ \text{cm}^4$$

$$W = 0.098\ \frac{(8^4 - 7^4)}{8}\ \text{cm}^3 = 20.8\ \text{cm}^3$$

The deflection is:

$$f = \frac{1}{77} \cdot \frac{250\ \text{N} \cdot 8^3 \cdot 10^6\ \text{cm}^3}{7 \cdot 10^6\ (\text{N/cm}^2) \cdot 83\ \text{cm}^4} = 2{,}9\ \text{cm}$$

The stress is:

$$\sigma = \frac{0.125 \cdot 250\ \text{N} \cdot 800\ \text{cm}}{20.8\ \text{cm}^3} = 12\ \frac{\text{N}}{\text{mm}^2}$$

Deflection and stress are acceptable.

4.3.3 Calculation of electrical surface field strength

The corona effect on the conductor surface of overhead lines is a partial electrical discharge in the air when the electrical field strength exceeds a critical value on the conductor surface.

There is no specification for the permissible surface field strength for outdoor installations. In general for overhead lines up to 19 kV/cm, in individual cases up to 21 kV/cm are approved. These values should also be retained with switchgear installations. The surface field strength *E* can be calculated with the following formula:

$$E = \frac{U}{\sqrt{3}} \cdot \frac{\beta}{r_L \cdot \ln\left(\frac{a}{r_e} \cdot \frac{2 \cdot h}{\sqrt{4\,h^2 + a^2}}\right)}$$

$$\text{where } \beta = \frac{1 + (n - 1)\; r_L / r_T}{n}$$

$$r_e = \sqrt[n]{n \cdot r_L \cdot r_T^{\,n-1}}$$

$$r_T = \frac{a_T}{2 \cdot \sin(\pi / n)}$$

The following apply in the equations:

- E electrical surface field strength
- U nominal voltage
- β multiple conductor factor (for tube = 1)
- r_L conductor radius
- r_T radius of the bundle
- r_e equivalent radius of bundle conductor
- a_T centre-to-centre distance of sub-conductors
- a centre-to-centre distance of main conductors
- h conductor height above ground
- n number of sub-conductors per bundle

Example:

Lower busbars in a 420-kV outdoor installation with Al/St 2 × 560/50 mm² at a medium height of 9.5 m above ground: U = 380 kV, r_L = 1.61 cm, a_T = 20 cm, a = 500 cm, h = 950 cm, n = 2. With these figures, the above equations yield:

$$r_T = \frac{20\text{ cm}}{2 \cdot \sin\frac{\pi}{2}} = 10.0\text{ cm}$$

$$r_e = \sqrt[2]{2 \cdot 1.61 \cdot 10.0^3} = 5.66\text{ cm}$$

$$\beta = \frac{1 + (2 - 1)\;\frac{1.61}{10.0}}{4} = 0.58$$

$$E = \frac{380\text{ kV}}{\sqrt{3}} \cdot \frac{0{,}58}{1.61\text{ cm} .\ \ln\left(\frac{500}{5.66} \cdot \frac{2 \cdot 950}{\sqrt{4 \cdot 950^2 + 500^2}}\right)} = 17.8\,\frac{\text{kV}}{\text{cm}}$$

The calculated value of 17.8 kV/cm is below the permissible limit. This configuration can be designed with these figures.

4.4 Dimensioning for continuous current rating

4.4.1 Temperature rise in enclosed switch boards

Electrical equipment in switchboards gives off loss heat to the ambient air. To ensure fault-free function of this equipment, the specified limit temperatures must be retained inside the switchboard.

The following applies according to the relevant IEC or VDE specifications

- with open installations as ambient temperature the temperature of the ambient room air (room temperature ϑ).
- in closed installations as ambient temperature the temperature inside the enclosure (inside air temperature ϑ_i).
- as temperature rise the difference between inside air temperature (ϑ_i) and room air temperature (ϑ).

The most significant heat sources inside the enclosure are the conducting paths in the main circuit. This includes the circuit-breakers and fuses, including their connections and terminals and all the auxiliary equipment in the switchboard.

Inductive heat sources such as eddy currents in steel parts only result in local temperature rises. Their contribution is generally negligible for currents < 2500 A.

The power dissipation for the electrical equipment can be found in the relevant data sheets of the manufacturers.

In fully enclosed switchboards (protection classes above IP 50) the heat is dissipated to the outside air primarily by heat radiation and external convection. Thermal conduction is negligibly small.

Experiments have shown that in the inside temperature is distributed depending on the height of the panel and on the equipment configuration. The density variations of the heated air raises the temperature in the upper section of the enclosure.

The temperature distribution can be optimized when the electrical equipment with the greatest power dissipation is positioned in the lower part of the panel, so the entire enclosure is involved in heat dissipation as far as possible.

When installed on a wall, the panel should have 8…10 cm clearance from the wall. This allows the rear wall of the panel to be involved effectively in dissipating heat.

The average air temperature inside the enclosure, neglecting the heat radiation, can be calculated as follows:

$$\Delta \vartheta = \frac{P_{\text{V eff}}}{\alpha \cdot A_M}$$

$\Delta \vartheta$ Temperature increase of air inside enclosure

$P_{\text{V eff}}$ power dissipation with consideration of load factor as per IEC 60439-1 (VDE 0660 Part 500) Table 1

A_M heat-dissipating surface of enclosure

α Heat transfer coefficient:

6 W/(m^2 · K) sources of heat flow are primarily in the lower half of the panel,

4.5 W/(m^2·K) sources of heat flow are equally distributed throughout the height of the panel,

3 W/(m^2 · K) sources of heat flow are primarily in the upper half of the panel.

If there are air louvres in the enclosure, such as with IP 30, heat dissipation is primarily by convection.

The heat transfer from the air in the interior of the enclosure to the ambient air is much better in this case than with fully enclosed designs. It is influenced by the following:

- the size of the panel (in particular the height)
- the ratio of air outlet and inlet vents to the entire heat-dissipating surface,
- the position of air inlets and outlets,
- the distribution of heat sources inside the panel and
- the temperature difference.

The internal air temperature will be in the range of 0.5 to 0.7 times of that calculated in the above equation.

If switchgear assemblies develop higher heat loss or if they have a non-linear flow model, they must be equipped with internal fans to force the heat generated out to the surrounding space. An air conditioning system will then be required to extract the heat from the switchgear room.

IEC 60439-1 (VDE 0660 Part 500) specifies + 40 °C as the upper limit for the room temperature and – 5 °C for the lower limit value.

The electrical equipment cannot be applied above this range without additional measures. Excessive ambient temperatures at the devices may affect functioning or loadability and will reduce the operating life. Hence the continuous current rating cannot always be fully used, because a room temperature of + 40 °C does not leave sufficient reserve for the overtemperature of the air inside the enclosure.

The assessment must be based on the assumption that the overtemperatures set in IEC 60439-1 (VDE 0660 Part 500) Table 3 should not be exceeded if the equipment is to operate properly.

Example:

Panel in protection class IP 54, fitted with 12 inserts. Every insert has fuses, air-break contactors and thermal overcurrent relays for motor control units. Heat sources are assumed to be evenly distributed throughout the height of the panel.

power dissipation P_v = 45 W per insert.

load factor a = 0.6 (as per IEC 60439-1 Tab. 1)

heat-dissipating enclosure surface A_M = 4 m^2.

With the stated component density, a check is required to ensure that the electrical equipment is subject to a maximum operating temperature of 55 °C. Room temperature ϑ = 35 °C.

Effective power dissipation $P_{V\,eff} = a^2 \cdot P_V = 0.6^2 \cdot 12 \cdot 45\ W = 194.4\ W$.

$$\Delta\vartheta = \frac{P_{V\,eff}}{\alpha \cdot A_M} = \frac{194.4\ W \cdot m^2\ K}{4.5\ W \cdot 4\ m^2} = 10.8\ K$$

$$\vartheta_i = \vartheta + \Delta\vartheta = 35 + 10{,}8 = 45.8\ °C.$$

For additional details on determining and assessing the temperature rise in switchboards, see also Section 7.3 of this publication.

4.4.2 Ventilation of switchgear and transformer rooms

Design criteria for room ventilation

The air in the room must meet various requirements. The most important is not to exceed the permissible maximum temperature. Limit values for humidity and air quality, e.g. dust content, may also be set.

For switchboards and gas-insulated switchgear a limiting value of 40 °C and a maximum value of 35°C for the 24h average are set for the ambient air temperature. The installation requirements of the manufacturers must be observed for auxiliary transformers, power transformers and secondary installations.

The spatial conditions for ventilation must also be considered. Ventilation cross sections may be restricted by auxiliary compartments and other obstacles. If necessary, the loss heat can be vented through a chimney. If HVAC (air-conditioning) installations and air ducts are installed, the required space and the configuration must be included at an early stage of planning.

Ultimately, economic aspects such as procurement and operating expenses must be taken into account as well as the reliability (emergency power supply and redundancy) of the ventilation.

At outside air temperatures of up to 30 °C, natural ventilation is generally sufficient. At higher temperatures there is danger that the permissible temperature for the equipment may be exceeded.

Figs. 4-27 and 4-28 show frequently used examples of room ventilation.

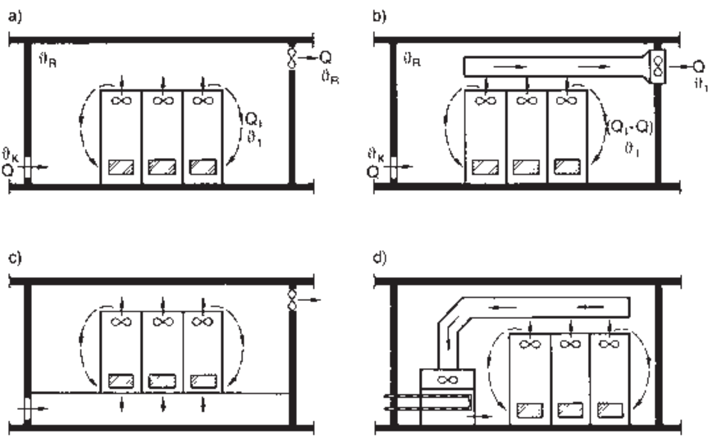


Fig. 4-27

Compartment ventilation: a) Simple compartment ventilation, b) compartment ventilation with exhaust hood above the switchboard, c) ventilation with false floor, d) ventilation with recirculating cooling system

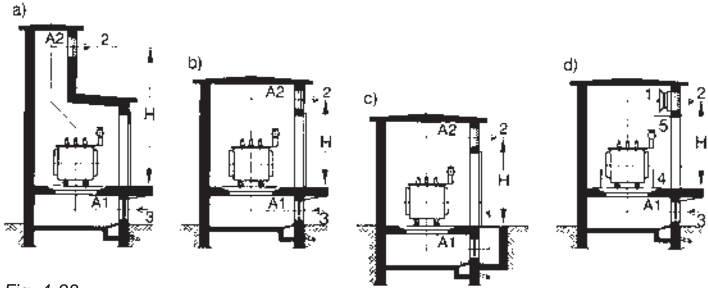


Fig. 4-28

Cross section through transformer cells:

a) incoming air is channelled over ground, exhaust air is extracted through a chimney. b) as in a), but without chimney. c) incoming air is channelled below ground, exhaust air is removed through an opening in the wall of the transformer compartment. d) transformer compartment with fan. A_1 *= incoming air cross section,* A_2 *= exhaust air cross section, H = "chimney" height, 1 = fan, 2 = exhaust air slats, 3 = inlet air grating or slats, 4 = skirting, 5 = ceiling.*

The ventilation efficiency is influenced by the configuration and size of the incoming air and exhaust air vents, the rise height of the air (centre of incoming air opening to centre of exhaust air opening), the resistance in the path of the air and the temperature difference between incoming air and outgoing air. The incoming air vent and the exhaust air vent should be positioned diagonally opposite to each other to prevent ventilation short circuits.

If the calculated ventilation cross section or the chimney opening cannot be dimensioned to ensure sufficient air exchange, a fan will have to be installed. It must be designed for the required quantity of air and the pressure head.

If the permissible room temperature is only slightly above or even below the maximum outside temperature, refrigeration equipment or air-conditioning is used to control the temperature.

In ventilated and air-conditioned compartments occupied by personnel for extended periods the quality regulations for room air technology specified by DIN 1946-2 must be observed.

The resistance of the air path is generally:

$$R = R_1 + m^2 R_2.$$

Here: R_1 resistance and acceleration figures in the incoming air duct, R_2 resistance and acceleration figures in the exhaust air duct, m ratio of the cross section A_1 of the incoming air duct to the cross section A_2 of the exhaust air duct. Fig. 4-28 shows common configurations.

The total resistance consists of the components together. The following values for the individual resistance and acceleration figures can be used for an initial approximation:

acceleration	1	slow change of direction	0…0.6
right-angle bend	1.5	wire screen	0.5…1
rounded bend	1	slats	2.5…3.5
a bend of 135 °	0.6	cross section widening	0.25…0.9[1)]

1) The smaller value applies for a ratio of fresh air cross section to compartment cross section of 1:2, the greater value for 1:10.

Calculation of the quantity of cooling air:

$$\dot{V}_0 = \frac{Q_L}{c_{pL} \cdot \Delta\vartheta}; \qquad \Delta\vartheta = T_2 - T_1$$

With temperature and height correction[1] the following applies for the incoming air flow:

$$\dot{V}_1 = \dot{V}_0 \cdot \frac{T_1}{T_0} \cdot e^{-g \cdot H / (R_L \cdot T_0)}$$

V_0 = standard air volume flow at sea level, p_0 = 1013 mbar, T_0 = 273 K = 0 °C,
T_1 = cooling air temperature (in K),
T_2 = exhaust air temperature (in K),
g = gravitational acceleration, $g = 9.81 \frac{\text{m}}{\text{s}^2}$,
H_0 = height above sea level,
R_L = gas constant of the air, $R_L = 0.287 \frac{\text{kJ}}{\text{kg} \cdot \text{K}}$,
c_{pL} = specific heat capacity of the air, $c_{pL} = 1.298 \frac{\text{kJ}}{\text{m}^3 \cdot \text{K}}$,
Q_L = total quantity of heat exhausted by ventilation: $Q_L = P_V + \Sigma Q$,
P_V = device power loss,
ΣQ = heat exchange with the environment.

[1] May be neglected at up to medium installation height and in moderate climates

At high power dissipation and high temperatures, solar radiation and thermal conduction through the walls can be neglected. Then $Q_L = P_V$.

Example:
At given incoming air and exhaust air temperature, the power dissipation P_V should be exhausted by natural ventilation. The volume of air required should be calculated:
T_2 = 40 °C = 313 K, T_1 = 30°C = 303 K, P_V = 30 kW = 30 kJ/s, height above sea level = 500 m

$$\dot{V}_1 = \frac{P_V}{c_{pL}\,(T_2 - T_1)} \cdot \frac{T_1}{T_0} \cdot e^{-g \cdot H / (R_L \cdot T_0)} = 2{,}4 \, \frac{\text{m}^3}{\text{s}} = 8640 \, \frac{\text{m}^3}{\text{h}}$$

If the warm air is exhausted directly over the heat source, this will increase the effective temperature difference $\Delta\vartheta$ to the difference between the temperature of the outside air and the equipment exhaust air temperature. This will allow the required volume of cooling air to be reduced.

Calculation of the resistances in the air duct and the ventilation cross section:

Based on the example in Fig. 4-28a, the following applies:

for incoming air:	acceleration		1
	screen		0.75
	widening in cross section		0.55
	gradual change of direction		0.6
		R_1 =	2.9
for exhaust air:	acceleration		1
	right-angle bend		1.5
	slats		3
		R_2 =	5.5

If the cross section of the exhaust air duct is 10 % larger than the cross section of the incoming air duct, then

$$m = \frac{A_1}{A_2} = \frac{1}{1.1} = 0.91 \text{ and } m^2 = 0.83.$$

Then $R = 2.9 + 0.83 \cdot 5.5 = 7.5$.

The ventilation ratios can be calculated with the following formula

$$(\Delta \vartheta)^3 \cdot H = 13.2 \frac{P_V^2}{A_1^2} (R_1 + m^2 R_2).$$

Numerical value equation with $\Delta \vartheta$ in K, H in m, P_V in kW and A_1 in m^2.

Example:

Transformer losses $P_V = 10$ kW, $\Delta \vartheta = 12$ K, $R = 7.5$ and H = 6 m yield:

$$A_1 \approx 1 \text{ m}^2.$$

Practical experience has shown that the ventilation cross sections can be reduced if the transformer is not continuously operated at full load, the compartment is on the north side or cooling is favoured by other factors. A small part of the heat is also dissipated through the walls of the compartment. The accurate calculation can be done as per DIN V 4701-10. For the design of transformer substations and for fire-prevention measures, see Section 4.7.5 to 4.7.6.

Fans for switchgear and transformer rooms

Ventilation fans, in addition to their capacity for the cooling air flow, must compensate for the pressure losses in the air path and provide blow-out or dynamic pressure. This static and dynamic pressure can be applied with $\Delta p \approx 0.2 \ldots 0.4$ mbar.

Then the propulsion power of the fan is:

$$P_L = \frac{\dot{V} \cdot \Delta p}{\eta}, \qquad \eta = \text{efficiency}$$

Example:

For the cooling air requirement of the transformer in the example above, where
$P_v = 30$ kW, with $\dot{V} = 2.4$ m³/s, $\eta = 0.2$, $\Delta p = 0.35$ mbar = 35 Ws/m³
the fan capacity is calculated as:

$$P_L = \frac{2.4 \cdot 0.35}{0.2} = 0.42 \text{ kW}.$$

Resistances in the ventilation ducts and supplementary system components, such as dust filters, must be considered separately in consultation with the supplier.

For sufficient air circulation, a minimum clearance between the equipment and the wall is required, depending on the heat output. For auxiliary transformers, this is about 0.4 m, for power transformers about 1 m.

4.4.3 Forced ventilation and air-conditioning of switchgear installations

Overview and selection

When planning switchgear installations, thermal loads resulting from heat dissipation from the installation and environmental conditions (local climate) must be taken into account. This is generally done by:

– designing the switchgear installation for increased temperature or
– reducing the thermal load by ventilating, cooling or air-conditioning installations (HVAC).

In compliance with relevant DIN and VDI requirements, the following simplified installation configuration can be used:

– *ventilation devices and installations* for ventilation and exhaust, e.g. when the permissible ambient temperature is higher than the (max.) outside temperature, see Fig. 4-29
– *refrigeration units and installations* for heat exhaust only, e.g. when the permissible ambient temperature is equal to or less than the (max.) outside temperature, see Fig. 4-30
– *air-condtioning units and installations* for air-conditioning, when in addition to heat removal specific ambient climate conditions are required (temperature, humidity, air quality, etc.), see Fig. 4-31.

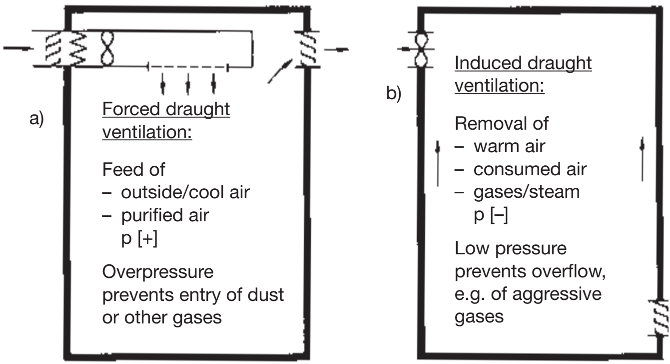


Fig. 4-29

Schematic view of a ventilation system: a) forced draught ventilation, b) Induced draught ventilation

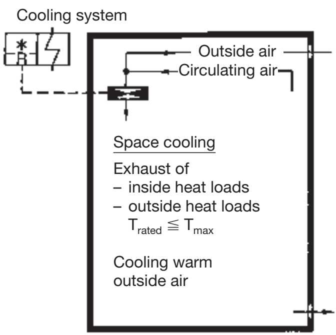


Fig. 4-30
Schematic view of a cooling system

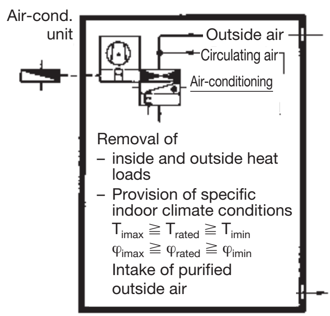


Fig. 4-31
Schematic view of an air-conditioning system

- *As permissible ambient temperatures* the maximum ambient air temperatures as specified for indoor switchgear in IEC or other standards must be taken into account
- Telecommunications and electronics modules require special *environmental conditions* as specified in EN 50178 (VDE 0160).
- In addition to the technical requirements, human (physiological) requirements may determine the *compartment climate*, e.g. the workplace regulations in Germany.
- The (max.) *outside temperature* is defined as the maximum outside temperatures occurring at the set-up area. It is selected from relevant climate tables, such as given in an encyclopedia or using information from meteorological organizations.
- *Space heating systems* in substation design is only relevant for rooms where personnel is present normally. It is used almost exclusively in connection with ventilation or air-conditioning systems.
- Some of the most important and internationally accepted *regulations (standards) are listed below:*
  - *DIN V 4701-10 – Calculating heat requirements –*
  - *VDI 3802 – Ventilation engineering –*
  - *VDI 2078 – Calculating cooling loads –*
  - *Ashrae Handbook (NEW YORK)*
  - *Carrier Handbook of air-conditioning system design (NEW YORK)*.

Basis for HVAC design is calculation of the thermal loads (Q_{th}) (heat balance).

Q_{th} = $Q_{tr} + Q_{str} + Q_i + Q_a$

Q_{tr} = heat transmission by the areas around the room (outside heat loads)

= A (m²) · k (W/m² · K) · ΔT (K)

Q_{str} = radiation heat from exterior areas exposed to the sun

Q_i = installation and personnel heat (inside heat loads)

Q_a = heat from outside air, humidifiers and dehumidifiers (outside heat loads)

= $\dot{m}$ (kg/h) · c (W h / kg · K) · ΔT (K) (without dehumidifiers)

= $\dot{m}$ (kg/s) · Δh (kJ/kg) (with dehumidifiers)

A = *areas around the compartment (m²)*
k = heat transmission coefficient (W/m²)
ΔT = temperature difference
$\dot{m}$ = quantity of air flow/outside air flow (kg/h])
c = specific heat capacity of air (Wh/kg.K)
Δh = difference of the specific outside air enthalpy (Wh/kg)

This is calculated in compliance with various DIN, VDI or relevant international rules.

4.4.4 Temperature rise in enclosed busbars

Busbars in medium and low-voltage substation design are often installed in small compartments or in conduits. For this reason they are subject to more severe thermal conditions than busbar configurations in open installations.

Therefore it is not possible to select the busbar cross sections directly from the load tables in Section 13.1.2. Because of the number of parameters influencing the temperature of enclosed busbars (such as position of the busbars in the conduit, conduit dimensions, ventilation conditions, ambient temperatures), the permissible current load must be calculated for the specific configuration.

The heat network method has proven useful for this calculation; Fig. 4-32 b.

Heat flows are generated by electric power losses.

Symbols used:

- α Heat transfer coefficient
- A Effective area
- P Heat output
- R Equivalent thermal resistance
- $\Delta\vartheta$ Temperature difference
- D *Throughput of circulating cooling medium ($D = V/t$)*
- C *Radiant exchange number*
- T *Absolute temperature*
- c_p Specific heat
- ρ Density

Indices used:

- D Forced cooling
- K Convector
- S Radiation
- O Environment
- 1 Busbar
- *2 Inside air*
- 3 Enclosure

Thermal transfer and thermal resistances for radiation:

$$P_S = \alpha_S \cdot A_S \cdot \Delta\vartheta \text{ or } R_S = \frac{1}{\alpha_S \cdot A_S}$$

$$= C_{13} \cdot A_s \cdot (T_1^4 - T_3^4) \quad \text{where } \alpha_s = \frac{C_{13}\,(T_1^4 - T_3^4)}{\Delta\vartheta}$$

for the convection:

$$P_K = \alpha_K \cdot A_K \cdot \Delta\vartheta \text{ or } R_K = \frac{1}{\alpha_K \cdot A_K}$$

for the circulating cooling medium:

$$P_D = c_p \cdot \rho \cdot D \cdot \Delta\vartheta \text{ or } R_D = \frac{1}{c_p \cdot \rho \cdot D}$$

For additional information, see Section 1.2.5.

For information on temperature rise of high-current busbars, see Section 9.2.

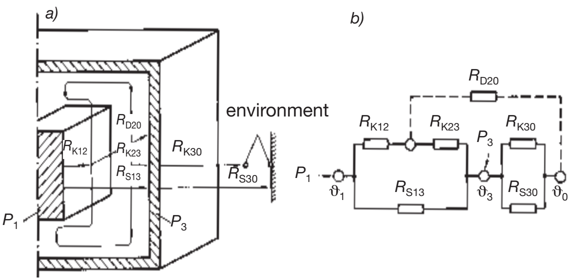


Fig. 4-32

Temperature rise in enclosed busbars
a) thermal flow,
b) heat network

4.4.5 Temperature rise in insulated conductors

Conductors offer a resistance to electrical current resulting in heat losses. This causes current thermal losses by current flow. The conductors and the insulation around them become warmer.

The heat quantity developed in the conductor per second (electric loss power) is derivided into two parts, one part

$P_c = c \cdot \gamma \cdot A \dfrac{d}{dt} \Delta \vartheta$ is stored and the other part

$P_A = \alpha \cdot U \cdot \Delta \vartheta$ is dissipated to the environment.

The heat process can be described as follows:

$$\frac{c \cdot \gamma \cdot A}{\alpha \cdot U} \cdot \frac{d}{dt} \Delta \vartheta + \Delta \vartheta = \frac{A \cdot \rho}{\alpha \cdot U} \left(\frac{I}{A}\right)^2$$

Here:

$\Delta \vartheta$ = conductor overtemperature K
$\Delta \vartheta_e$ = end value of the conductor overtemperature K
α = heat transfer coefficient (9…40 W/(m^2 K)
c = specific heat (384.38 Ws/K · kg for copper)
γ = density (8.92 · 10^{-3} kg/cm^3 for copper)
ρ = specific resistance (0.0178 Ωmm^2/m at 20 °C for copper)
A = conductor cross section
U = conductor circumference
I = current in conductor A

The stationary state in the temperature rise occurs when all the electric loss power generated can be dissipated to the environment. This is the case when the temperature change is zero:

$$\Delta \vartheta_e = \frac{\rho \cdot A}{\alpha \cdot U} \left(\frac{I}{A}\right)^2.$$

The solution of the differential equation yields the overtemperature in relation to time:

$$\Delta \vartheta = \Delta \vartheta_e \cdot (1 - e^{-\frac{1}{T}}).$$

T is referred to as the thermal time constant. It is the scale for the time after which the end temperature $\Delta \vartheta_e$ would be reached if the temperature rise were constant, therefore if the generated heat is completely stored in the conductor and the thermal dissipation is equal to zero. It is:

$$T = \frac{c \cdot \gamma \cdot A}{\alpha \cdot U} = \frac{\text{thermal storage capacity}}{\text{thermal dissipation capacity}}$$

The result of this is that *T* increases with the cross section of the conductor and by α also depends on the way it is laid and the accumulation of conductors. For example, multicore PVC copper conductors or cables laid well apart on the wall have the following heating time constants:

A =	1.5	2.5	4	10	25	95	150	240	mm^2
T =	0.7	1.0	1.5	3	6	16	23	32	min

Continuous operation occurs when the equilibrium temperature is reached. 95% of this state is achived after three times the value of the time constant. A higher load may be approved for intermittent operation.

Excessively high conductor temperatures endanger the conductors and the environment. Care must be taken to ensure that non-permissible temperatures cannot occur. The limit temperature of the conductors for continuous load is:

– with rubber insulation 60 °C
– with plastic insulation 70 °C and
– with plastic insulation with increased heat resistance 100 °C.

In the event of a short circuit, the DIN VDE regulations allow a higher limit temperature for a brief period, see also Section 4.2.5.

4

The maximum load duration t_{Bmax} in which a conductor with the current carrying capacity I_z at higher load $I_a = a \cdot I_z$ has been heated to the still permissible limit temperature is:

$$t_{Bmax} = T \cdot \ln\left(\frac{a^2}{a^2 - 1}\right)$$

Example:

Is a conductor of 1.5 mm² Cu for a three-phase a.c. motor ($I_{start} = 6 \cdot I_{n\,Mot}$) sufficiently protected against overload with the motor protection switch when the rotor is blocked?

The current-carrying capacity of the conductor is $I_{n\,Mot} \cdot 0.8$.

$$a = 0.8 \cdot 6 = 4{,}8$$
$$T = 0.7 \text{ min} = 42 \text{ s}$$
$$t_{Bmax} = 42 \text{ s} \cdot \ln\left(\frac{4.8^2}{4.8^2 - 1}\right) = 1.86 \text{ s}$$

Because the overload protection device only responds after about 6 s at 6 times current value, a 1.5 mm² Cu is not sufficiently protected. After 6 s this wire already reaches
152 °C. A larger conductor cross section must be selected.

A 2.5 mm² Cu wire (utilization 0.53) only reaches the limit temperature after 6.2 s.

4.4.6 Longitudinal expansion of busbars

Temperature changes in busbar conductors result in longitudinal expansion or contraction. This is calculated from

$$\Delta l = l_o \, \alpha \, \Delta \vartheta.$$

For a busbar of 10 m in length at 50 K temperature difference, the following typical values are obtained:

with Cu: $\Delta l = 10 \cdot 0.000017 \cdot 50 = 0.0085 \text{ m} = 8.5 \text{ mm}$,
with Al: $\Delta l = 10 \cdot 0.000023 \cdot 50 = 0.0115 \text{ m} = 11.5 \text{ mm}$.

These temperature-caused longitudinal changes may cause significant mechanical stresses on the conductors, on their supports and on connections to apparatus if there are no *expansion sections* installed in long line segments.

The forces generated are very easy to calculate if the longitudinal change caused by the difference in temperature $(\vartheta - \vartheta_0) = \Delta\vartheta$ is assumed to be equal to the longitudinal change that would be caused by a mechanical force F, which means:

$$\Delta l = l_o \, \alpha \, \Delta \vartheta = \frac{F \, l_o}{E A}$$

Where:

l_0 length of the conductor at temperature at which it was laid ϑ_o

$\Delta\vartheta$ temperature difference

F mechanical stress

A conductor cross section

α linear coefficient of thermal expansion, for Cu = 0.000017 K^{-1}, for Al = 0.000023 K^{-1}

E module of elasticity, for Cu = 110 000 N/mm², for Al = 65 000 N/mm².

The above equation gives the mechanical stress as:

$$F = \alpha \cdot E \cdot A \cdot \Delta\vartheta$$

and for $\Delta\vartheta = 1$ K and $A = 1$ mm² the specific stress:

$$F' = \alpha \cdot E.$$

Therefore, for copper conductors:

$$F'_{Cu} = 0.000017 \cdot 110\,000 = \approx 1.87 \text{ N/(K} \cdot \text{mm}^2)$$

and for aluminium conductors:

$$F'_{Al} = 0.000023 \cdot 65\,000 = \approx 1.5 \text{ N/(K} \cdot \text{mm}^2).$$

4.5 Rating power systems for earthquake safety

4.5.1 General principles

Earthquakes in 95 of 100 cases originate from faults at the edges of the tectonic plates. The remainder are caused by volcanic action and inner collapses. The tectonic plates float on the surface of the viscous mantle of the earth and are subject to strong convection currents. The relative motion of the rigid plates in relation to one another generates local mechanical tension peaks at their edges, which from time to time are released by sudden deformations. These vibrations are spread by seismic waves, which propagate in accordance with the laws of wave propagation by reflection and refraction in complex waveforms and occur primarily as energetic surface waves in the frequency range of 0.1 Hz to 30 Hz with strong *horizontal* acceleration at the surface of the earth. The most energetic waves are therefore in the range of the natural frequencies of devices and components in high-voltage substations, but they must not adversely affect their functioning in the preset limits. The ground acceleration amplitudes are mostly in the range of 0.3 to 0.7 g. The strong earthquake phase only lasts a few seconds. In total, an earthquake rarely lasts more than 1 to 2 minutes.
The edges of the plates subject to earthquakes are primarily found in line reaching from south-eastern Europe through central Asia to Indonesia and around the Pacific Ocean. Even in central Europe earthquakes of moderate power occur occasionally. For this reason, even here nuclear installations also require verification of earthquake safety for all important components. This is also required for high-voltage power systems.

The most important parameter of an earthquake with respect to the mechanical stress on equipment and installations is the limit value of the acceleration of the ground at the installation site.

Characteristic values are:

– 5 m/s² (≈ 0.5 g, qualification class AF5),

– 3 m/s² (≈ 0.3 g, qualification class AF3) and

– 2 m/s² (≈ 0.2 g, qualification class AF2)

For the oscillation in the horizontal direction (x and y component). The vertical stress is calculated with half that value for every case. Of primary importance for the mechanical stress of equipment and device combinations is their mechanical natural frequencies, which are generally in the frequency spectrum of the seismic excitation. When verifying earthquake safety, the excitation with the natural frequency values of the equipment must be regarded as the “worst case”.

The temporal process of the seismic excitation, i.e. the process of the oscillation of the ground at the installation site, can be selected differently for the verification. The following options are available:

– Continuous sine wave with natural frequencies
– Several (5) groups of 5 sinusoidal increasing and decreasing load cycle oscillations with natural frequency (5-sine beat, Fig. 4-33) separated by pauses
– Exponentially damped decaying load cycle oscillations with natural frequency (e-beat, Fig. 4-34)
– Simulation of an earthquake sequence typical for the installation site (Fig. 4-35)

The earthquake safety of equipment and installations can be verified as per IEC 61166 (VDE 0670 Part 111) and IEC 60068-3-3 in different ways, i.e.

– by testing,
– by a combination of testing and calculation or
– by calculation alone.

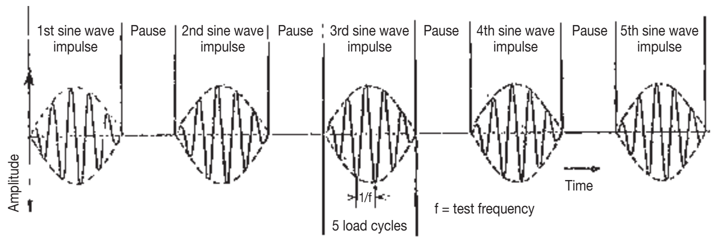


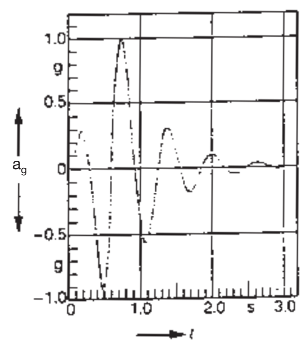
Fig. 4-33

Result of 5 sine wave impulses with 5 load cycles each

Fig. 4-34

a_g ground acceleration

Exponential beat,
“e-beat” for short,
as excitation function for simulation
of an earthquake shock



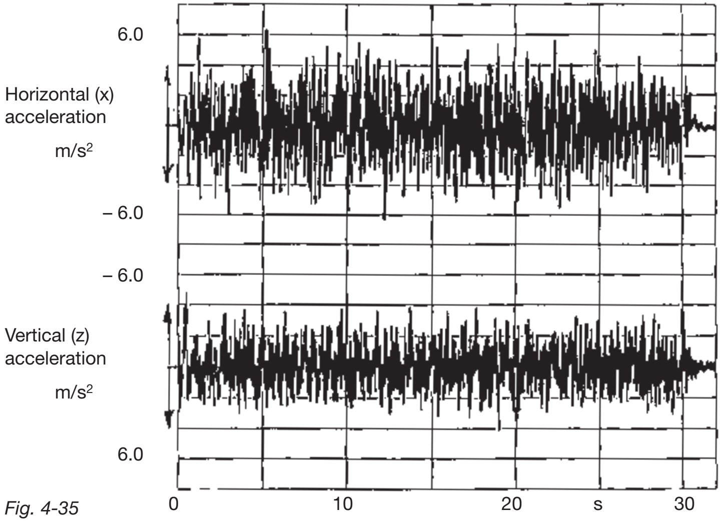


Fig. 4-35

Process of acceleration of the test table during a simulated earthquake
1 $m/s^2 \approx 0.1$ g

Medium-voltage switchgear installations and equipment, are difficult to handle by calculation because of their complex design, but their compact dimensions make it possible to test them fully in existing test installations. High-voltage equipment can also be tested, but particularly in the development phase and with spatially extended installations a calculated verification of earthquake safety is preferred, particularly when dealing with rotation-symmetrical configurations. For spatially extended installations verification is possible by calculation only since test plants with dimensions as required for are not available.

4.5.2 Experimental verification

Very complex test installations are required for these tests, such as a vibration table with an area of 5 x 5 m and a mass of up to 25 t, which can vibrate with the above parameters in all three axes.

Before the actual qualification test, the natural mechanical frequencies of the test object are determined in a resonance search run. A continuous sine wave with which the relevant frequency range of 0.5 Hz – 35 Hz with a speed increase of 1 octave/min in all 3 axes running through in succession is selected as the test excitation. The acceleration here is only about 0.1 g.

During the qualification test, one of three different processes of the excitation of oscillations can be selected:

– Continuous sine wave method

  The relevant frequency range is run corresponding to the resonance search run procedure, with the difference that the amplitude is increased to the required value.

This test procedure only reproduces the stresses in practice poorly and represents an unrealistically sharp stress for the test object.

- Sine beat method (5-sine beat)

  The vibration table is excited with several sine impulses separated by pauses in this test procedure, as shown in Fig. 4-33. The frequency of the load cycle oscillation corresponds to the natural frequencies, i.e. the test is run in all natural frequencies of the installation in 2 axes, with generally one horizontal axis being combined with one vertical axis.

  A test with sine impulses yields quite useful conclusions respecting the response of the test object to an earthquake and is particularly useful if there is no accurate seismic information available for the installation site. However, the test takes time if the installation has many natural frequencies.

- Time history method

  This process simulates an actual earthquake. It lasts for about 30 s and the excitation is on 2 or 3 axes. An example of a synthetic earthquake time characteristic is shown in Fig. 4-35.

  This procedure simulates an earthquake best if accurate information on ground acceleration is available. It also enables safety-relevant functions such as secure contact of conducting paths or tripping and reclosing the switchgear to be checked during the test. For this reason this test is often required for nuclear installations.

After the qualification test, the resonance search run is generally repeated to check whether the test object has deteriorated because of the test. If the natural frequencies have changed significantly, this indicates damage.

When developing medium-voltage switchgear ABB verifies for earthquake safety by testing, in some cases with the 5-sine-beat method, in part while using the time history method with excitation accelerations to 0.7 g.

4.5.3 Verification by calculation

In the past, the dynamic load resulting from earthquakes was generally only roughly estimated with static loads. The dynamics of the process were simulated with correction and damping factors. The development of powerful computers now makes it possible to use mathematical simulation with the finite-element method (FEM), which has been in use around the world for some time as a tool for investigating complex processes of any type. Its application to the stress on switchgear, modules and complete switchbays caused by earthquakes is possible in principle, but the expense of modelling the relevant basic variants at present still limits the investigations to individual components and device combinations. However, it is easier to analyse variations of the basic variant here than at the vibration test. Natural frequencies, stiffness and the maximum permissible mechanical basic data are input into the computer as starting parameters. The excitation of oscillations by the earthquake is best simulated here by the exponentially decaying load cycle surge, the e-beat (Fig. 4-34).

The FEM was initially successfully used by ABB to determine the stress caused by earthquakes in the finely structured model for some ABB switchgear, such as the 550-kV circuit-breakers of the ELF SP 7-2 type including device table, the 245-kV pantograph disconnector of the TFB 245 type, the 123 kV rotary disconnector of the SGF 123 type and a 245-kV switchbay with pantograph disconnector, current transformer, circuit-breaker and rotary disconnector. Sufficiently exact approximate solutions are currently being developed in two directions, one target is to develop an FEM with a more roughly structured model and the other target to get an alternative calculation procedure with statically equivalent loads derived from the dynamic process. The application of statically equivalent loads derived from the dynamic process with earthquakes appears to be the most promising solution and it would simplify the calculation method considerably.

4.6 Minimum clearances, protective barrier clearances and widths of gangways

Key to symbols used

U_m	kV	maximum voltage for apparatus, rated voltage
U_n	kV	nominal voltage of a system
U_{rB}	kV	rated lightning impulse withstand voltage
U_{rS}	kV	rated switching impulse withstand voltage
N	mm	minimum clearance (Table 4-10)
B_1	mm	protective barrier clearances for solid-panel walls (≥ 1800 mm high) with no openings. The dimension applies from the interior of the solid wall. $B_1 = N$
B_2, B_3	mm	protective barrier clearances with wire mesh, lattice fences or solid walls with openings (≥ 1800 mm high) ≤ 52 kv: $B_2 = N$ + 80 mm and protection class IP2X, > 52 kV: $B_3 = N$ + 100 mm and protection class IP1XB.
O_1, O_2	mm	protective clearances for obstacles, such as rails, chains, wires, lattice fences, walls (< 1800 mm high) for indoor installations: $O_1 = N$ + 200 mm (minimum 500 mm), for outdoor installations: $O_2 = N$ + 300 mm (minimum 600 mm). rails, chains and wires must be placed at a height of 1200 mm to 1400 mm. With chains or wires, the protective barrier clearance must be increased by the sag.
C, E	mm	protective barrier clearances at the outer fence (≥ 1800 mm high) with solid walls C = N + 1000 mm, with wire mesh, screens (mesh size ≤ 50 mm) E = N + 1500 mm
H	mm	minimum height of live parts (without protective barrier) above accessible areas H = N + 2250 mm (minimum 2500 mm)
H'	mm	minimum height of overhead lines at the outer fencing.
T	mm	minimum transport clearance for vehicles T = N + 100 mm (minimum 500 mm)

4.6.1 Minimum clearances and protective barrier clearances in power systems with rated voltages over 1 kV as per DIN VDE 0101

Minimum clearances

The clearances of live parts of a system from one another and from earthed parts must at least comply with Table 4-10. This table lists the minimum clearances for the maximum apparatus voltages assigned to the associated insulation levels of the insulation coordination as per IEC 60071-1 (VDE 0111 Part 1). The various insulation levels available should be selected in accordance with the insulation coordination as per this standard.

In the range of 1 kV < U_m < 300 kV, the rated lightning impulse withstand voltage is the basis for the rating. In the range U_m ≥ 300 kV, the rated switching impulse withstand voltage is the basis for the rating

Table 4-10

Minimum clearances in air of live parts of a system from one another and from earth as per DIN VDE 0101 (HD 637 S1).

Voltage range A (1 kV < U_m < 52 kV)

Nominal voltage of the system	Maximum voltage for apparatus	Short-duration power frequency withstand voltage	Rated lightning impulse withstand voltage 1.2/50 µs	Minimum clearance (*N*) phase-to-earth and phase-to-phase	
				Indoor	Outdoor
				installation	
U_n	U_m		U_{rB}		
kV	kV	kV	kV	mm	mm
3	3.6	10	20	60	120
			40	60	120
6	7.2	20	40	60	120
			60	90	120
10	12	28	60	90	150
			75	120	150
15 [1)]	17.5	38	75	120	160
			95	160	160
20	24	50	95	160	
			125	220	
30	36	70	145	270	
			170	320	
36 [2)]	41.5	80	170	320	
			200	360	

1) These nominal voltages are not recommended for planning of new networks.

2) This voltage value is not included in IEC 60071-1.

Voltage range B (52 kV ≤ U_m < 300 kV)

Nominal voltage U_n kV	Maximum voltage for apparatus U_m kV	Short-duration power frequency withstand voltage kV	Rated lightning impulse withstand voltage 1.2/50 µs U_{rB} kV	Minimum clearance (*N*) phase-to-earth and phase-to-phase mm
45 [1]	52	95	250	480
66 [2]	72.5	140	325	630
70 [6]	82.5	150	380	750
110 [3]	123	185 [4]	450	900
		230	550	1100
132	145	185 [4]	450	900
		230	550	1100
		275	650	1300
150 [1]	170	230 [4]	550	1100
		275	650	1300
		325	750	1500
220	245 [5]	325 [4]	750	1500
		360	850	1700
		395	950	1900
		460	1050	2100

[1] These nominal voltages are not recommended for planning of new networks.
[2] For U_n = 60 KV the values for U_n = 66 kV are recommended.
[3] For U_n = 90 KV / U_n = 100 kV the lower values are recommended.
[4] The values in this line should only be considered for application in special cases.
[5] A fifth (even lower) level for 245 kV is given in IEC 60071-1.
[6] This voltage value is not included in IEC 60071-1.

Voltage range C (U_m ≥ 300 kV)

Nominal voltage	Maximum voltage for apparatus	Rated switching impulse withstand voltage phase-to-earth 250/2500 µs	Minimum clearance (*N*) phase-to-earth		Rated switching impulse withstand voltage phase-to-phase 250/2500 µs	Minimum clearance phase-to-phase	
			Conductor/ design	Bar/ design		Conductor/ conductor parallel	Bar/ conductor
U_n kV	U_m kV	U_{rS} kV	mm	mm	kV	mm	mm
275	300	750	1600	1900	1125	2300	2600
		850	1800	2400	1275	2600	3100
380	420	950	2200	2900	1425	3100	3600
		1050	2600	3400	1575	3600	4200
480	525	1050	2600	3400	1680	3900	4600
		1175	3100	4100	1763	4200	5000
700	765	1425	4200	5600	2423	7200	9000
		1550	4900	6400	2480	7600	9400

Protective barrier clearances

As per DIN VDE 0105-100 (VDE 0105 Part 100), bare live parts are surrounded by a danger zone whose dimensions comply with the maximum values of the minimum clearances *N* given in Table 4-10. (Exception: U_m = 380 kV, both values are applicable there). Being at the outer limit of the danger zone and its penetration by body parts or objects are treated as work on live systems.

The protection against direct contact in installations as per DIN VDE 0101 (≙ HD 637 S1) must therefore prevent such a hazardous proximity to live parts. In locked electrical premises, protection against accidental contact is sufficient. This can be done by installing protective barriers, e.g. solid walls, doors, screens (wire mesh), arc screens, rails, chains or ropes. An additional safety clearance is required corresponding to the possibilities of reaching through between the danger zone (minimum clearance *N*) and the protective barrier (Fig. 4-36).

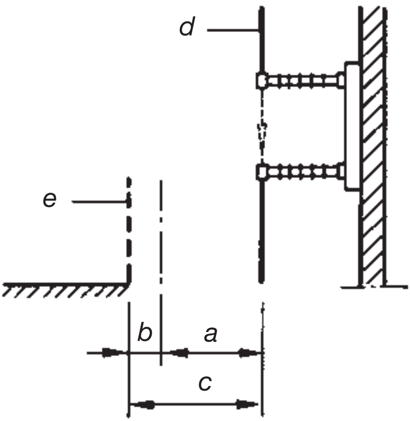


Fig. 4-36

Minimum clearance + safety clearance = protective barrier clearance:
a = minimum clearance,
b = safety clearance,
c = protective barrier clearance,
d = live part,
e = protective barrier

The position of abbreviations and explanations at the beginning of this section meets the requirements of DIN VDE 0101 (≙ HD 637 S1) with reference to the minimum clearances from the various types of obstacles. Tables 4-11 and 4-12 list the maximum values of the assigned minimum clearances *N* listed in Table 4-10 and the associated protective barrier minimum clearances for all standard-nominal system voltages as guidance values.

Protection against accidental contact is then assured when live parts above walkways, where they are not behind barriers, are installed at the minimum heights *H* or *H'* given in Tables 4-11 and 4-12 (Fig. 4-37), where the greatest conductor sag must be considered. With transport paths, the height of the transport units may make it necessary to increase the height requirements.

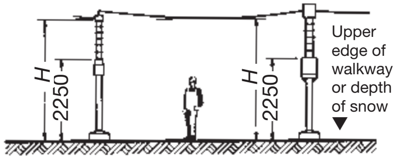


Fig. 4-37

Minimum heights of live parts over walkways

The upper edge of an insulator base must be at least 2250 mm over walkways if there is no protective barrier installed.

If the protective clearance is partly or completely bridged by insulators, protection against direct contact must be assured by barriers like panel walls, panel doors, lattice fences or lattice doors with a minimum height of 1800 mm (Fig. 4-38). Where the insulators are installed above 2250 mm, rails, chains or wires are sufficient (Fig. 4-38).

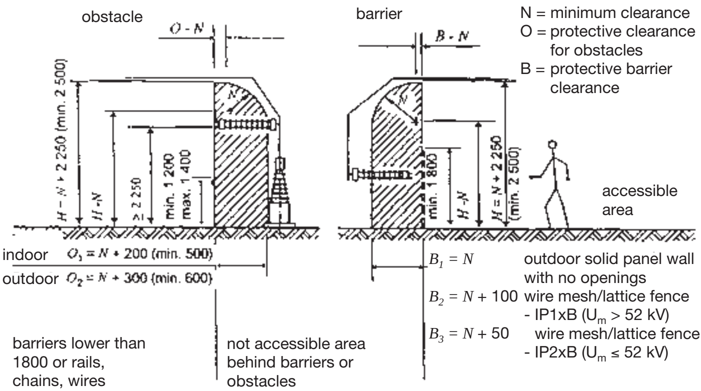


Fig. 4-38

Protection against direct contact by barriers/obstacles in locked electricial premises Dimensions in mm

Walkways over live parts accessible during operation must be of solid plate. If rails, chains or wires are installed as protective barriers, they must be widened by the safety clearance and a minimum 50 mm high edge must be installed as a limit. This is intended to prevent objects from falling on live parts.

4.6.2 Walkways and gangways in power installations with rated voltages over 1 kV (DIN VDE 0101)

The minimum width of gangways in indoor installations should be 800 mm. For safety reasons these dimensions must not be reduced, not even by projecting parts such as fixed drives, control cabinets, switchgear truck in isolated position. Cubicle doors must slam shut in the escape direction. When the door is open, the gangway width must still be 500 mm. For service aisles behind metall-enclosed installations; a minimum gangway width of 500 mm is permissible.

In the case of transport paths inside locked electrical premises, the dimensions for the transport unit must be agreed between the installer and the operator. The following regulations are applicable (Fig. 4-39):

Vehicles and similar may pass below live parts (without protection devices) or in their vicinity when

- the vehicle, even with its doors open, and its load do not come into the danger zone (minimum transport clearance $T = N + 100$ mm; minimum 500 mm) and
- the minimum height H of live parts over walkways is maintained.

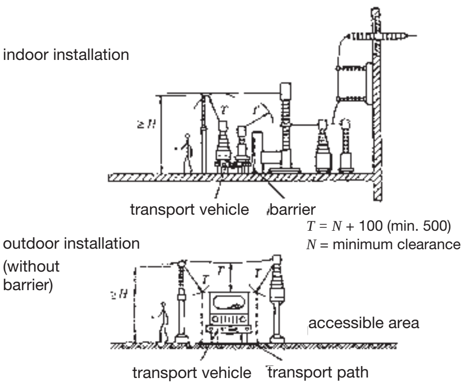
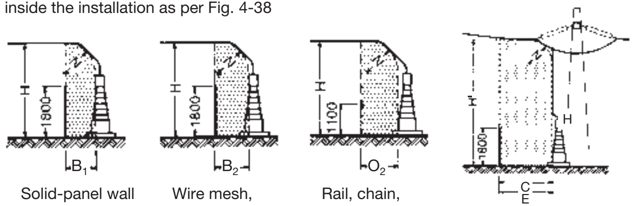


Fig. 4-39

Transport clearances

Table 4-11

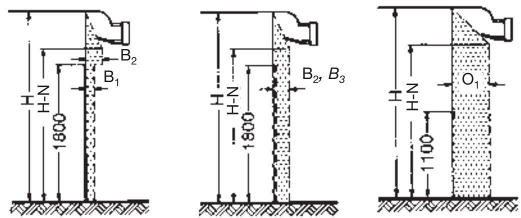
Minimum height and protective barrier clearances in outdoor installations as per DIN VDE 0101 (H' as per DIN VDE 0210)



Nominal voltage U_n kV	Maximum voltage for equipment U_m kV	Minimum clearances *N* as per Table 4-10 N mm	Minimum height H mm	Protective barrier clearances of live parts inside the installation as per Fig. 4-38: Solid-panel wall B_1 mm	Wire mesh, screen B_2, B_3 mm	Rail, chain, rope O_2 mm	at the outer fence H' mm	Solid wall C mm	Screen E mm	Transport clearances as per Fig. 4-39 T mm
3	3.6	120	2 500	120	200	600	5 000	1 120	1 620	500
6	7.2	120	2 500	120	200	600	5 000	1 120	1 620	500
10	12	150	2 500	150	230	600	5 000	1 150	1 650	500
20	24	220	2 500	220	300	600	5 000	1 220	1 720	500
30	36	320	2 570	320	400	620	5 000	1 320	1 820	500
45	52	480	2 730	480	560	780	5 600	1 480	1 980	580
60	72.5	630	2 880	630	730	930	5 700	1 630	2 130	730
110	123	1 100	3 350	1 100	1 200	1 400	6 000	2 100	2 600	1 200
150	170	1 500	3 750	1 500	1 600	1 800	6 300	2 500	3 000	1 600
220	245	2 100	4 350	2 100	2 200	2 400	6 700	3 100	3 600	2 200
380	420	3 400	5 650	3 400	3 500	3 700	7 900	4 400	4 900	3 500
480	525	4 100	6 350	4 100	4 200	4 400	8 600	5 100	5 600	4 200
700	765	6 400	8 650	6 400	6 500	6 700	10 900	7 400	7 900	6 500

Table 4-12

Minimum height and protective barrier clearances in indoor installations as per DIN VDE 0101



Solid-panel wall — Wire mesh, screen — Rail, chain or rope

Nominal voltage	Maximum voltage for equipment	Minimum clearances *N* as per Table 4-10	Minimum height	Protective barrier clearances of live parts		
				Solid-panel wall	Wire mesh, screen	Rail, chain or rope
U_n kV	U_m kV	N mm	H mm	B_1 mm	B_2, B_3 mm	O_1 mm
3	3.6	60	2 500	60	140	500
6	7.2	90	2 500	90	170	500
10	12	120	2 500	120	200	500
20	24	220	2 500	220	300	500
30	36	320	2 570	320	400	520
45	52	480	2 730	480	560	680
60	72.5	630	2 880	630	730	830
110	123	1 100	3 350	1 100	1 200	1 300

4.6.3 Gangway widths in power installations with rated voltages of up to 1 kV as per DIN VDE 0100-29 (VDE 0100 Part 729)

Specifications for the arrangement of switchgear installations

They apply for both type-tested and partially type-tested switchgear installations and switchboards

Control and service gangways

Switchgear installations and distribution boards must be configured and installed so the width and height of gangways are not less than the dimensions shown in Fig. 4-40. The exits must also be accessible in emergencies even when the panel and housing doors are open. These conditions are considered fulfilled if doors slam shut in the escape direction or open completely. The remaining minimum accesses may not be less than 500 mm.

Service and operational accesses with a length of more than 20 m must be accessible from both ends. Access from both ends is also recommended for gangways that are longer than 6 m. Exits must be placed so that the escape path inside a room of electrical or enclosed electrical premises is no more than 40 m long.

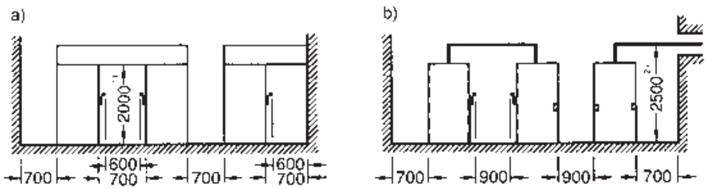


Fig. 4-40

Minimum dimensions for gangways

a) gangways for low-voltage installations with the minimum degree of protection IP 2X as per IEC 60529 (VDE 0470 Part 1)

b) gangways for low-voltage installations with degrees of protection below IP 2X.

1) minimum passage height under obstacles, such as barriers
2) minimum passage height under bare live parts

Fig. 4-40a shows the minimum dimensions for closed installations. The minimum dimensions in Fig. 4-40b are applicable for open installations in locked electrical premises only.

See Section 5.7 for degrees of protection.

The values of DIN VDE 0101 as the dimension for gangways are also applicable for the gangway widths where low-voltage and high-voltage switchgear combinations are installed front-to-front in the same room (see Section 4.6.2).

In the case of barriers, such as wooden railings, the gangway widths must meet the minimum dimensions for operating handles (900 or 700 mm) listed in Fig. 4-40b and also the additional minimum clearance of 200 mm between barrier and live part given in Fig. 4-41 must be observed.

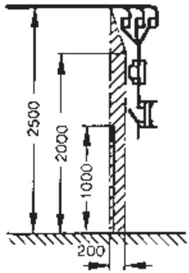


Fig. 4-41

Minimum dimensions for barriers

4.7 Civil construction requirements

The civil engineering consultant must determine a large quantity of information and details for the structural drawings required to design switchgear installations. The structural drawings are the basis for producing the structural design plans (foundation, shell and reinforcement plans, equipment plans). In Germany the Arbeitsgemeinschaft Industriebau e. V. (AGI) has issued the following datasheets:

datasheet J11 for transformer compartments
datasheet J12 for indoor switchgear
datasheet J21 for outdoor transformers
datasheet J31 for battery compartments

The structural information includes the following data:

- spatial configuration of the installation components
- aisle widths for control, transport and assembly
- main dimensions of the station components
- load specifications
- doors, gates, windows with type of opening and type of fire-preventive or fire-resistant design
- ceiling and wall openings for cables, pipes or conduits
- information on compartments with special equipment
- information on building services
- ventilation, air-conditioning information
- floors including steel base frames
- foundation and building earth switches
- lightning protection
- drainage
- fire protection.

The following design details must be observed:

4.7.1 Indoor installations

When planning indoor installations (substation buildings and switchboard rooms), in addition to configuration to meet operational requirements, ensure that the selected rooms are not affected by groundwater and flooding and are also easily accessible for control and transport equipment and also for fire fighting. The current applicable construction codes, regulations and directives must be observed. Construction laws include regulations that must be observed and in addition, the generally accepted engineering requirements apply.

Walls, ceilings and floors must be dry. Pipes carrying liquids, steam and flammable gases must not be laid in, above or under rooms intended for switchgear installations. If, however, necessary, structural measures for protection of the electrical installations are required.

The clearance dimensions of an equipment room depend on the type, size and configuration of the switchbays, on their number and on the operating conditions. The required minimum aisle widths and safety clearances are specified in DIN VDE 0101.

The exits must be located so that the escape route from the installation is no more than 40 m for rated voltages over 52 kV and no more than 20 m for rated voltages of up to 52 kV. A service aisle more than 10 m long must have two exits, one of which may be an emergency exit.

The interiors of the switchgear house walls must be as smooth as possible to prevent dust from accumulating. The brickwork must be plastered, but not the ceilings in the area of open installations, so switchgear parts are not subject to falling plaster.

The floor covering must be easy to clean, pressure-resistant, non-slippery and abrasion-proof (e.g. stoneware tiles, plastic covering, gravel set in concrete with abrasion-resistant protective coating to reduce dust formation); the pressure load on the floor from transport of station components must be considered. The electrostatic properties of the floor covering are of importance in rooms with electronic devices.

Steps or sloping floor areas must always be avoided in switchgear compartments.

Opening windows must be positioned so they can be operated. In open areas, this must not place personnel in danger of contacting live parts.

Windows in locked electrical premises must be secured to prevent access. This condition is considered to be met by one of the following measures:

– The window consists of unbreakable materials.
– The window is barred.
– The bottom edge of the window is at least 1.8 m above the access level.
– The building is surrounded by a fence at least 1.8 m high.

Ventilation

The rooms should be ventilated sufficiently to prevent the formation of condensation. To prevent corrosion and reduction of the creepage distance by high humidity and condensation, it is recommended that the typical values for climatic conditions listed in DIN VDE 0101 and IEC 60694 (VDE 0670 Part 1000) be observed in switchgear rooms. The following apply:

– the maximum relative humidity is 95 % in the 24 hour average,
– the highest and lowest ambient temperature in the 24 hour average is 35 °C and – 5 °C with “Minus 5 Indoor” class.

In areas of high pollution, the compartments must be kept at a low level of overpressure with filtered air. The air vents required for this must be protected against rain, spray water and small animals. Prod-proof plates must also be installed behind the vents below heights of about 2.50 m above ground. See Sections 4.4.2 and 4.4.3 for additional information on ventilation.

SF_6 installations

For SF_6 installations, it is recommended that the building be extended by the length of one bay for installation and renovation purposes and that a hoist system with a lifting capacity equal to the heaviest installation components be installed.

Natural cross-ventilation in above-ground compartments is sufficient to remove the SF_6 gas that escapes because of leakage losses. This requires about half of the required ventilation cross section to be close to the floor.

It must be possible to ventilate compartments, conduits and the like under compartments with SF_6 installations, for instance by mechanical ventilation.

Mechanical ventilation is not necessary so long as the gas content of the largest contiguous gas space including the content of all connected SF_6 tanks (based on atmospheric pressure) does not exceed 10% of the volume of the compartment receiving the leakage gas.

Mechanical ventilation may be required in the event of faults with arcing.

Reference is also made to the requirement to observe the code of practice "SF_6 Installations" (BGI 753, edition 2004-08) of the BGFE (professional association for precision engineering and electrical engineering in Germany).

Pressure relief

In the event of an accidental internal arc in a switchgear installation, significant overpressure occurs in switchgear compartments, in particular in those with conventional air insulation with high arc lengths. Damage to walls and ceilings caused by unacceptably high pressure load can be prevented by appropriate pressure relief vents. Floor plates must be properly secured. Pressure relief facilities in switchgear rooms should meet the following criteria:

– they should normally be closed to prevent the entry of small animals, snow, rain etc.; light, self-actuating opening of the facility at an overpressure of less than 10 mbar;
– pressure relief in an area where there are usually no personnel;
– no parts should become detached during pressure relief.

Cable laying

The options listed below are available for cable laying:

Tubes or cable conduit forms, covered cable conduits, cable conduits accessible as crawl space, cable floors and accessible cable levels.

Tubes or cable conduit forms are used to lay single cables. To avoid water damage when laid outside they should be sloped. The bending radius of the cable used should be observed for proper cable layout.

Covered cable conduits are intended when several cables are laid together, with the width and depth of the conduit depending on the number of cables. The covers of the conduits should be fireproof, non-slip and non-rattling and should not have a raised edge. They must be able to take the weight of transport vehicles carrying electrical equipment during installation. The conduits should be placed before the compartments to allow cable work to be done at any time without having to disconnect equipment.

Cable conduits accessible as crawl spaces and cable floors should be at least 1.50 m wide; the overhead clearance should not be less than 1.00 m to allow for any cable crossings. Access and ventilation openings and the required cable accesses must be taken into account.

Accessible cable conduits and cable levels are required for a large accumulation of cables in larger installations. A height of 2.10 m (to the lower edge of the support girder) is recommended to provide space for the required lighting and suspended cables. The cables can be laid on cable racks and also fastened to supports using cable clamps. Escape paths (emergency exits) must be available. Access doors must open outwards, should be airtight when closed, must be fire-resistant and have a panic lock.

Auxiliary cables are laid on separate cable racks or on supports beneath the ceiling.

The VDEW directives “Empfehlungen für Maßnahmen zur Herabsetzung von transienten Überspannungen” (recommendations for measures to reduce transient overvoltages) in secondary lines are particularly important in the selection and laying of cables; for this reason power cables should be laid apart from control cables. Separate conduits should be provided for cable laying where possible.

The cable conduits, particularly for the power cables, must be dimensioned to provide sufficient space for the heat from power dissipation.

4.7.2 Outdoor installations

Foundations

Foundations for portals, supports (for equipment) and similar and also for transformers are constructed as simple concrete foundations.

As well as the static loads, they must be able to resist operational loads, such as the effects of switching forces, short-circuit forces, tension caused by temperature variations and wind and ice load. The foundation types, such as slab or individual, depend on the soil quality or other installation-specific criteria.

Foundation design is determined by the installation structure and the steel structure design.

The base of the foundation must be frost-free, i.e. at a depth of around 0.8 – 1.2 m. The foundations must have the appropriate openings for earth wires and any necessary cables.

The relevant regulations for outdoor construction specified in DIN VDE 0210 apply for the mechanical strength analyses.

Access roads

The type, design, surveying and layout of access roads is determined by the purpose of the roads and the installation design:

– for transport of switchgear (up to approx. 123 kV roads are provided only in specially extended installations (for higher voltage levels as necessary) min. 2.50 m wide and with a load rating corresponding to the maximum transport component;
– for transport of transformers, min. 5 m wide, load capacity corresponding to the transport conditions. When laying out the road, the radius of the curves should be suitable for multi-axle transport vehicles.

When planning the roads, the required cable conduits, such as for earthing conductors or cable connections that cross the road, must be taken into account.

The height of live parts over access roads depends on the height of the transport units (this must be agreed between the contractor and the operator) and the required minimum clearances T as shown in Fig. 4-39.

Design and dimensions must be suited for transport of the heaviest station components.

4

Cable trenches

Covered cable trenches are planned for cables in outdoor installations. In large installations with conventional secondary technology, an accessible cable trench with single or double-sided cable racks may be required for most of the control cables.

Main trenches should not be more than 100 cm wide because of the weight of the cover plates. The depth depends on the number of cables. Cable racks are installed on the sides.

Branch ducts, which can be designed as finished parts, run from the control cabinets or relay compartments to the high-voltage equipment. The upper part of the main conduits and branch ducts is placed a little above ground level to keep the trench dry even in heavy rain.

Cables to individual devices can also be laid in prefabricated cable ducts or directly in the ground and covered with bricks or similar material.

Further refer to the information given in Section 4.7.1 on laying cables as applicable. For preferred cable trench designs, see Section 11.3.2 Fig. 11-11.

4.7.3 Installations subject to special conditions

Electrical installations subject to special conditions include:

- installations in equipment rooms that are subject to the German Elt-Bau-VO,
- installations in enclosed design outside locked electrical premises,
- mast and tower substations to 30 kV nominal voltage,
- installations in premises subject to fire hazard.

Installations that are subject to the Elt-Bau-VO are subject to the implementation regulations for Elt-Bau-VO issued by the various German states with respect to their structural design. This particularly covers structural measures required for fire prevention.

The other installations subject to special conditions are subject to the structural requirements as in Section 4.6.1.

4.7.4 Battery rooms and compartments (EN 50272-2)

Batteries must be protected by installation in separate rooms. If necessary electrical or locked electrical premises must be provided.

The following kinds of installations may be chosen:

- Special rooms for batteries inside buildings,
- Special separate areas within electrical premises,
- Panels or containers inside or outside of buildings,
- Battery compartments inside switchboards (Combi-Panels).

When designing a battery compartment the following criteria should be taken into account:

- Protection against external dangerous influences , i.e. fire, water, shocks, vibration, vermin,
- Protection against dangers resulting from the battery itself, i.e. high voltage, explosion, electrolytic fluid, corrosion,
- Protection against access of unauthorised persons,
- Protection against extreme ambient conditions, i.e. temperature, humidity, pollution.

In special rooms for batteries the following requirements must be fulfilled, as applicable:

- The floor must be designed according to the weight of the battery. A margin for later extensions should be kept.
- The electrical installations has to be in line with the standards for electrical installations of buildings.
- If access is granted to authorised personnel only a lockable anti-panic door must be applied.
- For closed battery types the floor covering must be leak-proof and chemically resistant or the battery must be installed in relevant tubs.
- Ventilation must fulfil the requirements explained further below.
- The floor covering of insulating material in a distance of one arm length around the battery must have a conductivity high enough to prevent electrostatic charging. But the floor covering material must also be of sufficiently high insulating capability to protect persons against electrical shocks. Therefore the discharge resistance to earth measured according IEC 61340-4-1(VDE 0303 Part 83) must be in the following ranges:
  - With battery voltages ≤ 500V: 50kΩ ≤ R ≤ 10MΩ
  - With battery voltages > 500V: 100kΩ ≤ R ≤ 10MΩ.
- Close to the battery a water tab or any kind of water reservoir must be provided to allow people to clean off splashed electrolytic fluid.

During charging, compensating charging or overcharging gases are escaping from cells and batteries. These gases consisting of hydrogen and oxygen are created by the current in the electrolytic process from water. When entering into the ambient atmosphere an explosive mixture of gases will develop as soon as the hydrogen component exceeds 4%. By ventilation the hydrogen component must be kept below this limiting value.

The necessary air-flow volume for ventilating a battery room or compartment shall be calculated according to the following equation as per EN 50272-2:

$Q = 0{,}05\ n\ I_{gas}\ C_N\ 10^{-3}\ m^3/h$

With:

n number of cells (in series)

I_{gas} specific current effecting the development of hydrogen gas, in mA per Ah of battery capacity

C_N battery capacity in Ah, C_{10} for lead batteries, C_5 for NiCd batteries.

The specific current I_{gas} is depending on the type of the battery (lead battery, closed or sealed, NiCd battery) and also depending on the charging mode (maintenance charging or rapid recharging). Further a safety factor and an emission factor characteristic for the battery type must be taken into account. For details see EN 50272-2.

The air-flow volume Q is preferably to be achieved by natural ventilation or by forced ventilation when necessary. For this battery rooms or compartments need an access and an escape opening each with a minimum size A as per equation

$A = 28\ Q\ \text{cm}^2$

The openings for access and escape must be arranged at suitable places to provide the most favourable conditions for the exchange of air, i. e.

- openings in opposite walls or
- a distance between the openings of 2m at least, when they are in the same wall.

With forced ventilation the loading device and the fan motor must be interlocked to provide sufficient air-flow volume according to the charging current. The air moved out of the battery room must be released into the open air outside the building.

In ranges close to the battery the reduction of the hydrogen content of the air cannot always be ensured to the necessary extend. Therefor a safety distance must be kept where neither flash-over discharges nor glowing components of installations may occur (i.e. 300mm for 100Ah batteries, 650mm for 1000Ah batteries, 750mm for 1500Ah batteries).

Further requirements for the installation of batteries are given in Section 15.3.5, further information about ventilation are in Section 4.4.3.

4.7.5 Transformer installation

The transformers and switchgear compartments should be configured for easy access, because the utilily section of the transformer substation must be quickly and safely accessible from outside at all times.

The compartment dimensions must be determined from the point of view of temperature rise, noise generation, transmission of structural noise, fire hazard and replacement of equipment. The structure must be planned subject to these criteria. See Section 1.2.6 for information on measuring noise and noise reduction.

Oil-insulated transformers may be installed in large buildings only with specified structural and electrical requirements satisfied.

Indoor and outdoor oil-insulated transformers do not require special protection against environmental influences. Cast-resin transformers in the IP00 design (without housing) may be installed in dry indoor rooms. Outdoor installation of cast-resin transformers requires a housing complying with the degree of protection of minimum IP23 with a roof protecting them against rain.

The requirements of the relevant national standards on low-voltage and high-voltage switchgear must be observed for the installation and connection of transformers. The installation of surge arrestors is recommended as protection against overvoltages caused by lightning and switching operations (Section 10.6).

If transformers are installed in indoor compartments for natural cooling, sufficiently large cooling vents above and below the transformers must be provided for venting the heat dissipation. If natural ventilation is not sufficient, forced ventilation is required, see Section 4.4.2, Fig. 4-28.

In detail, the following requirements for installation of transformers must be observed:

- clearances
- safety distances
- design of high-voltage connections
- accessibility for operation and maintenance
- transport paths
- cooling/ventilation (see Section 4.4.3)
- fire prevention (see Section 4.7.6)
- auxiliary equipment
- setup
- withdrawal provisions for future replacement of transformers.

For construction details see AGI datasheet J21 (Arbeitsgemeinschaft Industriebau).

Catchment pans, sumps and sump groups must be installed under transformers with liquid insulation (cooling types O and L) for fire and water protection. Their design must prevent the insulation fluid from leaking into the soil.

Connection lines between catchment pans and sumps must be designed to prevent insulation fluid from continuing to burn in the collection sumps (longer pipes or gravel system).

Catchment or collection sumps must be large enough to catch water flowing in (rain, extinguishing and washing water) as well as insulation fluid.

Water flows must be directed to an oil separator, or otherwise it must be possible to pump out the contents of the catchment sump.

The local water authority may allow concessions in accordance with DIN VDE 0101 for specified local conditions (soil characteristics) and transformers with less than 1000 l of insulation fluid .

Fig. 4-42 shows the preferred configuration of oil catchment equipment.

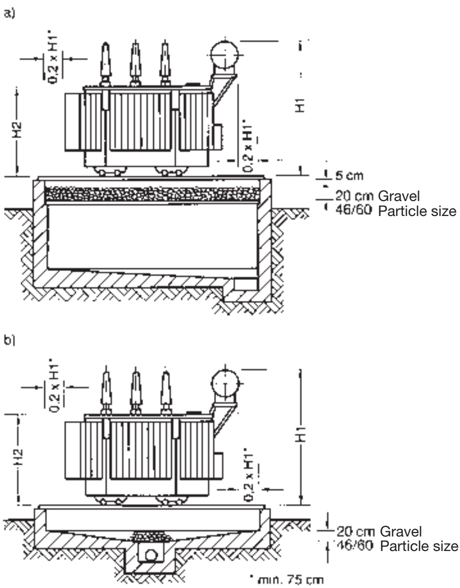


Fig. 4-42

Configuration of oil sumps a) and oil catchment pans b)

4.7.6 Fire prevention

The possibility of fire in switchgear and transformer rooms cannot be excluded. The seriousness of the fire risk depends on the type of installation, the structure, the installation components (devices, apparatus etc.) and on the fire load.

Targeted structural fire prevention measures (e.g. small fire compartments, fire-reducing and fire-resistant barriers, cable and conductor compartmentalization) can significantly reduce the risk of a fire spreading.

Fires caused by electrical equipment may occur due to: internal arcing, unacceptable temperature rise caused by operational overload or short-circuit currents.

Fire load, effects of fire

The fire load corresponds to the theoretical energy that can be released from all flammable material with reference to a defined area. It is expressed in kWh per m^2 of fire compartment area. Data from the association of insurers (VdS) provides guidance values on the combustion heat of cables and wires.

Measures

The following measures for protection of installations are applied mainly in cable compartments, in cable ducts and at transformers:

a) partitioning at cable transitions through ceilings and walls, see Fig. 4-43

b) partitioning at cable entrance in to switchgear cubicles or bays, see Fig. 4-44

c) cable sheathing – protective layer formation

d) fire-resistant enclosures at cable racks

e) compartmentalization of cable ducts, use of small fire compartments,
see Fig. 4-45, installation of fire-protection valves in inlet and outlet air ducts

f) sprinkler systems in buildings

g) installation of venting and smoke removal systems

h) fire-protection walls for transformers, see Fig. 4-46

i) oil catchment systems for transformers, see Section 4.7.5, Fig. 4-42

k) water spray extinguishing systems for transformers, see Fig. 4-47, for fighting fires in leaked flammable insulation and cooling fluids
Alternative: CO_2 fire extinguishing installation or nitrogen injection system (Sergi)

l) fire alarms, see Section 15.4.4.

If cables and conductors are run through walls and ceilings with planned fire resistance class (e.g. F 30, F 90), the openings must be closed with tested cable barrier systems in accordance with DIN 4102, Part 9, of a corresponding fire-resistance class (e.g. S 30, S 90).

Functional endurance of cable and wiring systems

On the basis of DIN VDE 0108 and in accordance with DIN 4102 Part 12, there are special fire-prevention requirements for the functioning of cables and wires for “buildings of special types or usage”. Various German states have introduced corresponding administrative regulations covering the above structural standards. These requirements specifically cover goverment-supported safety equipment.

According DIN 4102 Pert 12 there are the functional endurance classes E 30, E 60 and E 90 corresponding to the fire resistance classes. These requirements can be satisfied by laying cables under plaster, in tested cable ducts or by the electrical cables and wires themselves.

The functional duration for government-supported and required safety equipment must be at least:

- 30 minutes with
  - Fire alarm systems
  - Installations for alarming and distributing instructions to visitors and employees
  - Safety lighting and other emergency electric lighting, except for branch circuits
  - Lift systems with evacuation setting
- 90 minutes with
  - Water pressure-lifting systems for water supply for extinguishing fires
  - Ventilation systems for safety stairwells, interior stairwells
  - Lift shafts and machinery compartments for firefighting lifts
  - Smoke and heat removal systems
  - Firefighting lifts

Escape routes

All installations must have escape routes leading outside. They must be protected by fire-preventive and fire-resistant structures. The maximum permissible escape route length in accordance with the German Muster bauordnung is 40 m or in accordance with the general workplace regulations 35 m. See also Section 4.7.1.

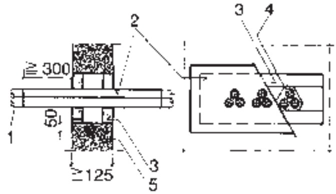


Fig. 4-43

Partition construction of a cable transition for wall or ceiling:

1 cable, 2 sheath of fire-resistant insulation material, 3 mineral fibre plates, 4 mineral wool stuffing, 5 firewall

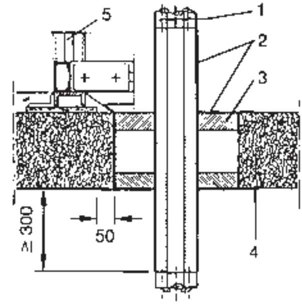


Fig. 4-44

Partition construction of a switchgear cubicle infeed:

1 cable, 2 sheath of fire-resistant insulation material, 3 mineral fibre plates, 4 fire ceiling, 5 base frame of cubicle

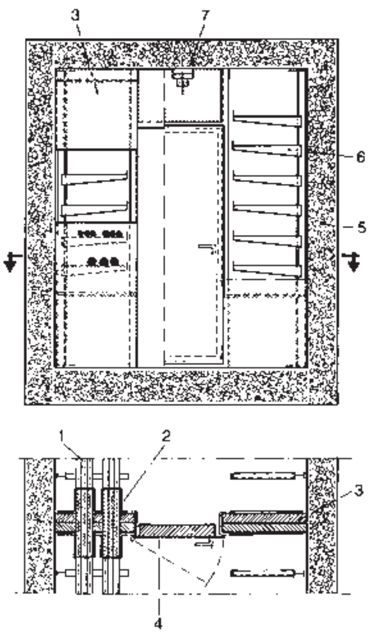
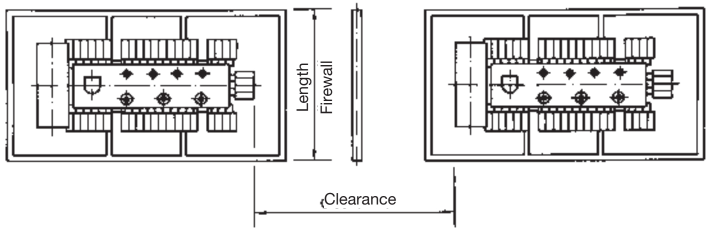


Fig. 4-45

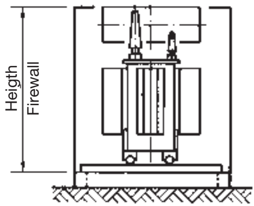
Partition construction of an accessible cable duct:

1 cable, 2 sheath of fire-resistant insulation material, 3 mineral fibre plates, 4 fire-protection door, 5 concrete or brickwork, 6 cable rack, 7 smoke alarm

a)



b)



c)

Transformer output over	Clearances less than
1 MVA	3 m
10 MVA	5 m
40 MVA	10 m
200 MVA	15 m

Fig. 4-46

Configuration of firewall for transformers:

a) Top view b) Side view c) Typical value table for installation of firewalls, dependent on transformer output and clearance

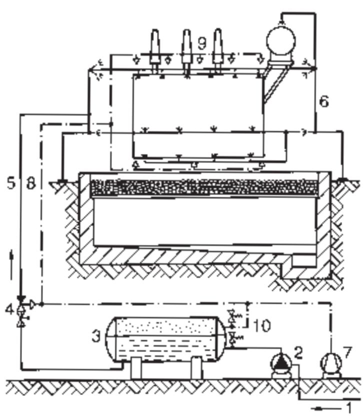


Fig. 4-47

Spray fire-extinguishing system (sprinkler) for a transformer with the following functional elements:

1 *Water supply*
2 *Filler pump*
3 *Air/Water pressure vessel*
4 *Valve block*
5 *Water feed*
6 *Pipe cage with spray nozzles*
7 *Compressor*
8 *Detector line*
9 *Pipe cage with detectors*
10 *Safety valves*

4.7.7 Shipping dimensions

Table 4-13

Container for land, sea and air freight, general data as per ISO 668 and ISO 1486-1.

Type (' foot, " inch) ft. in.	External dimensions			Internal dimensions – minimum dimension –			Clearance dimension of door – minimum –		Volume	Weights Total weight [1] permitted	Tare weight	Cargo weight max.
	Length mm	Width mm	Height mm	Length mm	Width mm	Height mm	Width nm	Height mm	about m^3	about kg	about kg	about kg
20' × 8' × 8'6" ISO-size 22GO	6 058	2 438	2 591	5 867	2 330	2 350	2 286	2 261	33,2	24 000	2 250	21 750
40' × 8' × 8'6" ISO-size 42GO	12 192	2 438	2 591	11 998	2 330	2 355	2 286	2 261	67,7	30 480	3 780	26 700
40' × 8' × 9'6" ISO-size 45GO	12 192	2 438	2 896	11 998	2 330	2 655	2 286	2 566	76,3	30 480	4 020	26 460

[1] Observe permissible load limit for road and rail vehicles.

[2] High Cube, observe overheight for road and rail transport.

5 Protective Measures for Persons and Installations

5.1 Protection against electric shock in low voltage electrical installations up to 1000V (VDE 0100)

5.1.1 Protection against direct contact / protection under normal conditions / basic protection as per IEC 60364-4-41

The danger of touching live parts is particularly great with this kind of switchgear, because in locked electrical premises this equipment does not require any electric shock protection by an enclosure (IP 00), or the electric shock protection may become ineffective on opening the cubicle doors.

According to IEC 60364-4-41 (VDE 0100 Part 410), protection against direct contact is always required regardless of the voltage. Exception: the voltage is generated in accordance with the regulations for extra low voltage SELV and does not exceed 25 V AC or 60 V DC (cf. Section 5.1.3!).

Protection against direct contact (basic protection) assured by complete covering with insulation or by barriers or enclosures with a degree of protection of at least IPXXB or IP2X is essential for installations operated by electrically untrained personnel. Basic protection by placing out of reach or by obstacles is permitted where the access to the installations is permitted to skilled and instructed persons only.

With enclosed low-voltage switchgear assemblies, intervention is sometimes required to restore things to the normal conditions, e.g. actuate miniature circuit-breakers or replace indicator lamps, in areas where life parts are not completely covered with

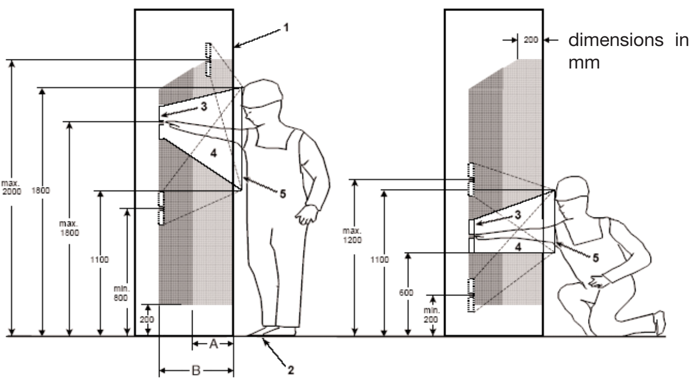


Fig. 5-1 Maximum and minimum values for the height of the base areas of the spaces of protection for upright standing and kneeling position

Areas for operating devices:
A ≤ 300mm, sideways mounted
B ≤ 500mm, rear mounted

1 front of switchgear assembly
2 stand for operator
3 base areas
4 spaces of protection (back of the hand protection)
5 access areas (500 mm distance from base areas)

insulation. Such activities may only be carried out by at least electrically instructed personnel. EN 50274 (VDE 0660 Part 514) specifies the areas inside switchgear assemblies in which operating devices for restoring normal conditions may be installed (Fig. 5-1).

For access to these operating devices areas of protection are specified where hazardous life parts must be protected with a degree of protection of at least IPXXA (back of the hand protection). The same applies for equipment installed at doors or covers. In close vicinity of the operational key (R30) and over a depth of at least 80mm an operating device must have finger protection (IPXXB) and within a further distance (R100) and over a depth of 25mm at least back of the hand protection is requested

dimensions in mm

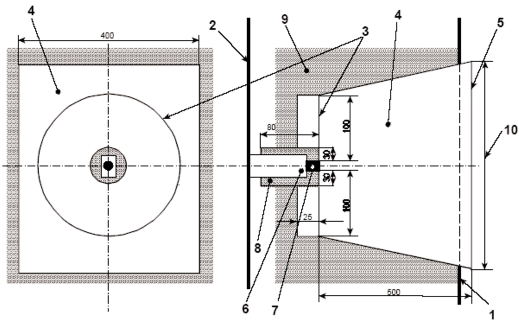


Fig. 5-2

Space of protection for push-button operation

1 front of switchgear assembly
2 mounting plate
3 base area
4 back of the hand protection
5 access area
6 base of switch
7 push-button
8 area of finger protection
9 no additional protection requested
10 500 mm for kneeling position
700 mm for standing position

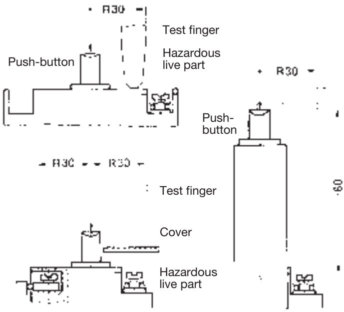


Fig. 5-3

Examples for finger-proof arrangement of shock-hazard parts

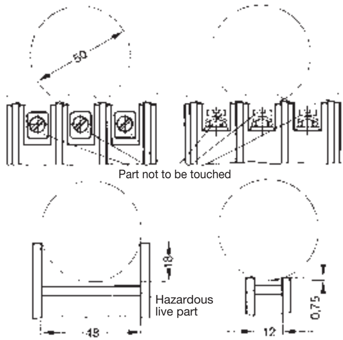


Fig. 5-4

Examples for arrangement of shock-hazard parts to prevent contact with the back of the hand

The standard EN 50274 applies for all switchgear, including those in locked electrical premises. It does not apply for installations that are operated at voltages up to 50V AC or 120V DC, as long as these voltages are generated by sources with a protective separation. If hazardous live parts are not protected according IPXXB at least the switchgear assemblies must be located in areas with access of skilled and instructed persons only or the opening of doors and covers of these assemblies must not be possible without keys or tools.

Additional protection in case of direct contact by RCD

The purpose of additional protection is to ensure that potentially fatal currents cannot flow through the body in the event of direct contact of live parts, for instance due to carelessness of the user. The additional protection is provided particularly for TN and TT systems by the use of highly sensitive residual current protective devices (RCDs), each with a rated fault current ≤ 30 mA. The additional protection in case of direct contact is not permissible as the sole form of protection; the requirements for protection against direct contact must always be met.

IEC 60364-7 specifies in numerous parts in which circuits under certain conditions or in certain special locations additional protection by RCD is to be applied.

5.1.2 Protection against indirect contact / protection under fault conditions / fault protection

The hazard from touch voltages in the event of a malfunction (earth fault to frame) can be avoided as per IEC 60364-4-41 (VDE 0100 Part 410) by several different protection concepts. Two concepts that are most commonly used in switchgear installation design are discussed here.

Protection by automatic tripping of the power supply

The following are regarded as limit values for the touch voltage:

50V AC and
120V DC, ripple free.

Protection by tripping ensures that in the event of faults, hazardous touch voltages are automatically prevented from persisting by protection devices. During the period prior to the interruption of the circuit the expected touch voltage must not have any dangerous physiological effects on human or live stock bodies. These protective measures require coordination of the earthing of the system (Fig. 5-5) and the protection device , which has to trip the faulty component within the set break time (between 0.1s and 5s, Table 5-1). Since here only the operating principle of a many-layered technical solution can be presented, it is recommended to follow strictly IEC 60364-4-41 as a basic safety standard in practice.

The metallic enclosures of the equipment must be connected with a protective conductor or direct to earth. Enclosures which can be touched simultaneously must be connected to the same earthing system.

TN system

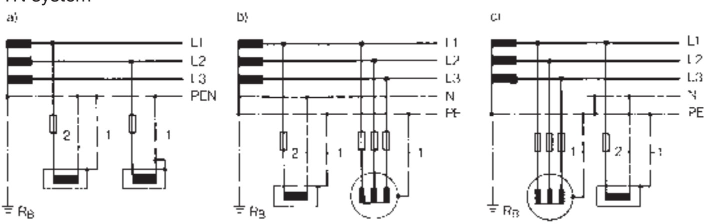


Fig. 5-5 (Part 1)

Overview of the types of earthing for systems:

a) TN-C system: Neutral conductor and protective conductor combined;
b) TN-S system: Neutral conductor and protective conductor separate;
c) TN-C-S system: Combination of layouts a) and b).
1 wire colour green/yellow, 2 wire colour light blue.

TT system IT system

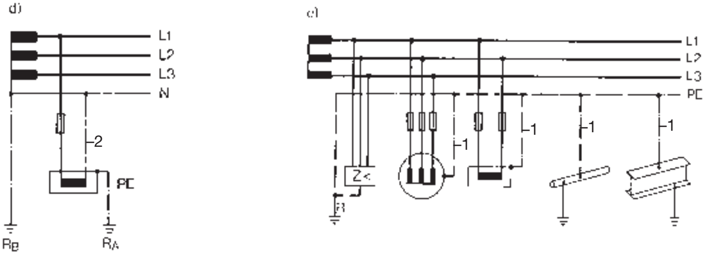


Fig. 5-5 (Part 2)

Overview of the types of earthing for systems:

d) TT system, neutral conductor and protective conductor (exposed conductive part) separately earthed, e) IT system, system not earthed or high-resistance earthed, metallic enclosures, earthed in groups or individually, Z<: insulation monitoring device.

Table 5-1

Protection devices and tripping conditions of the systems for AC

System	Protection device	Tripping current I_a	Protection criteria
TN-S and TN-C-S	Overcurrent- RCD-	$I_a = I_k$ $I_a = I_{\Delta n}$	$Z_S \cdot I_a \leq U_0$ (disconnect. device)
TN-C	Overcurrent-	$I_a = I_k$	
TT	Overcurrent- RCD-	$I_a = I_k$ $I_a = I_{\Delta n}$	$R_A \cdot I_a \leq 50$ V (earthing resist)
IT	Overcurrent- RCD-	$I_a = I_k$ $I_a = I_{\Delta n}$	First failure: $R_A \cdot I_d \leq 50$ V (earthing resist.) Second failure: - individual earthing of enclosures: $R_A \cdot I_a \leq 50$ V (as TT-System) - common earthing of enclosures without neutral conductor*): $Z_S \cdot 2\, I_a \leq U$ (disconnect. device)

Z_S Impedance of the fault loop consisting of current source, line conductor and protective conductor
Note: Z_S can be found by calculation, measurement or with network analyser.

R_A Earthing resistance of earth of metallic enclosures

I_a Current automatically tripping the protection device in case of a failure within the specified disconnecting times. Where an over current protection device is used, this is the rated short-circuit tripping current ($I_a = I_k$), where RCDs are applied, it is the rated residual operating current ($I_a = I_{\Delta n}$).

I_d Fault current of the IT system in the event of a first fault with negligible impedance between a line conductor and a metallic enclosure. The value of I_d considers the leakage currents and the total impedance of the system against earth.

U_0 Rated voltage (r.m.s.) against earth.

U Rated voltage (r.m.s.) between line conductors.

*) Protection criteria for IT systems with distributed neutral conductor are in IEC 60364-4-41 Section 411.6.4.

Different maximum disconnecting times are specified for the different types of systems.

For *TN systems* the disconnecting times are specified as follows:

- For final circuits not exceeding 32A, e.g. for supplying handheld or transportable devices, depending on the nominal voltage U_0,

	at	120V	≤0.8s
	at	230V	≤0.4s
	at	400V	≤0.2s
	at	>400V	≤0.1s

- For distribution circuits and other circuits not covered under the above item ≤5s

For *TT systems* the following disconnecting times are requested:

- For final circuits not exceeding 32A, depending on the nominal voltage U_0,

	at	120V	≤0.3s
	at	230V	≤0.2s
	at	400V	≤0.07s
	at	>400V	≤0.041s

- For distribution circuits and other circuits not covered by the above item (including delay for selective tripping) ≤1s

In IT systems disconnecting is not requested at the occurrence of the first failure. After the second failure the following disconnecting times are specified, taking into account the method of connecting the metallic enclosures to earth:

- For installations with metallic enclosures and exposed conductive parts interconnected by a protective conductor and collectively earthed, the limit values and conditions for disconnecting times as specified above for TN systems apply, referred to the relevant nominal voltage U.
- For installations with metallic enclosures and exposed conductive parts earthed in groups or individually, the limit values and conditions for disconnecting times as specified above for TT systems are valid, referred to the relevant nominal voltage U.

An essential requirement for protection by disconnecting is a main equipotential bonding conductor connecting all conductive parts inside a building as protective conductor, main earth conductor, lightning protection earthing, main water and gas pipes and other metallic tube and reinforcment systems of the building.

An additional (local) equipotential bonding is necessary, if the protection criteria as specified for the different systems cannot be met (Table 5-1) or if it is requested by standards of Part 7 of IEC 60364 for special installations or locations. The additional (local) equipotential bonding must include all enclosures of devices which can be touched simultaneously, all protective conductors, all conductive foreign parts and the concrete steel reinforcement (as far as accessible).

In TN systems the characteristic values of the tripping devices (I_k, $I_{\Delta n}$) and the impedance of the fault current loop must be coordinated to ensure disconnecting within the specified disconnecting times. As well overcurrent devices as RCDs can be used. Only in TN-C systems RCDs are not appropriate.

In TT systems the characteristic values of the tripping devices must be chosen to ensure disconnecting when the touch voltage of a metallic enclosure exceeds the permissible value. The enclosures of all system components which are collectively protected by the same protective device shall be connected by the protective conductor to an earth electrode common to all those enclosures.

For IT systems which are used for reasons of continuity of supply an insulation monitoring device is mandatory. Live parts of IT systems shall be insulated from earth or connected to earth through a sufficiently high impedance. In case of a single fault to earth (to a metallic enclosure or direct to earth) disconnection is not requested in an IT system, as long as the protection criterion (Table 5-1) is not exceeded. In case of a second failure depending on the kind of earthing applied the condition of the TT system (for individual or group earthing) are valid or those of the TN system (for common earthing). When using RCDs for disconnecting each system component with a metallic enclosure should be protected by an individual disconnecting device.

The following are used as protecting devices:
Low-voltage fuses as per IEC 60269-1 (VDE 0636 Part 10)
Circuit breakers as per IEC 60947-2 (VDE 0660 Part 101)
Circuit breaker for household and similar
applications as per IEC 60898-1 (VDE 0641 Part 11) and
IEC 60898-2 (VDE 0641 Part 12)
Residual current operated circuit breakers
(RCCB) as per IEC 61008-1 (VDE 0664 Part 10)
(RCBO) as per IEC 61009-1 (VDE 0664 Part 20)
Insulation monitoring devices
for IT systems as per IEC 61557-8 (VDE 0413 Part 8).

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In TN or TT systems, the total earthing resistance of all functional earths should be as low as possible to limit the voltage rise against earth of all other conductors, particularly the protection or PEN conductor in the TN network if an earth fault occurs on a phase. A value of 2 Ω is considered sufficient in TN systems. If the value of 2 Ω cannot be reached in soils of low conductivity, the following condition must be met:

$$\frac{R_B}{R_E} \leq \frac{50\ \text{V}}{U_0 - 50\ \text{V}}$$

R_B in Ω total earthing resistance of all parallel earths of the system

R_E in Ω assumed lowest earth resistance of conductive parts which are not connected to a protective conductor and over which an earth fault can occur

U_0 rated voltage (r.m.s.) against earth.

In the TT system, the implementation of overcurrent protection devices is problematic because of the required very low continuous earth resistances (system earth and earth of metallic enclosures of installations). Here a supplementary (local) equipotential bonding is necessary usually. In IT systems however an earth resistance of ≤ 15 Ω is generally sufficient when all metallic enclosures of equipment are connected to a common earth.

If a supplementary equipotential bonding is required in an electrical installation, its effectiveness must be verified by the following condition:

$$R \leq \frac{50\ \text{V}}{I_a}$$

R in Ω Resistance between metallic enclosures and other conductive parts that can be touched at the same time.

I_a in A Current that effects the automatic tripping of the protection device

$I_a = I_{\Delta n}$ for residual current operated protection devices.
$I_a = I_k$, the 5s operating current for overcurrent devices.

Protection against indirect contact by equipment of safety class II

Another common measure, against the occurrence of hazardous touch voltages that is also used in switchgear installation design is protection by equipment of safety class II (IEC 60436-4-41 (VDE 0100 Part 410)) or by type-tested assemblies with total insulation (type-tested assemblies with total insulation as per IEC 60439-1 (VDE 0660 Part 500)) or by application of an equivalent supplementary insulation.

Equipment of safety class II and type-tested assemblies with total insulation are identified with the symbol ⧈.

Conductive parts within the enclosure must not be connected to the protective conductor, otherwise it will be a device in safety class I. If protective conductors must be routed through equipment, with double or reinforced insulation, they must be insulated like live conductors.

Exceptions from protection against indirect contact

Measures for protection in case of indirect contact are not required for the following equipment:
– lower parts of overhead line insulators (except when they are within reach)
– steel towers, steel-concrete towers, packing stands
– equipment that is not likely to come into contact by any part of the human body because of its small dimensions (e.g. 50 mm x 50 mm) or because of its configuration,
– metal enclosures for protection of equipment of safety class II or equivalent.

5.1.3 Protection by extra low voltage

As per IEC 60364-4-41 (VDE 0100 Part 410) the use of the SELV and PELV extra low-voltage systems (Fig. 5-6) can offer protection in case of direct and indirect contact. Extra low voltages in accordance with these specifications are AC voltages ≤ 50 V and DC voltages ≤ 120 V. Protection measures against direct contact however may be omitted only in parts of this voltage range. Protection by extra low voltage has achieved a higher importance due to the application of low voltage lighting and building service bus systems. Moreover protection by extra low voltages is recommended for special installations or locations of higher risk as in Chapter 7 of IEC 60364.

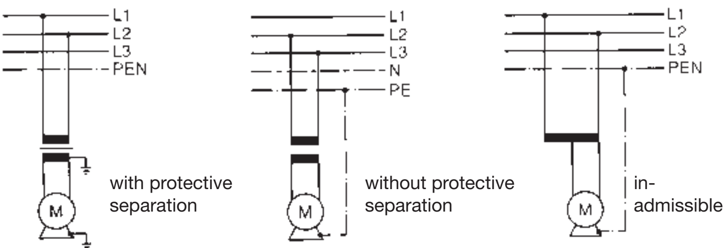
Current sources for supplying extra low-voltage systems of the SELV and PELV types must provide protective separation against the higher voltage supply system and all other systems, e.g. as isolating safety transformer with double or reinforced insulation or with a protective screen (IEC 61558-2-6 (VDE 0570 Part 2-6)), motor generator etc. but not as autotransformer, potentiometer or semiconductor devices.

The SELV extra low voltage, apart from protective separation of the supply and other circuits, requires that neither live parts nor metallic enclosures must be earthed. Protective measures to prevent direct contact, such as barriers, enclosures or insulation are not necessary here under normal dry service conditions if the rated voltage does not exceed AC 25V and DC 60V.

Live parts and metallic enclosures may be earthed with the PELV extra low voltage. Protective measures against direct contact are also not necessary here with rated voltages below and including AC 25V and DC 60V and normal dry service conditions, if metallic enclosures and other conductive parts, which can be touched simultaneously and/or live parts are connected to the same earthing system.

The FELV extra low voltage may be supplied by a current source without a protective separation. FELV is applied if also other devices of the circuit do not provide protective separation. The current source shall have basic insulation against the supplying system. Auto transformers etc. are not applicable. FELV is frequently used for control circuits, particularly for SPS controls. Earthing the current circuits is permitted. Metallic enclosures must be connected to the protective conductor on the primary side of the current source. Protection against direct contact by covers, enclosures or insulation is generally required. In case of an ingress of voltage from the supplying system protection against indirect contact is provided by the protection scheme of the supply side.

Auxiliary circuits in switchgear installations are often operated with extra low voltage. With reference to protection in case of indirect contact, the systems with protective separation (SELV, PELV) are to be recommended, particularly with small wire sections, because in contrast to the FELV system, no additional measures are required. Consistent protective separation from the supply network must be assured by the selection of the equipment in the entire current circuit.



extra low voltages SELV and PELV (no earthing of active parts or metallic enclosures in the SELV system) | extra low voltage FELV | autotransformer

Fig. 5-6 Power sources for extra low voltages

5.1.4 Protective conductors, PEN conductors and equipotential bonding conductors

Requirements as specified by DIN VDE 0100-540 (VDE 0100 Part 540)

The following may be used as protective conductors:

- conductors in multicore cables and wires,
- insulated or bare conductors in the same covering together with phase conductors and the neutral conductor, e.g. in electrical conduits or trunking system,
- permanently installed bare or insulated conductors,
- metallic enclosures, such as sheaths, shields and concentric conductors of cables and wires,
- metal pipes or other metallic coverings, such as electrical conduits, housings for busbar systems,
- external conductive parts,
- sectional bars, other than steel and not used as a support for devices.

If structural components or external conductive parts are used as protective conductors, their conductivity must correspond to the specified minimum cross section, and their continuous electrical connection must not be interrupted by temporary structures or affected by mechanical, chemical or electrochemical influences. Guy wires, suspension wires, metal hoses and similar must not be used as protective conductors.

The cross sections for protective conductors must be dimensioned according DIN VDE 0100-540. Recommended values are in Table 5-2. Cross sections can be calculated by the following formula for break times up to max. 5 s

$$A = \frac{\sqrt{I^2 t}}{k}$$

Here:

- A minimum cross section in mm^2,
- I r.m.s. value of the fault current in A, which can flow through the protective device in the event of a dead short circuit,
- t response time in s for the tripping device,
- k material coefficient, which depends on
  - the conductor material of the protective conductor,
  - the material of the insulation,
  - the material of other parts,
  - the initial and final temperature of the protective conductor, see Tables 5-3 and 5-4.

PEN conductors, a combination of protective and neutral conductors, are permitted in TN networks if they are permanently laid and have a minimum conductor cross section of 10 mm^2 Cu or 16 mm^2 Al. The protective conductor function has priority with PEN conductors. If the concentric conductor of cables or wires is used as a PEN conductor, the minimum cross section can be 4 mm^2 if all connections and joints are duplicated for the course of the concentric conductor. PEN conductors must be insulated for the highest expected voltage; except within switchgear installations.

Table 5-2

Minimum cross sections of protective conductors to the cross section of the phase conductors (recommended values acc. general experience in l.v.systems)

1	2	3	4	5
Nominal cross sections				
Phase conductor[4]	protective conductor or PEN conductor[1]		protective conductor[2) 3)] laid separately	
	power cables	0.6/1-kV cable with 4 conductors	protected	unprotected
mm^2	mm^2	mm^2	mm^2	mm^2
0.5	0.5	–	2.5	4
0.75	0.75	–	2.5	4
1	1	–	2.5	4
1.5	1.5	1.5	2.5	4
2.5	2.5	2.5	2.5	4
4	4	4	4	4
6	6	6	6	6
10	10	10	10	10
16	16	16	16	16
25	16	16	16	16
35	16	16	16	16
50	25	25	25	25
70	35	35	35	35
95	50	50	50	50
120	70	70	70	70
150	95	95	95	95
185	95	95	95	95
240	–	120	120	120
300	–	150	150	150
400	–	240	240	240

[1] In cables PEN conductor ≥ 4 mm^2.
[2] PEN conductor ≥ 10 mm^2 Cu or ≥ 16 mm^2 Al. } as per DIN VDE 0100-540
[3] For phase conductor cross sections ≥ 95 mm^2, bare conductors are preferred.
[4] Minimum cross section for aluminium conductors: 16 mm^2.
For minimum conductor cross sections for phase conductors and other conductors, see also DIN VDE 0100-520, and also Chapters 7 and 13.

After a PEN conductor has been split into protective and neutral conductor, they must not be joined again and the neutral conductor must not be earthed. The PEN conductor must be connected to the protective conductor terminal.

The conductor cross sections for equipotential bonding conductors can be found in Table 5-5.

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When insulated conductors are used as protective or PEN conductors they must be coloured green-yellow throughout their length. The insulated conductors of single-core cables and sheathed cables are an exception. They must have durable green-yellow markings at the ends.

Equipotential bonding conductors may be marked green-yellow.

Non-insulated conductors do not require the green-yellow marking.

Green-yellow markings are not approved for anything other than the above conductors.

Table 5-3

Material coefficients *k* in A $\sqrt{s}$/mm² for insulated protective conductors in cables

	G	PVC	VPE, EPR	IIK
ϑ_i in °C	60	70	90	85
ϑ_f in °C	200	160	250	220
	k in A $\sqrt{s}$/mm²			
Cu	141	115	143	134
Al	87	76	94	89

Further material coefficients are in DIN VDE 0100-540 Tables 2 to 5.

Symbols used in Tables 5-3 and 5-4:

ϑ_i	Initial temperature at conductor
ϑ_f	Max. permitted temperature at conductor
G	Rubber insulation
PVC	Insulation of polyvinyl chloride
XLPE	Insulation of cross-linked polyethylene
EPR	Insulation of ethylene propylene rubber
IIK	Insulation of butyl rubber

Table 5-4

Material coefficients *k* for bare conductors in cases where there is no danger to the materials of adjacent parts from the temperatures given in the table

Conductor material	Conditions	Visible and in delimited areas*)	Normal conditions	If fire hazard
Cu	ϑ_f in °C	500	200	150
	k in A $\sqrt{s}$/mm²	228	159	138
Al	ϑ_f in °C	300	200	150
	k in A $\sqrt{s}$/mm²	125	105	91
Fe	ϑ_f in °C	500	200	150
	k in A $\sqrt{s}$/mm²	82	58	50

Note: The initial temperature ϑ_i on the conductor is assumed to be 30 °C.

*) The given temperatures only apply if the temperature of the joint does not impair the quality of the connection.

Table 5-5

Cross-sections for equipotential bonding conductors

Dimension limits	Main equipotential bonding	Additional equipotential bonding	
normal	≥ 0.5 × cross-section of the largest protective conductor of the installation	Between two exposed conductive parts:	≥ 1 × cross-section of the smaller protective conductor
		Between a metallic enclosure and an external conductive part:	≥ 0.5 × cross-section of the protective conductor of the enclosure
minimum	6 mm^2	With mechanical protection:	2.5 mm^2 Cu or Al
		Without mechanical protection:	4 mm^2 Cu or Al
upper limitation	25 mm^2 Cu or equivalent conductivity	—	—

5.2 Protection against electric shock in installations above 1000 V as per DIN VDE 0101 (German version HD 637S1)

5.2.1 Protection against direct contact/protection against electric shock under normal conditions

To provide protection against direct contact, measures are required to prevent people from coming dangerously close, indirectly or directly with tools or objects to active components, wich may be live. Examples are:

- live parts
- components of an installation where earthed enclosures or conductive layers of cables have been removed
- power cables and accessories without metal shields or earthed conductive layers and conductors without any conductive shield
- cable terminations and conductive cable shields if hazardous touch voltages are possible
- insulating bodies of insulators and other components, e.g. of those with a cast resin insulation (not covered by an earthed conductive layer)
- racks and enclosures of capacitors, converters etc.
- windings of electrical machines, transformers, reactor coils.

Depending on the location of the electrical installation, the following is required:

- complete protection against direct contact for installations outside locked electricial premises,
- non-complete protection against direct contact for installations inside locked electricial premises.

Protective measures against direct contact:

- protection by covering (enclosures)
  When installed outside locked electrical premises the degree of protection of the covering (enclosure) shall be IP23D (complete protection), inside locked electrical premises IP2X is permissible (non-complete protection).
- protection by protective barriers
  Protection by barriers (non-complete protection) can be achieved by solid walls, doors, wire mesh and lattice fences (≤ 52kV: IP2X, > 52kV: IP1XB, e.g.40mm width of meshes, minimum height 1800mm, clearances B_1, B_2 and B_3 as per Tables 4-11 and 4-12).
- protection by obstacles
  For obstacles (non-complete protection) solid walls, doors, lattice fences and chains may be used (height 1200 to 1400 mm, clearances O_1 and O_2 according Fig. 4-38 and Tables 4-11 and 4-12).
- protection by clearances
  The minimum height values H and H' for unprotected live parts above accessible areas provide protection by clearances according Fig. 4-38 and Tables 4-11 and 4-12 (H' complete protection, H non-complete protection). Also the minimum height of the top of the base of a post type insulator according Fig. 4-37 provides (non-complete) protection by clearance.

Protective barriers must meet the following requirements:

- mechanically robust and reliably fastened (in installations outside locked electrical premises they must be removable only with tools). Guard rails that can be removed without tools must be of non-conductive materials or wood.
- solid or wire mesh doors (40 mm mesh, IP2X or IP1XB) may be opened only with keys, including socket-type keys. Safety locks are required for installations outside locked electrical premises.
- rails, chains or ropes must be installed at a height of 1200 to 1400 mm; in the case of chains and ropes, the clearance to the protective barrier must be greater depending on the amount of sag.

5.2.2 Protection against indirect contact / protection against electric shock under fault conditions

In systems above 1000V protection against indirect contact is based on correct design and dimensions of the earthing system according DIN VDE 0101 (german version of a HD 637 S1). See also Chapter 5.3. In the event of a short circuit in the system with earth contact, the earth carries at least part of the short-circuit current. Voltage drops that could result in potential differences are associated with this partial short-circuit current. The potential differences may be bridged by humans; they represent a danger to personnel, particularly in the form of a touch voltage.

The protective earth system must be designed so that the earth fault current flows over the protective earthing in the event of an earth fault in the system.

When using protective earthing, all non-live equipment parts and installations must be earthed if they can come into contact with live parts as a result of creepage paths, arcing or direct contact. Metallic sheathing, armouring and screening of cables must be connected to one another at the joints and with the metallic joint boxes and earthed at the end seals. It may be desirable to earth three-core sheathed and single-conductor cables at one end only because of inductive effects in the sheaths. In this case, insulated end seals are necessary. In long cable units with end seals earthed at one end only, the touch voltage may become too high because of the induced voltage in the cable sheath. So earthing cable sheats at one end only is restricted to short cable units of less than 500m of length. Low-voltage circuits of instrument transformers and surge arresters must also be connected to the protective earthing.

Certain resistance values are not stipulated for protective earthing systems in DIN VDE 0101. However limiting values of the permissible touch voltage are specified depending on the duration of the fault. The touch voltage is that part of the potential difference between earthing system and reference earth that can be shunted by a human body (hand-foot) in horizontal direction.

The diagram in Fig. 5-7 (FIG: 9.1 of DIN VDE 0101) is based on investigations with respect to the values of the body resistance and about values and effects of currents passing the body, as published in IEC 60479-1(DIN V VDE V 0140-479). The shorter the duration of the fault, the higher the current may be passing the body without critical physiological effects and as a consequence also the permissible touch voltage is higher the shorter the failure duration is kept. If the permissible touch voltages according Fig. 5-7 are not exceeded, one remains on the save side since in this diagram additional resistances, e.g. dry skin, shoes, have not been taken into account. Earthing systems fulfilling the requirements with respect to the touch voltages will in general also not produce any critical step voltages.

Remark: In case of longer durations a value af 75 V permissible.

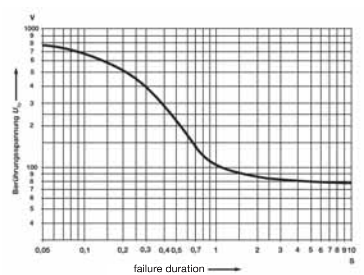

Fig. 5-7

Highest permissible touch voltage U_{TP} for limited failure duration (according DIN VDE 0101)

5.3 Earthing

5.3.1 Fundamentals, definitions and specifications

In DIN VDE 0101 the criteria are laid down for dimensioning, installation, testing and maintenance of earthing systems, to ensure safety of persons under all circumstances and to prevent damage to property. Further also conditions are given for common earthing systems for high and low voltage systems. When designing earthing systems the following requirements must be met:

– withstand against mechanical impact and against corrosion

– withstanding the thermal effects of the highest failure currents

– avoiding damages on goods and devices

– providing safety for persons

For dimensioning earthing installations the failure current and its duration and also the properties of the soil are of decisive influence.

The general layout of a complete earthing system with sections for low voltage, high voltage and buildings and building services is shown in Fig. 5-8. In earthing plants for different high voltage systems the requirements must be fulfilled for each of the systems.

The most important definitions related to earthing are grouped below.

Earth is the term for the earth as a location and for the earth as material, e.g. the soil types of humus, clay, sand, gravel, rock.

Reference earth (neutral earth) is that part of the earth, particularly the surface outside the area of influence of an earth electrode or an earthing system, in which there are no detectable voltages resulting from the earthing current between any two random points.

Earth electrode is a conductor embedded in the ground and electrically connected to it, or a conductor embedded in concrete that is in contact with the earth over a large area (e.g. foundation earth).

Earthing conductor is a conductor connecting a system part to be earthed to an earth electrode, so long as it is laid out of contact with the ground or is insulated in the ground.

If the connection between a neutral or phase conductor and the earth electrode includes an isolating link, a disconnector switch or an earth-fault coil, only the connection between the earth electrode and the earth-side terminal of the nearest of the above devices is deemed to be an earthing conductor.

Main earthing conductor is an earthing conductor to which a number of earthing conductors are connected.

It does not include:

a) Earthing conductors joining the earthed parts of the single units of three-phase assemblies (3 instrument transformers, 3 potheads, 3 post insulators etc.),

b) with panel-type switchboards: earthing conductors that connect the earthed parts of several devices of a compartment and are connected to a (continuous) main earthing conductor within this compartment.

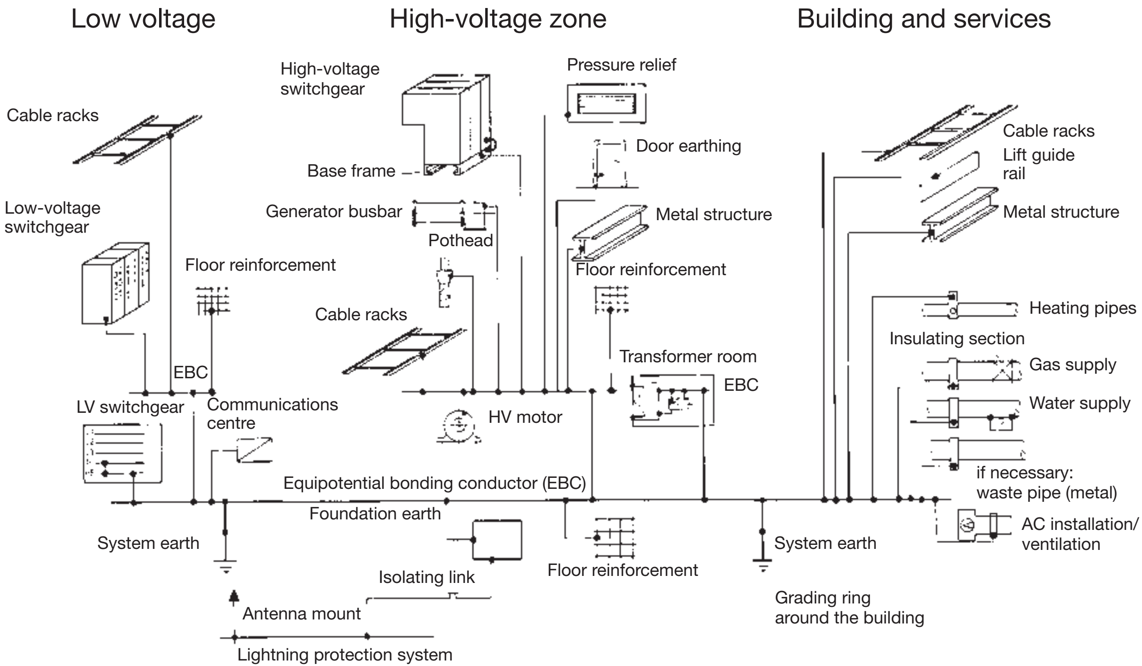

Fig. 5-8

Earthing system with equipotential bonding between HV/LV indoor switchboards and building services

Earthing system is a locally limited assembly of conductively interconnected earth electrodes or metal parts operating in the same way (e.g. tower feet, armouring, metal cable sheaths) and earthing conductors.

To earth means to connect an electrically conductive part to the ground via an earthing system.

Earthing is the total of all measures used for earthing.

Specific earth resistivity ρ_E is the specific electrical resistivity of the ground. It is generally stated in $\Omega\ m^2/m = \Omega\ m$ and indicates the resistance between two opposite cube faces of a cube of soil with sides of 1 m.

Earth-electrode resistance R_A of an earth electrode is the resistance of the earth between the earth electrode and the reference earth.
R_A is in practice a real resistance.

Earthing impedance Z_E is the AC impedance between an earthing system and the reference earth at operating frequency. The value of the earthing impedance is derived from parallelling the dissipation resistances of the earth electrodes and the impedances of connected conductor strings, e.g. the overhead earth wire and cables acting as earth electrodes.

Impulse earthing resistance R_{st} is the resistance presented to the passage of lightning currents between a point of an earthing system and the reference earth.

Protective earthing is *the* earthing of a conductive component that is not part of the main circuit for the protection of persons against unacceptable touch voltages.

System earthing is the earthing of a point of the main circuit necessary for proper operation of devices or installations.

It is termed:

a) direct, if it includes no resistances other than the earthing impedance.
b) indirect, if it is established via additional resistive, inductive or capacitive resistances.

Lightning protection earthing is the earthing of a conductive component that is not part of the main circuit to avoid flashovers to the operational live conductors resulting from lightning as much as possible (back flashovers).

Earthing voltage U_E is the voltage occurring between an earthing system and the reference earth.

Earth surface potential φ is the voltage between a point on the surface of the earth and the reference earth.

Touch voltage U_T is the part of the earthing voltage that can be shunted through the human body, the current path being through the human body from hand to foot (horizontal distance from exposed part about 1m) or from hand to hand. Fig. 5-7 gives the highest permissible touch voltage U_{TP} for limited current duration according DIN VDE 0101.

Step voltage U_S is that part of the earthing voltage that can be shunted by a person with a stride of 1m, with the current path being through the human body from foot to foot.

Potential control consists in influencing the earth potential distribution, particularly that of the earth surface potential, by earth electrodes to reduce the step and touch voltage in the outer area of the earthing system.

Earth fault is an electrical connection between a conductor of the main circuit with earth or an earthed part caused by a defect. The electrical connection can also be caused by an arc.

Earth fault current I_F is the current passing to earth or earthed parts when an earth fault exists at only one point at the site of the fault (earth fault location).

This is

a) the capacitive earth-fault current I_C in networks with isolated neutral

b) the earth-fault residual current I_{Rest} in networks with earth-fault compensation

c) the zero-sequence current I''_{k1} in networks with low-resistance neutral earthing.

c) also includes networks with isolated neutral point or earth-fault compensators in which the neutral point is briefly earthed at the start of the fault.

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Earthing current I_E is the total current flowing to earth via the earthing impedance. The earthing current I_E is the component of the earth-fault current I_F which causes the rise in potential of an earthing system.

Types of earth electrodes

Classification by location

The following examples are distinguished:

a) *surface earth electrodes* are earth electrodes that are generally positioned at shallow depths to about 1 m. They can be of strip, bar or stranded wire and be laid out as radial, ring or meshed earth electrodes or as a combination of these.

b) *deep earth electrodes* are earth electrodes that are generally positioned vertically at greater depths. They can be of tubular, round or sectional material.

c) *Foundation earths* are conductors embedded in concrete that is in contact with the ground over a large area . Foundation earths may be treated as if the conductor were laid in the surrounding soil.

Classification by shape and cross section

The following examples are distinguished:

Strip, stranded wire and tube earth electrodes.

Natural earth electrodes are metal parts in contact with the ground or water, directly or via concrete, whose original purpose is not earthing but they act as an earth electrode. They include pipes, caisson walls, concrete pile reinforcement, steel parts of buildings etc.

Cables with earthing effect are cables whose metal sheathing, shield or armouring provides a leakage to earth similar to that of strip earth electrodes.

Control earth electrodes are earth electrodes that by their shape and arrangement are more for potential control than for retaining a specific earth-electrode resistance.

Rod earth electrodes of any significant length generally pass through soil horizons of varying conductivity. They are particularly useful where more conductive lower soil horizons are available and the rod earth electrodes can penetrate these horizons sufficiently (approximately 3 m). To determine whether more conductive lower soil horizons are available, the specific resistance of the soil at the site is measured (see Section 5.3.4).

Relevant standards on earthing

DIN VDE 0100 Part 540.
Installation of power systems with nominal voltages to 1000 V; selection and installation of electrical equipment, earthing; protective conductors; equipotential bonding conductors.

DIN VDE 0151
Materials and minimum dimensions of earth electrodes with reference to corrosion.

DIN VDE 0101
Power installations exceeding AC 1kV

IEC-Report 60479-1
(DIN V VDE V 0140-479)
Effects of current on human beings and livestock

IEEE Std 80-2000 IEEE Guide for Safety in AC Substation Earthing.

5.3.2 Earthing material

Earth electrodes (under ground) and earthing conductors (above ground) must conform to specific minimum dimensions regarding mechanical stability and possible corrosion resistance as listed in Table 5-6.

Selection of material for earth electrodes with respect to corrosion (no connection to other materials) may be made in accordance wtih the following points (DIN VDE 0151):

Hot-dip galvanized steel is very durable in almost all soil types. Hot-galvanized steel is also suitable for embedding in concrete. Contrary to DIN 1045, foundation earths, earthing conductors embedded in concrete, equipotential bonding conductors and lightning conductor leads of galvanized steel can be connected to reinforcing steel if the joints are not subjected to prolonged temperatures higher than 40 °C.

Copper is suitable as an earth electrode material in power systems with high fault currents because of its significantly greater electrical conductivity compared to steel.

Bare copper is generally very durable in the soil.

Copper coated with tin or zinc is, like bare copper, generally very durable in the soil. Tin-plated copper has no electrochemical advantage over bare copper.

Copper with lead sheath. Lead tends to form a good protective layer underground and is therefore durable in many soil types. However, it may be subject to corrosion in a strongly alkaline environment (pH values ≥ 10). For this reason, lead should not be directly embedded in concrete. The sheath may corrode under ground if it is damaged.

Table 5-6

Minimum dimensions for earth electrodes
(according DIN VDE 0101)

Material	Form	Minimum dimensions Diameter mm	Cross-section mm^2	Thickness mm	Remarks
Copper, bare	strip		50	2	
	round wire		25[4)]		for surface earths
	stranded wire	1,8[1)]	25		
	tube	20		2	
Copper, tin-coated	stranded wire	1,8[1)]	25		
Copper, zink-coated	strip		50	2	
Copper, with lead coating	stranded wire	1,8[1)]	25		
	round wire		25		
Steel, hot-dip zink-coated[2)]	strip		90	3	edges rounded
	sectional bar		90	3	
	tube	25		2	
	round bar	16			for deep earths
	round wire	10			for surface earths
Steel, with lead coating[3)]	round wire	8			for surface earths
Steel, with copper coating	round bar	15			for deep earths
Steel, copper-plated	round bar	14,2			for deep earths

1) for the individual wire
2) appropriate for embedding in concrete
3) not for embedding in concrete
4) in case of particularly low danger of corrosion also 16mm² are permissible

For earthing conductors the following minimum cross-section values are to be observed with respect to mechanical withstand and withstand against corrosion:

copper: 16 mm^2 (second. circuits of instrument transformers, protected laying, ≥ 2,5 mm^2)
aluminium: 35 mm^2
steel: 50 mm^2

For equipotential bonding conductors the same dimensions are recommended as for earthing conductors. Equipotential bonding conductors in buildings may also be dimensioned according Table 5-5 as per DIN VDE 0100-540.

When connecting different materials of an earthing systems laid in the soil refer to Table 5-7 (DIN VDE 0151).

Table 5-7

Connections for different earth electrode materials with respect to corrosion
Ratio of large area : small area ≥ 100:1

Material with small surface area	Material with large surface area							
	Steel, hot-dip zinc-coated	Steel	Steel in concrete	Steel, hot-dip zinc-coated in concrete	Copper	Copper tin-plated	Copper, hot-dip zinc-coated	Copper with lead cladding
Steel, hot-dip zinc-coated	+	+ Zinc loss	—	+ Zinc loss	—	—	+	+ Zinc loss
Steel	+	+	—	+	—	—	+	+
Steel in concrete	+	+	+	+	+	+	+	+
Steel with lead cladding	+	+	○ Lead loss	+	—	+	+	+
Steel with Cu cladding	+	+	+	+	+	+	+	+
Copper	+	+	+	+	+	+	+	+
Copper tin-plated	+	+	+	+	+	+	+	+
Copper zinc-coated	+	+ Zinc loss	+ Zinc loss	+ Zinc loss	+ Zinc loss	+ Zinc loss	+	+ Zinc loss
Copper with lead cladding	+	+	+ Lead loss	+	+ Lead loss	+	+	+

\+ Good for joining
○ Can be joined
— must not be joined

The area rule means that the ratio of the anode area F_A (e.g. steel) to the cathode area F_K (e.g. copper) is crucial for the formation of corrosion elements. As the area ratio F_A/F_K decreases, the rate of corrosion of the anode area increases. This is why coated steel pipe conductors are in danger when connected to a copper earthing system, because the surface ratio of steel to copper at fault positions in the pipe coating is unfavorable and causes fast corrosion (breakthrough). Connecting such tube conductors to earth electrodes of copper is not approved as per DIN VDE 0151.

5.3.3 Dimensioning of earthing systems

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Dimensioning currents for earthing systems

In case of an earth fault against the earthed enclosure of a device or against a conductive foreign part, which is connected either to the earthing system of a plant or by means of an earth electrode directly to earth, currents will occur in the earthing system, resulting in thermal stresses on earthing conductors and earths but also in earth voltages between the earthing system and reference earth. Table 5-8 gives an survey on the different currents to be expected according to the type of the system and to be checked with respect to their influences critically.

For systems with low-resistance or temporary low-resistance earthing systems there is no general formula for calculating the earth current I_E when checking the touch voltage values. Here it must be investigated in each case whether a critical current may occur.

Dimensioning of earthing systems with respect to thermal stresses

The cross sections of earth electrodes and earth conductors must be dimensioned so that in the event of a fault current, the strength of the material is not reduced. The necessary conductor cross section may be calculated for failure duration times up to 5s by means of the formula given in Section 5.1.4 for the dimensioning of protective conductors, applying the material coefficients as in Tables 5-3 and 5-4.

Suitable standard values of cross-sections for bare copper conductors depending on the single line fault current and fault duration are given in Table 5-9.

Dimensioning of earthing systems with respect to touch and step voltages

Personnel safety in the event of earth failures is ensured when the step and touch voltages do not exceed the specified limit values as given in Fig. 5-7. The exact prove by calculation or measurement is a very extensive task. However it is also accepted as a prove if it is shown, that one of the following conditions is met:

Condition C1: The installation is part of a "global earthing system”, i.e. it is situated in a high-density housing area or in an industrial plant (Quasi-equipotential surface).

or

Condition C2: The earthing voltage, found by measurement or calculation does not exceed 2-times the value of the permissible touch voltage as per Fig. 5-7, where the earthing voltage U_E is the potential the earthing system may adopt against reference earth in case of a failure.

Table 5-8

Significant currents for dimensioning earthing systems according DIN VDE 0101 (HD 637 S1)

Type of the high-voltage system			Significant for the thermal stress: Earth electrodes	Significant for the thermal stress: Earthing conductors	Significant for earthing and touch voltage
Systems with insulated neutral			—	I''_{kEE}	$I_E = r \cdot I_C$ or I''_{kEE}
Systems with earth fault compensation	in installations with compensating reactor		—	I''_{kEE}	$I_E = r \cdot \sqrt{I_L^2 + I_{RES}^2}$
	in installations without compensating reactor				$I_E = r \cdot I_{RES}$
Systems with low-ohmic earthed neutral			I''_{k1}	I''_{k1}	I_E
Systems with earth fault-compensatuion and temporary low-ohmic earthed neutral	in installations, where temporary earthing is carried out		I''_{k1}	I''_{k1} or I''_{kEE}	I_E
	in all other installations	with compensating reactor	—	I''_{kEE}	$I_E = r \cdot \sqrt{I_L^2 + I_{RES}^2}$
		with out compensating reactor			$I_E = r \cdot I_{RES}$

I_C Calculated or measured capacitive earth fault current.
I_{RES} Earth fault current. If a precise value is not available, 10% of I_C may be assumed.
I_L Total of the rated currents of all parallel connected compensating reactors of the installation.
I''_{kEE} Double earth fault current, calculated according IEC 60909-0 (VDE 0102). For I''_{kEE} a maximum value of 85% of the three-phase initial symmetrical short-circuit current may be taken into account.
I''_{k1} Single-phase initial symmetrical short circuit current, calculated according IEC 60909 (VDE 0102)
I_E Earthing current
r Reduction coefficient. When cables and lines terminating at the same installation have different reduction coefficients, the individual earth fault current component of each of the cables or lines must be evaluated separately.

Table 5-9 Standard cross-sections

$I''_{k1} = I''_{k3} \dfrac{3}{2 + x_0/x_1}$			Standard cross-sections for earthing material of copper in mm²					
I''_{k3} in *kA*	x_0/x_1	I''_{k1} in *kA*	$\vartheta_i = 30$ °C, $\vartheta_f = 300$ °C 1.0 s	0.5 s	0.2 s	$\vartheta_i = 30$ °C, $\vartheta_f = 150$ °C 1.0 s	0.5 s	0.2 s
	1	80	—	4 × 95	2 × 95	—	4 × 120	4 × 70
80	2	60	—	2 × 120	2 × 95	—	4 × 95	2 × 120
	3	48	—	2 × 95	120	—	4 × 70	2 × 95
	1	63	—	2 × 120	2 × 95	—	4 × 95	2 × 120
63	2	47.3	—	2 × 95	120	—	4 × 70	2 × 95
	3	37.8	—	2 × 95	95	—	2 × 120	2 × 70
	1	50	—	2 × 95	120	—	4 × 70	2 × 95
50	2	37.5	—	2 × 70	95	—	2 × 120	2 × 70
	3	30	—	120	95	—	2 × 95	120
	1	40	2 × 120	2 × 95	95	4 × 95	2 × 120	2 × 70
40	2	30	2 × 95	120	95	2 × 120	2 × 95	120
	3	24	2 × 70	95	70	2 × 95	2 × 70	95
	1	31.5	2 × 95	120	95	2 × 120	2 × 95	120
31.5	2	23.6	2 × 70	95	70	2 × 95	2 × 70	95
	3	18.9	120	70	50	2 × 70	120	70
	1	25	2 × 70	95	70	2 × 95	2 × 70	95
25	2	18.8	120	70	50	2 × 70	120	70
	3	15	95	70	35	120	95	50
	1	20	120	95	50	2 × 95	120	70
20	2	15	95	70	35	120	95	50
	3	12	70	50	35	95	70	50
	1	16	95	70	50	120	95	70
16	2	12	70	50	35	95	70	50
	3	9.6	70	50	35	70	50	35
	1	12.5	70	50	35	95	70	50
12.5	2	9.4	50	35	35	70	50	35
	3	7.5	50	35	35	70	50	35
	1	10	70	50	35	95	70	35
≤ 10	2	7.5	50	35	35	70	50	35
	3	6	35	35	35	50	35	35

x_0/x_1: Ratio of zero-sequence reactance to positive-sequence reactance of the system from the point of view of the fault location; 1 for faults near the generator, heavily loaded networks and in case of doubt; 2 for all other installations; 3 for faults far from the generator.

The earthing voltage U_E is calculated according

$$U_E = Z_E \cdot I_E$$

with:

Z_E earthing impedance, from measurement or calculation

I_E earthing current

The earthing voltage U_E in low-resistance earthed networks is given approximately by:

$$U_E = r \cdot I''_{K1} \cdot Z_E$$

with

r reduction factor

Overhead earth wires or cable sheaths connected to the earthing system carry some of the fault current in the event of malfunction as a result of magnetic coupling. This effect is expressed by the reduction factor r. If overhead earth wires or cable sheaths are not connected, r = 1. Typical values for r given in Table 5-10 apply.

Table 5-10

Typical values for reduction factors r according DIN VDE 0101 at 50 Hz

earth connection		r
Earth wires of 110kV over head lines		
	Steel 50 – 70 mm²	0.98
	Al/St 44/32 mm²	0.77
	Al/St 300/50 mm²	0.61
10kV and 20kV cables, paper-insulated		
	Cu 95 mm²/1,2 mm lead cladding	0.2 – 0.6
	Al 95 mm²/1,2 mm aluminium cladding	0.2 – 0.3
10kV and 20kV single-core XLPE cable		
	Cu 95 mm²/16 mm² copper shield	0.5 – 0.6
110kV single-core oil cable		
	Cu 300 mm²/2,2 mm aluminium cladding	0.37
110kV gas pressure cable in steel tube		0.01 – 0.03
110kV single core XLPE cable		
	Cu 300 mm²/1,7 mm steel	
	Cu 300 mm²/35 mm² copper shield	0.32
400kV single-core oil cable		
	Cu 1200 mm²/1200 mm² aluminium cladding	0.01

The earthing impedance Z_E is derived from the parallel switching of the dissipation resistance R_A of the installation and the impedance Z_P of parallel earth electrodes (cable, overhead cables, water pipes, railway tracks etc.). The following is approximate:

$$Z_E = \left(\frac{1}{R_A} + \frac{1}{Z_P}\right)^{-1}$$

The dissipation resistance of the mesh earth electrodes of a switchgear installation can be calculated as follows:

$$R_A = \frac{\rho}{4}\sqrt{\frac{\pi}{A}}$$

Where:
ρ : specific resistance of the soil in Ωm
A: area of mesh earth electrode in m^2

The specific resistance of the soil varies considerably depending on the type of soil, the granularity, the density and the humidity content. Varying humidity contents may also result in temporary variations. The guidance values given in Table 5-11 (acc. DIN VDE 0101 amendment K (HD 637 S1)) apply for the specific resistance of various soil types. For further values see Table 3-9 (acc. DIN VDE 0228 and CCITT) in Chapter 3.

5

Table 5-12 shows guidance values for the parallel resistances Z_P of various earth electrodes. The values listed there only apply from a specific minimum length. The values for overhead lines only apply for steel towers.

The dissipation resistances of surface and deep earth electrodes can be seen in Figs. 5-9 and 5-10. The broken curve in Fig. 5-10 shows the results of a measurement for comparison.

Table 5-11

Specific resistivity of different soils

Type of soil	Specific resistance of the soil in Ωm
Boggy soil	5 to 40
Clay, loam, humus	20 to 200
Sand	200 to 2500
Gravel	2000 to 3000
Weathered rock	generally below 1000
Sandstone	2000 to 3000
Granite	to 50000
Ground moraine	to 30000

Table 5-12

Parallel resistances of earth electrodes

earth electrode type	Zp [Ω]	Minimum length km
overhead line with 1 earth wire St 70	3.2	1.8
overhead line with 1 earth wire Al/St 120/20	1.3	4.2
overhead line with 1 earth wire Al/St 240/40	1.2	5.4
overhead line with 2 earth wires Al/St 240/40	1.1	6.8
10-kV cable NKBA 3 × 120	1.2	0.9
Water pipe NW 150	2.3	1.5
Water pipe NW 700	0.4	3.0
Electric rail 1 track	0.6	8.0
Electric rail 2 tracks	0.4	6.9

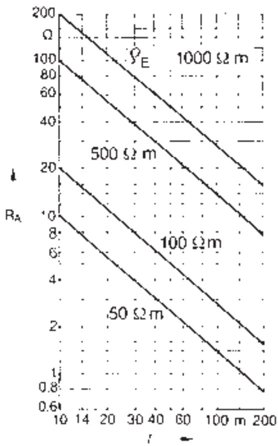


Fig. 5-9

Dissipation resistance R_A of surface earth electrodes (strip, bar or stranded wire) laid straight in homogenous soil in relationship to the length l with different resistivities ρ_E

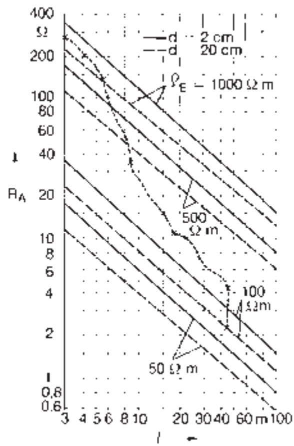


Fig. 5-10

Dissipation resistance R_A of deep earth electrodes placed vertically in homogenous soil in relationship to the electrode length l with various diameters and resistivities ρ_E, curve x ... x: Measured values

5.3.4 Earthing measurements

The resistivity ρ_E of the soil is important for calculating earthing systems. For this reason, ρ_E should be measured before beginning construction work for a switchgear installation; the measurements are made using a four probes measuring methode (e.g. according F. Wenner: A Method of Measuring Earth Resistivity, Scientific papers of the Bureau of Standards, No. 248, S. 469-478, Washington 1917).

Measuring the step and touch voltages after setup of a switchgear installation is one way to confirm the safety of the system; the measurements are conducted in accordance with the current and voltage method in DIN VDE 0101, Supplements G and N (HD 637 S1).

The current and voltage method also allows the earthing impedance (dissipation resistance) of the installation to be calculated by measuring the potential gradient.

Use of earth testers to measure dissipation resistance should be restricted to single earth electrodes or earthing systems of small extent (e.g. rod earth electrode, strip earth electrode, tower earth electrode, earthing for small switchgear installations).

5.4 Lightning protection

Damage caused by lightning cannot be completely prevented either technically or economically. For this reason, lightning protection facilities cannot be specified as obligatory. However it is generally agreed practice to provide lightning protection systems for outdoor switchgear installations and for the buildings of indoor switchboards.

The probability of direct lightning strikes can be greatly reduced on the basis of model experiments, measurements and years of observation with the methods described below.

5.4.1 General

A distinction is made between external and internal lightning protection.

External lightning protection is all devices provided and installed outside and in the protected installation to capture and divert the lightning stroke current to the earthing system.

Internal lightning protection is the total of the measures taken to counteract the effects of lightning stroke and its electrical and magnetic fields on metal installations and electrical systems in the area of the structure.

The earthing systems required for lightning protection must comply with DIN VDE 0101, with particular attention paid to the requirements for lightning protection in outdoor switchgear (e.g. back flashover).

Lightning arresters installed in an installation generally only protect the installation against incoming atmospheric overvoltages caused by a far remote lightning stroke on an overhead line (see Sec. 10.6). Overhead earth wires or lightning rods may be installed on the strain portals of the busbars and overhead lines as a protection against direct lightning strokes for an outdoor installation. Separate support structures may sometimes be required for this purpose. The overhead earth wires of the incoming overhead lines end at the strain structures of the outdoor installation.

Overhead earth wires and lightning rods must be corrosion-resistant (e.g. Al/St stranded wire, or hot-dip galvanized steel pipes, or bars for rods).

Key to symbols used

A		live part
B		overhead earth wire lightning rod
C	m	distance between lightning rods
H	m	height of earth wire height of lightning rod (height of capture electrode)
2H	m	twice the height of the earth wire
3H	m	three times the height of the lightning rod
h	m	height of live part over ground level (object height)
h_B	m	radius of lightning sphere, flashover distance to earth
h_x	m	lowest height of protected zone at midpoint between two lightning rods
L	m	distance overhead earth wire to equipment distance lightning rod to equipment
L_x	m	distance live part from axis of lightning rod (protected distance)
M		centre of arc for limitation of outer protective zone
M_1		centre of arc for limitation of inner protective zone
R	m	radius for M_1-B
r_x	m	radius for limitation of protected zone at height h

5.4.2 Methods of lightning protection

The lightning sphere principle

In practice for the design of lightning protection systems to prevent direct strokes on buildings, industrial plants, outdoor switchgear installations or overhead lines different methods are available, which are all based on the lightning sphere principle. The principle is demonstrated in Fig. 5-11. When the lightning sphere is rolled around the model on a flat surface, all objets below the sphere are in the protected area, as long as the sphere is in touch with the lightning capture devices. The principle is based on the experience that every lightning main discharge is initiated by a partial flash-over across the final gap between ground potential and the end of the discharge channel growing forth from the atmosphere. The length of this flash-over gap, which is decisive for the spatial positioning of the main discharge channel, depends on the energy content of the developing main discharge. The lightning sphere radius chosen for the sphere method, is equal to the smallest length of the gap of a final flash-over, which corresponds to the smallest main discharge current to be taken into account at the relevant location.

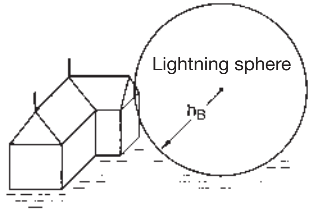


Fig. 5-11

Determining the effectiveness of lightning rods and conductors for protecting the building

The method according DIN V VDE V 0185

In DIN V VDE V 0185-3 (IEC 62305-3 is under consideration) four different classes are specified for designing a lightning protection system. This offers the chance to evaluate the importance of complete safety in relation to the expenditure needed. Different lightning parameters are coordinated to the four lightning protection classes. With respect to the protection performance of the capture electrodes this are: smallest main discharge current taken into account and lightning sphere radius h_B. Selecting these parameters could be based on long lightning statistics experience.

The lightning sphere radius is assumed in a fixed relation to the peak value of the main discharge current as per

$$h_B = 10 \cdot I^{0,65} \qquad h_B \text{ in m, } I \text{ in kA}$$

Table 5- 13

Minimum values of the lightning main discharge current and the relevant lightning sphere radius of lightning protection classes I to IV according DIN V VDE V 0185-3

Lightning capture parameters	Symbols	Units	Lightning protection class I	II	III	IV
Lowest main discharge current	I	kA	3	5	10	16
Lightning sphere radius	h_B	m	20	30	45	60

This table demonstrates how a nearly complete protection may be achieved, when a peak value of 3 kA is chosen for the lowest main discharge current to be taken into account. This requires a lightning sphere radius of 20m only and as a consequence a considerable more of capture electrodes and conductors than in case of a protection class IV system. All lightning strokes with a peak current value higher than the lowest current parameter value of the relevant lightning protection class will be caught by the capture electrodes and conductors and discharged to earth.

As further lightning parameters also the highest discharge energies to be expected have been coordinated to the lightning protection classes. These parameters are dimensioning for the protection system with respect to thermal and mechanical withstand. Here again we find the most challenging peak current value of 200kA in class I.

User and designer have to agree on the protection target and to select one of the protection classes I to IV according DIN V VDE V 0185-3.

The method according DIN VDE 0101 (HD 637 S1)

When building outdoor switchgear installations this method is in use already since many years. It is also based on the lightning sphere principle but simplified considerably with respect to the practical application. With this method the radius of the sphere is not chosen according to the lightning protection class, but it is based on the dimensions of the installation to be protected.

This method offers a nearly complete protection against lightning strokes.

The method described below for determining the protected zone of a high-voltage switchgear installation corresponds to the recommendations of DIN VDE 0101. It has the advantage of being simple for the designer to set the dimensions of the lightning protection facilities. It is the standard solution for installations of up to approximately 420 kV and protected zone heights of up to approximately 25 metres. For switchgear installations of higher voltage ratings or peculiar protection requirements user and designer have to find an agreement based on DIN V VDE V 0185.

5.4.3 Protected zones of overhead earth wires

The protected zone, which should enclose all equipment and also the transformers, is determined as shown in Fig. 5-12 or from a diagram (Fig. 5-13).

The sectional plane of the protected zone is bounded by an arc along an overhead earth wire as shown in Fig. 5-12, whose midpoint M_{2H} is equal to twice the height H of the earth wire both from ground level and from the overhead earth wire.

The sectional plane of the protected zone for two overhead earth wires, whose distance from each other is $C \leqq 2 \cdot H$, is shown in Fig. 5-12b. The outer boundary lines are the same as with one overhead earth wire. The sectional plane of the protected zone between the two overhead earth wires is bounded by an arc whose midpoint M_R is equal to twice the height 2H of the earth wire from ground level and is in the middle of the two overhead earth wires. The radius R is the distance between the overhead earth wire B and the midpoint M_R.

The angle between the tangents to the outer bounding lines and the perpendicular line is 30° at the point where the bounding lines meet the earth wires. If an angle of around 20° is required in extreme cases, the distance 1.5H must be selected instead of the distance 2H.

The arrangement of the overhead earth wires for a 245 kV outdoor installation is shown in Fig. 5-12 c. The bounding line of the protected zone must be above the live station components.

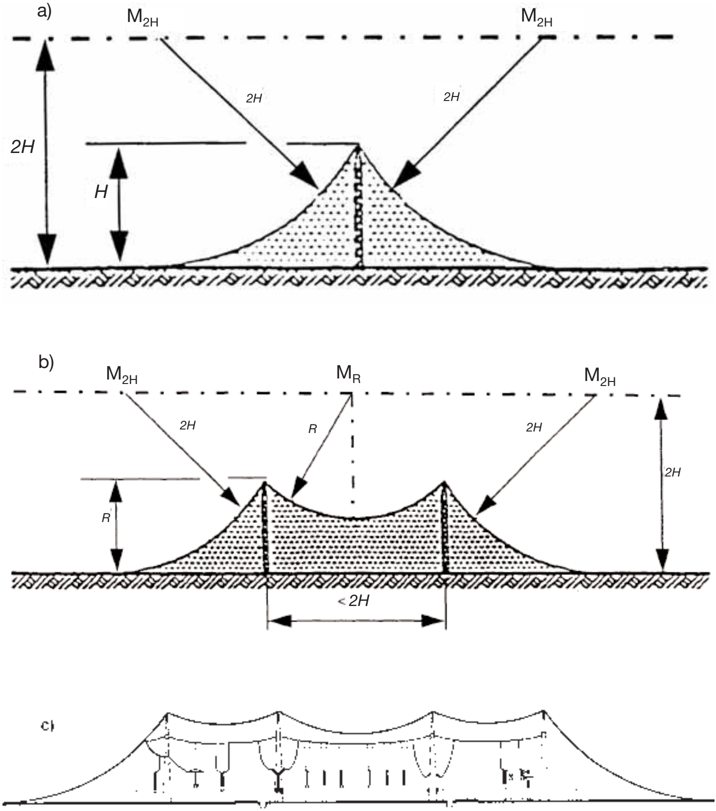


Fig. 5-12

Sectional plane of the protected zone provided by overhead earth wires:
a) sectional plane of the protected zone with one overhead earth wire,
a) sectional plane of the protected zone with two overhead earth wires,
c) arrangement of the overhead earth wires and protected zone of an outdoor switchgear installation.

The height H of the overhead earth wire can be calculated from Fig. 5-13. The curves show the sectional plane of the protected zone one overhead earth wire.

Example: equipment is installed at a distance of L = 12.5 m from the overhead earth wire, with the live part at height h = 9.0 m above ground level: The overhead earth wire must be placed at height H = 23.0 m (Fig. 5-13).

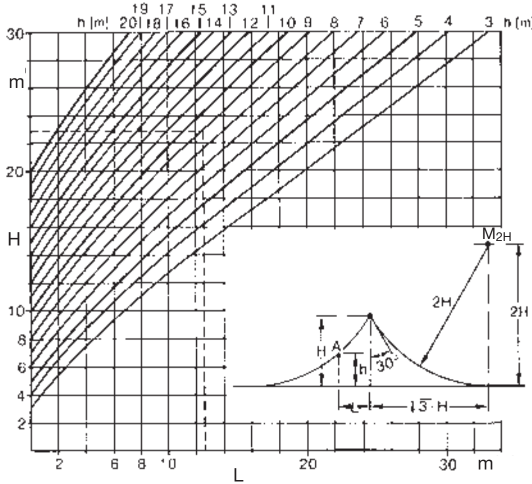


Fig. 5-13

Sectional plane of the protected zone for one overhead earth wire

5.4.4 Protected zones of lightning rods

Experience and observation have shown that the protected zone formed by rods is larger than that formed by wires at the same height since the partial flash-over discharges across the final gap (streamer) of the lightning path start earlier with rods than with earth wires.

A lightning rod forms a roughly conical protected zone, which in the sectional plane shown in Fig. 5-14 a) is bounded by the arc whose midpoint M_{3H} is three times the height H of the rod both from ground level and the tip of the lightning rod.

The area between two lightning rods whose distance from each other is $\leqq 3 \cdot H$ forms another protected zone, which in the sectional plane shown in Fig. 5-14 b) is bounded by an arc with radius R and midpoint M_R at $3 \cdot H$, beginning at the tips of the lightning rods.

Due to the simple relation between the heights of the midpoints and earth wires or lightning rods a simple graphic solution is possible. If necessary the height may be varied until all of the equipment to be protected is inside the protected area. Further by selecting either earth wires or rods an optimised solution may be developed if the types of electrodes has not been specified.

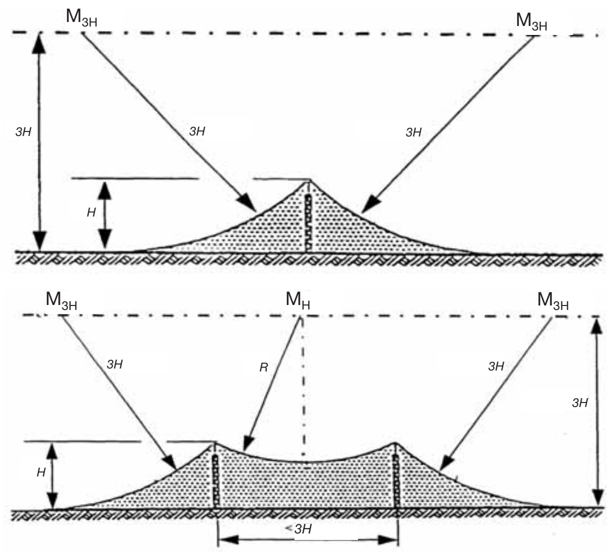


Fig. 5-14

Sectional plane of the zone protected by lightning rods: a) sectional plane of the protected zone with one lightning rod, b) sectional plane of the protected zone with two lightning rods.

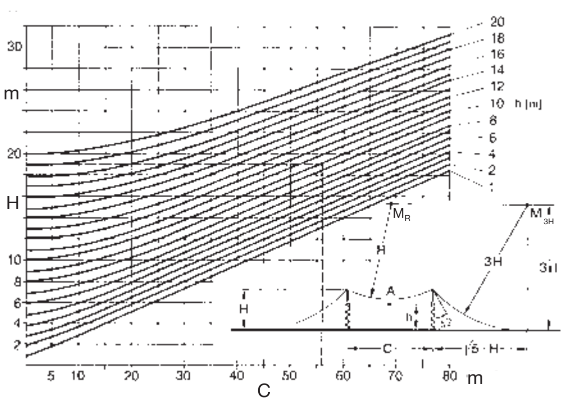


Fig. 5-15

Sectional plane of the protected zone for two lightning rods

The height H of the lightning rod can be calculated from Fig. 5-15. The curves show the protected zone for two lightning rods.

Example: equipment is centrally placed between two lightning rods, which are at distance C = 56 m from each other; the live part is at height h = 10.0 m above ground level: the lightning rods must be at a height of H = 19.0 m (Fig. 5-15).

The width of the protected zone L_x – at a specific height h – in the middle between two lightning rods can be roughly determined from Figs. 5-16 a) and 5-16 b) and from the curves in Fig. 5-16 c).

Example: equipment is centrally placed between two lightning rods at distance L_x = 6.0 m from the axis of the lightning rods; the live part is at height h = 8.0 m above ground level: When the lightning rods are at a distance of C = 40.0 m the height of the lightning rods must be H = 18.5 m (Fig. 5-16).

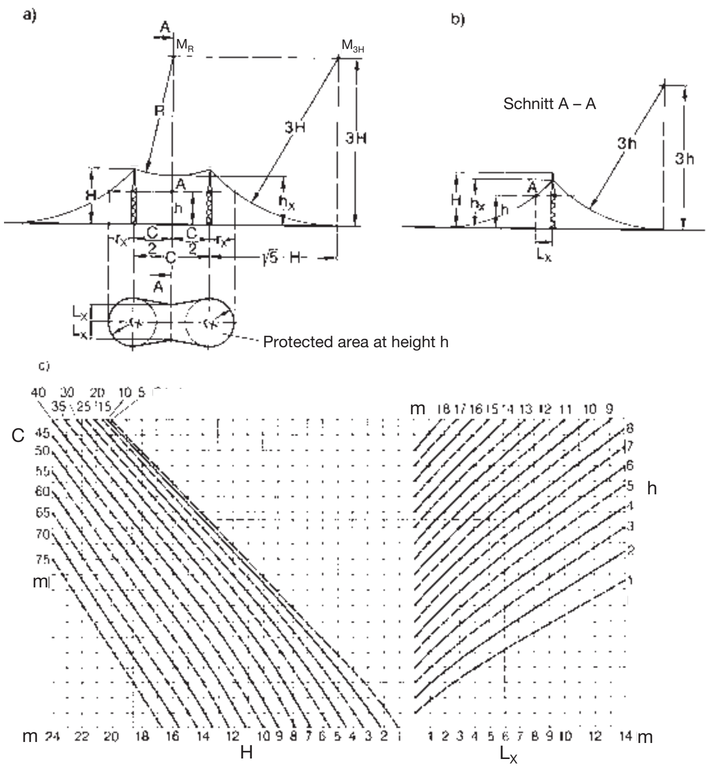


Fig. 5-16

Protected zone outside the axis of 2 lightning rods

5.5 Electromagnetic compatibility

The subject of electromagnetic compatibility (EMC) can be divided into two separate topics,

– the effects of electromagnetic fields on biological systems, particularly on humans, and

– electromagnetic compatibility of electrical and electronic systems.

Effects of electromagnetic fields on humans

The effects of electromagnetic fields on human beings have been investigated in numerous studies, and no injurious effects have been found from field intensities such as occur in practice in the transmission and distribution of electrical energy.

As the effective mechanisms are dependent on frequency, the effects of electromagnetic fields on humans are divided into a low-frequency range (0 Hz to 30 kHz) and a high-frequency range (30 kHz to 300 GHz). Limits or „approved values" have already been established for both ranges. The low-frequency range is of primary interest for the operation of switchgear installations. The work of standardization in this area is, however, still not complete.

In the low-frequency range, the current density occurring in the human body is the decisive criterion for setting the limit values. According to a study by the World Health Organisation (WHO), interaction between current and muscle and nerve cells occurs above a body current density of 1000 mA/m^2, with proven acute danger to health in the form of interference with the functioning of the nerves, muscles and heart. The lowest limit for perceivable biological effects is approximately 10 mA/m^2. Current densities below 1 mA/m^2 have no biological effects.

The governing law in Germany is the 26th Federal Regulation on the Federal Pollution Control Act (26th BImSchV, in force since 1 January 1997 for generally accessible areas without limitation on time of exposure for fixed installations with voltages of 1000 V and above). This regulation follows the recommendations of the International Commission on Non-Ionizing Radiation Protection (ICNIRP).

In 26th BImSchV, a body current density of 1-2 mA/m2 at 50 Hz was selected as the basic value for the derivation of approved field quantities. This yields permissible values of 5 kV/m for the electrical field and 100 μT for the magnetic flux density. These may be exceeded in the short term by up to 100% for a duration which is no longer than 5% of the assessment period in one day, and by no more than 100% in small spaces outside buildings.

26th BImSchV applies to all facilities for the transmission and distribution of electrical energy with voltages of 1 kV and above, for all generally accessible areas within those facilities and in their immediate vicinity. For all other areas in which electrical, magnetic or electromagnetic fields can occur, DIN VDE 0848-1 (2000-08) and DIN V VDE V 0848-4/A3 (1995-07) stipulate permissible values for the 0 Hz to 30 kHz range. DIN VDE 0848-44/A3 distinguishes between two exposure zones.

Exposure zone 1 comprises those areas in which persons are exposed to fields as a result of their work, or where a brief stay is otherwise ensured. Depending on the duration of the effects, basic levels of body current density of up to 10 mA/m^2 are permitted in exposure zone 1.

Exposure zone 2 comprises all areas in which not only short-term exposure can be expected, such as areas with residential and communal buildings, individual residential plots, grounds and facilities for sports, leisure and recreation, and places of work in which field generation is not expected in normal use. Body current densities of up to 2 mA/m^2 are permitted for exposure zone 2, although these were only exploited to around 50% in the stipulation of the corresponding permissible field intensities at 50 Hz.

Permissible field intensities at 50 Hz in exposure zones 1 and 2:

		Electrical field intensity	Magnetic flux density
Exposure zone 1	1h/d	60 kV/m	4240 μT
Exposure zone 1	2h/d	40 kV/m	2550 μT
Exposure zone 1	continuous	21.32 kV/m	1358 μT
Exposure zone 2		6 kV/m	424 μT

There are also regulations issued by the employers' liability insurance organizations on health and safety at work (BGV B11, 1999). These regulations follow the stipulations of DIN V VDE V 0848-4/A3.

The permissible field intensities were set with close attention to the effects perceivable in the body. High safety factors (100 – 500 x) were maintained in relation to the field strengths at which hazards to health are demonstrably to be expected. On account of the complex interactions between electrical, magnetic and electromagnetic fields on the one hand and the biological systems on the other hand, demands are frequently made for the permissible field intensities to be reduced. The results of studies available to date, however, for example with regard to the occurrence of carcinomas, provide no indication that this would be appropriate.

Readings in the field taken for instance under a 380 kV overhead line at the point of greatest sag, recorded a magnetic flux density of 15 to 20 μT (at half maximum load) and an electrical field intensity of 5 to 8 kV/m. The corresponding levels are lower with 220 kV and 110 kV lines. No notable electric fields occur outside metal-enclosed switchgear as a result of its design. The magnetic field also remains significantly below the limits set in 26^{th} BImSchV, even at full load.

Pacemakers and other implants may be influenced by electrical and magnetic fields. It is difficult to predict the general sensitivity of these devices. 26^{th} BImSchV – as expressly stated in section 1 – does not take account of the effects of electromagnetic fields on implants, nor do standards set down any binding stipulations. DIN VDE 0848-3-1:2002-05 (currently still a draft) explains the relationships between the field intensities at the location and the resulting disturbance voltages at the implant. The requirements of disturbance (voltage) thresholds and insensitivity of the devices to low frequency magnetic fields are deduced from these. The levels applicable to devices currently in use must be clarified in each individual case. Especially when implantees intend to expose themselves to the approved high limit values for workplace exposure, a careful check is to be made in conjunction with the manufacturer of the device.

Electromagnetic compatibility of electrical and electronic systems

Electromagnetic compatibility is the requirement for a device or component to function satisfactorily without causing interference (active EMC) and without being interfered with (passive EMC) (DIN VDE 0870-1).

The basis of this requirement is the EU Directive on Electromagnetic Compatibility (89/336/EEC 1989), which has been implemented in German law by the EMC Act (EMVG, 1998). For the protection of consumers, this directive requires that products may only be put on the market when they comply with the basic requirements for health and safety. The directive draws attention to the importance of harmonized standards in facilitating demonstration that products comply with the directive's protection aims. The standards however retain the status of non-binding texts, i.e. compliance with them confers upon the products a „presumption of conformance" with the protection aims.

The enshrinement of EMC requirements in directives and laws results on the one hand from increasingly compact designs which can increase the mutual interference between devices and on the other hand from the increasing use of electronic and power electronic components which can simultaneously cause and be affected by disturbances.

In the terms of Section 2, paragraph 9 of the EMC Act, „electromagnetic compatibility is the capacity of an electrical device to function satisfactorily in its electromagnetic environment without itself causing electromagnetic interference which would be unacceptable for other devices in that environment." In Section 3, paragraph 1, the protection requirements include the „operation of radio and telecommunications equipment and other devices in accordance with the regulations…" and an „…appropriate resistance to electromagnetic interference." The possible disturbances and their causes are extremely complex. This applies equally to the causes and the coupling mechanisms.

Figure 5-17 illustrates the complexity of the interrelationships.

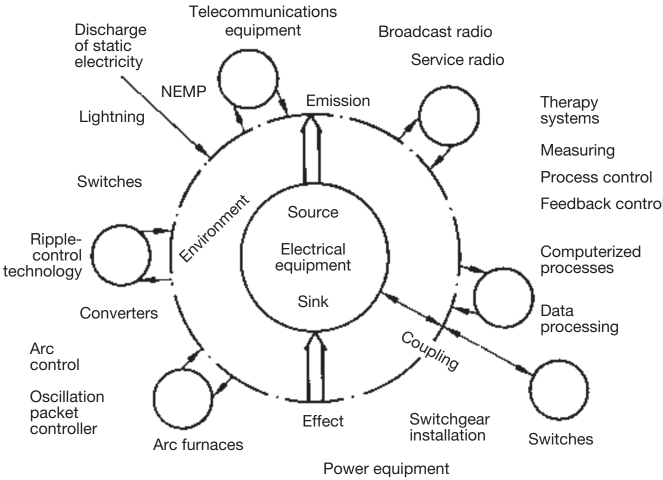


Fig. 5-17

Multilateral interference model

The EMC Act first makes a quantitative description of the emitted interference and of the electromagnetic immunity necessary, and then raises demands for testing and demonstration of results achieved with regard to EMC, and the assessment of those results.

Manufacturers of electrical components and systems are required to fulfil the specific requirements on EMC which may be integrated in various product standards or product family standards, depending on the type of product. Where no such standards exist, basic specifications which define limits for emitted interference and electromagnetic immunity are to be used.

In contrast to the product standards with which manufacturers are normally familiar, the basic specifications are general in character. This can be illustrated by the example of IEC 61000-6-2 (VDE 0839 Part 6-2) which, as a basic specification, defines the electromagnetic immunity requirements for equipment in industry. It is already stated in the section on applicability of the standard that it applies to equipment for which no specific product standard or product family standard is available. If a specific product standard or product family standard exists, „that standard shall have priority over this basic specification in all respects." The general character of the specification again becomes apparent in the assessment of test results: „The variety and diversity of the (…) equipment make it impossible to determine precise criteria for assessment of the results of electromagnetic immunity tests. If the device (…) becomes hazardous or unsafe, it is to be assumed that the device (…) has not passed the test."

In contrast, the descriptions in the product standards are much more precise. IEC 60439-1 (VDE 0660 Part 500) for example stipulates which acceptance criteria are decisive in the overall behaviour and functions of main and control circuits, annunciators and sensors which process signals and information. In contrast to type tests, for instance of temperature rise behaviour, „soft" acceptance or performance criteria are stipulated for electromagnetic immunity, against which a decision is made on whether a test specimen meets the requirements. For the function of displays and annunciators, for example, performance criterion B, „temporary visible changes or loss of information content; inadvertent lighting up of LEDs" is stipulated as acceptable. The range of interpretations of such a criterion is doubtless greater than when a specified limit temperature is exceeded.

In the selection of test specifications it is advisable to use harmonized standards – where these exist – on the basis of the provisions in Section 6 (2) of the EMC Directive: „The compliance of equipment with the relevant harmonised standards whose references have been published in the *Official Journal of the European Union* shall raise a presumption, on the part of the Member States, of conformity with the essential requirements referred to in Annex I to which such standards relate. This presumption of conformity is limited to the scope of the harmonised standard(s) applied and the relevant essential requirements covered by such harmonised standard(s)."

The EU Directive on electromagnetic compatibility and its national implementation in the EMC Act define the framework within which components, devices and systems may move with respect to their emissions and electromagnetic immunity. It remains however the prerogative of the manufacturer and/or installer to decide the way in which compliance with the limits can be established by EMC measures.

Numerous stipulations and design rules can however contribute to preventing or at least minimizing interference. In this context, attention is drawn to IEC 61000-5-5 and -5-7 (VDE 0847 Parts 5-5 and 5-7), which deal with installation guidelines and possible remedies.

The electromagnetic environment of a device is represented by the sum of all prevailing disturbances and the coupling paths (Figure 5-17). As the device can however also emit electromagnetic fields, there is mostly interaction in practice.

Ensuring electromagnetic compatibility (EMC) is essential at every phase of a switchgear installation project and extends from establishing the electromagnetic environment through selecting the suitable products and systems and checking the measures required to maintaining control over planning and changes or extensions to the installation. The electromagnetic environment is divided into Environment (Class) A and Environment (Class) B. Environment A refers to non-public or industrial low voltage networks, and Environment B to public low voltage networks. In the case of an actual fault, i.e. when there is impermissible interference, the bilateral interference model as shown in Figure 5-18 is sufficient to clarify the circumstances.

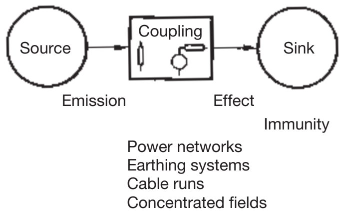


Fig. 5-18

Bilateral interference model

The interference variables and coupling paths must be known for performance of the analysis and implementation of countermeasures as described in Table 5-14.

Table 5-14

Schedule of activities in connection with EMC

Analysis
- Identifying sources of interference
- Determining interference quantities in terms of amplitude and frequency range
- Calculating/estimating/measuring coupling paths
- Determining the interference immunity of interference sinks (e.g. in secondary equipment)

Countermeasures
- Measures at interference sources
- Measures on coupling paths
- Measures at interference sinks

5.5.1 Origin and propagation of interference quantities

The interference quantity is a collective term that covers the actual physical terms of interference caused by voltage, current, signals, energy etc. (DIN VDE 0870-1). Interference quantities are caused by natural interference sources (lightning, atmospheric noise, etc.) and by artificial interference sources. The artificial interference sources can be further divided into intended signals (communications systems, induction furnaces, etc.) and unintended signals (switching operations, pulse edges in IT systems, etc.).

The term „interference" expresses the intention of considering the quantity in question in terms of its possible interference effects. A useful signal can inadvertently lead to disturbances elsewhere, and, depending on the apparatus concerned, be regarded in one case as a useful signal and in the other case as an interference signal. Figure 5-19 shows an overview of the most important interference sources in switchgear installations and their interference quantities and coupling paths.

Interference signals may be classified by origin, or also by their emission spectrum.

Periodic, sinusoidal interference quantities

These occur in power engineering in the form of carrier signals and ripple control signals. These interference quantities have a narrow frequency band with a discrete interference spectrum. Narrow-band and discrete mean here that the interference can in most cases be assigned to a single frequency.

Harmonics of the system voltage caused by non-linear loads (fluorescent lights, power packs, power electronics, etc.) mostly have a broad frequency band with a discrete interference spectrum. Broad-band and discrete mean that the interference is to be assigned to individual frequencies, between which however there is no interference amplitude. One example is the integer multiples of the basic frequency emitted into the network as a consequence of the switching processes in frequency converters. A Fourier transformation permits determination of the amplitude spectrum, i.e. which amplitude is to be assigned to which frequency. This relatively complex mathematical calculation is nowadays integrated in many measuring and recording instruments as a discrete Fourier transformation.

Other interference quantities

These occur in switching operations with a more or less steep transition from one switch status to the other. They can for example occur continuously in a broad frequency band in the so-called „brush fire" of brush motors, and are to be classified as permanent interference in those cases. Continuous means that this interference evenly occupies a broad frequency range with different amplitudes. It can however also become apparent as temporary interference resulting from switching or discharge processes, and is then referred to as a transient interference quantity.

The interference quantities which arise in the highly frequent switching operations on the high voltage (primary) side of switchgear are summarized in Table 5-15. They oscillate at high frequency.

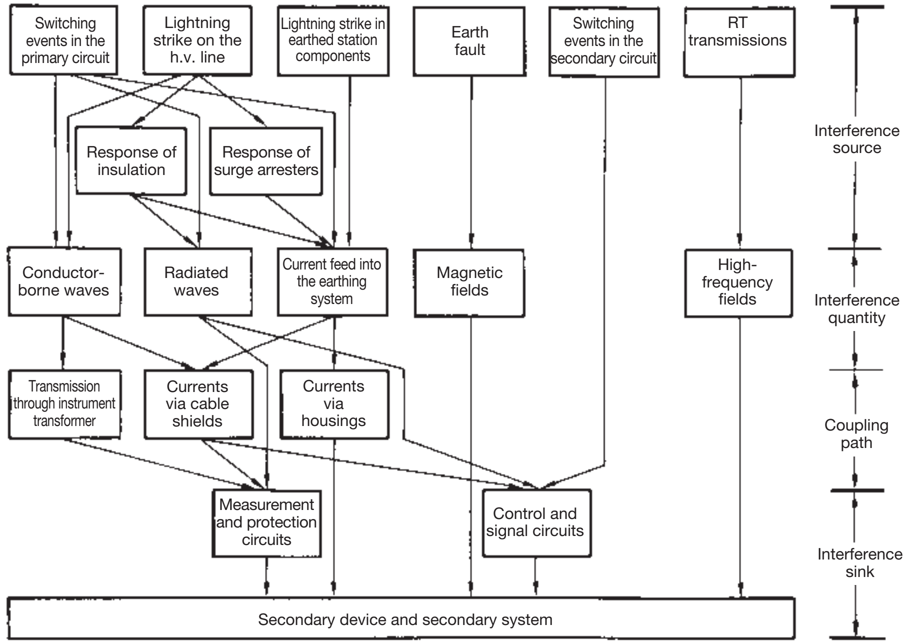
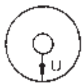
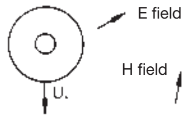
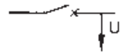
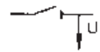


Fig. 5-19

Origin and propagation of interference quantities in switchgear installations.

Table 5-15

Characteristic parameters of interference quantities with switching operations in the primary circuit of high-voltage installations

SF_6 Gas-insulated switchgear (GIS)					Conventional outdoor switchgear installation (AIS)			
					 SF_6 Self-blast circuit breaker	 disconnector		
Quantity	Voltage U	Voltage U_K	E field	H field	Voltage U	Voltage U	E field	H field
Rise time Frequency Height Damping Geometrical distances	4 – 7 ns kHz – 10 MHz system-specific weak small	15 – 50 ns MHz system-specific strong large	 up to 20 MHz 1[1] – 50[2] $\frac{kV}{m}$ strong	 up to 20 MHz 2.5[1] – 125[2] $\frac{A}{m}$ strong	50 – 100 ns kHz – MHz system-specific strong large	200 ns kHz – MHz system-specific strong large	180 – 700 ns 5[3] – 50[4] $\frac{kV}{m}$ strong	60 – 100 ns 1[3] – 2[4] $\frac{A}{m}$ strong

[1] GIS with building
[2] GIS without building

[3] 345-kV breakers
[4] 500-kV breakers

Coupling mechanisms

The propagation of interference quantities and therefore their injection in other systems can take place
– galvanically,
– inductively,
– capacitively, or
– electromagnetically.

Galvanic coupling

If common return lines are used, changes in the current consumption of an assembly are transmitted as interference voltage across the impedance of the common return to the other systems which also use that return. Measures to reduce interference include electrical isolation, especially of circuits with extremely different signal levels, large conductor cross-sections, and separate reference conductors in parallel lines.

A further possible coupling results from earth loops which may be present intentionally or unintentionally. Measures to reduce interference here may comprise the installation of an earth potential surface or use of a solid equipotential bonding conductor, use of an isolating transformer or an optocoupler. The increasing problems of data processing systems with power supply from TN-C networks are also to be assigned to this type of coupling.

Inductive coupling

Adjacent conductor loops through which current flows are linked together magnetically by the coupling inductance of the magnetic field which is created by the current. The current flow and its changes create a voltage signal proportional to the frequency or to the rate of change and the coupling inductance.

Measures to reduce interference include the sole use of short parallel conductors, increasing the spacing, orthogonal arrangement of the conductor loops, twisting the cables for signal lines, and shielding the system which is subjected to the interference.

Capacitive coupling

Adjacent conductor loops are electrically connected by the coupling capacitance. As a result, potential differences proportional to the frequency or rate of change and the coupling capacitance and earthing impedance of the system subjected to interference are transmitted.

Measures to reduce interference include the sole use of short parallel conductors, increasing the spacing, use of lower earthing impedances in the more sensitive system and insertion of a cable shield.

Electromagnetic coupling

Electromagnetic waves can be emitted and absorbed. The field strength is proportional to the power of the interference source. Countermeasures can be taken at the system affected by the interference in the form of increasing the distance from the interference source and of suitable shielding.

The propagation of interference is influenced by damping and dispersion effects. Signal damping weakens the signal amplitude with increasing distance from the origin. Dispersion leads to a frequency-dependent propagation velocity of the interference. The interaction of these two effects leads, in the case of conductor-borne interference, to the splitting of an initially steep-edged pulse with decreasing amplitudes as the distance increases. On the other hand, the spectral energy density of the interference quantity induces natural oscillations in the entire system transmitting it; see Figure 5-20.

An interference quantity arises in a circuit whose conductors have impedances (predominantly capacitances) against earth. In this way, the interference quantity finds paths to earth or reference earth. The results are symmetrical (differential mode) and asymmetrical (common mode) interference voltage components.

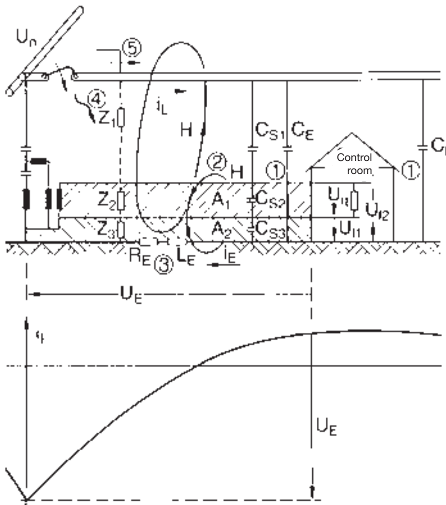


Fig. 5-20

Coupling mechanisms for interference quantities in a high-voltage switchgear installation

U_{l1}, U_{l2} components of longitudinal voltage, U_q transverse voltage

① *Capacitive coupling, C_E capacitance of high-voltage conductor to earth grid, C_{S1}, C_{S2}, C_{S3} capacitances of the secondary system conductors*

② *Inductive couplings, H influencing magnetic fields, A_1, A_2 induction areas*

③ *Galvanic coupling, R_E, L_E resistivity and inductivity of the earth grid, i_E current in earth grid resulting from coupling over C_E*

④ *Radiation coupling*

⑤ *Surge waves U_E from transient processes, Z_1, Z_2, Z_3 wave impedances*

5.5.2 Measurement of interference quantities

Measurement and quantification of interference quantities are the basis for providing evidence of compliance with the limits set down in specifications. Measurement is normally applied to interference voltages or currents, interference power and interference field intensity.

Interference voltages and currents

An object to be tested emits interference through power and/or data lines. This interference, acting as currents, will bring about an interference voltage drop at the internal impedance of the system. As the system impedances are highly dependent on their environment, the interference currents can cause different interference voltages depending on the location. For this reason, artificial networks whose structure is described in the relevant standards are used. Use of the artificial network first achieves decoupling from the supply system, so that any interference voltages present in the system do not impair the measurements. In addition, the artificial network represents a defined impedance, by means of which the emitted interference currents produce a defined and reproducible voltage drop. The frequency range for these measurements extends to around 30 MHz. This limit is fundamentally dependent on the geometrical dimensions of the object measured. If the dimensions reach around half of the wavelength of the interference signal, the signal is increasingly radiated. With further increases in frequency, therefore, measurement of interference voltage does not produce reliable results.

Interference field intensity

If the dimensions of the interference source including its connecting cables reach around half the wavelength, radiation of interference in the form of electromagnetic waves starts and increases. This radiation can be recorded as high frequency interference voltage on a measuring receiver with a suitable antenna. The measuring site must be as level as possible. If, as an alternative, the measurements are performed indoors, reflections from walls or ceilings are to be avoided by using absorber cones or ferrite cores.

Interference power

Measurement of the interference field strength is relatively complex. If the device dimensions are small in relation to the wavelength, radiation predominantly takes place via connecting lines. As an alternative, therefore, interference power measurement can be performed using the measurable interference current in the conductor in connection with the conductor impedance. The measurement is performed with an absorbing clamp, in which ferrite cores prevent reflections of emitted interference in the clamp and exclude interference present in the supply network from the measuring station.

5.5.3 EMC measures

EMC must be planned quantitatively. This means that the interface requirements (emission, immunity) must be specified for defined zones (EMC zones).

In the best case, the requirements for electromagnetic immunity can be fulfilled directly, i.e. without any further action.

If, however, these requirements are not fulfilled, additional measures are necessary, and these are in principle to be applied in the sequence of the interference source, coupling path and interference sink.

It is useful to assess the hierarchical elements of a system, such as the complete plant equipment, room, cubicle assembly, rack assembly, circuit board, circuit section and component, with respect to their electromagnetic environments on the various levels. It should be noted in this context that the persons and organizations responsible for the individual products bear responsibility for those levels. See figure 5-21.

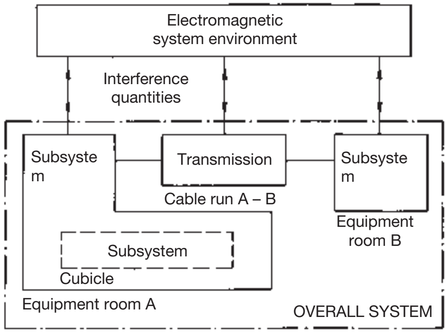


Fig. 5-21

EMC zones in their environment

The purpose of EMC measures is to reduce interference quantities at specific points between the point of origin (interference source) and the point of functional effect (interference sink). See table 5-16.

Table 5-16

EMC measures at the interference source, coupling path and interference sink

Zone	Source	Coupling path	Sink
Objective	Reduction in interference emission	Reduction in coupling interference	Increase in Immunity
Technical measures	Low inductance earthing	Avoidance of earth loops	Filtering
	Shunting of relay coils	Reduction in earth current impedance	Use of optocouplers
	Separate energy supplies for highly different power consumptions	Short distances with parallel conductors	Separate energy supplies for highly different power consumptions
	Lower earthing impedance	Increased spacing	Lower earthing impedance
	Pulse frequency only as high as necessary	Use of cable shield	Twisting of conductors
		Use of ferrite cores	Shielding
		Electrical isolation	
		Symmetrical signal transmission	
		Signal transmission by optical fibres	
Organizational measures	Separation of interference sources and interference sinks Use of fault-tolerant protocols		

The effectiveness of any measures must be assessed depending on the frequency; the relationship between the extension of a configuration and the frequency of the interference quantity leads to limit frequencies as shown in table 5-17. Above the upper limit frequency, radiation of interference increases, making conductor-borne measures ineffective. A rule of thumb for the limit frequency is the Lambda/10 rule (conductor length ≈ 1/10 wavelength). This assessment is to be applied to the length of earthing conductors, cable shields and their connections, to the side lengths and openings of shielding enclosures and to the grid size of bonding systems.

Table 5-17

Limit frequencies for the effectiveness of measures

Zone	Upper limit frequency	Max. length
Switchgear installation	100 kHz	300 m
Building	1 MHz	30 m
Equipment room	10 MHz	3 m
Cubicle	15 MHz	2 m
Device (rack – circuit board)	100 – 1000 MHz	30 – 3 cm

Decoupling measures

The interference level of an interference source acting on an interference sink can be reduced by a number of measures. In most cases, a single type of decoupling measure is not sufficient to achieve the required decoupling damping; several types of measures must be applied in combination.

Depending on the design in practice, the following list of options should be considered:

– Routing:
  Lines of different interference levels laid separately, minimum spacing > 0.2 m, avoidance of common lengths. Classification in cable categories: Category 1 for power cables, category 2 for data cables and category 3 for antenna and video cables. Assignment to a cable category takes account of the sensitivity of the connected interference sinks.

– Conductors:
  Two-wire lines instead of common returns, symmetrical signal transmission with symmetrical source and sink impedances.

– Potential isolation:
  Galvanic isolation of the signal circuits at the system boundary, attention to parasitic coupling properties of the isolating components.

– Equipotential bonding:
  By low-impedance connection of systems or circuit sections between which the potential difference should be as low as possible; basic requirement for effectiveness of shielding, filtering and limitation.

– Shielding:
  Usable on transmitters, conductors and receivers to avoid emissions and immissions. It must be clarified whether the shields are to be used to compensate for electrical, magnetic or electromagnetic influences.

– Filtering:
  Generally low-pass filters with concentrated components, located in the vicinity of the interference sink to dampen conductor-borne interference propagation.

– Limitation:
  Voltage-limiting components (surge arresters) to limit the voltage, but less influence on steepness; source of new interference quantities because of non-linearity; more for protection against destruction than to avoid malfunction.

Decoupling measures are only effective in restricted frequency ranges (see Figure 5-22).

This makes it all the more important to know what frequency range requires the greatest decoupling damping. It is also possible to combine different decoupling measures in series. The basic rule is to apply decoupling measures in the direction of propagation of the interference quantity

– from the interference source to the environment with the decoupling of high frequencies, and

– from the environment to the interference sink with the decoupling of low frequencies.

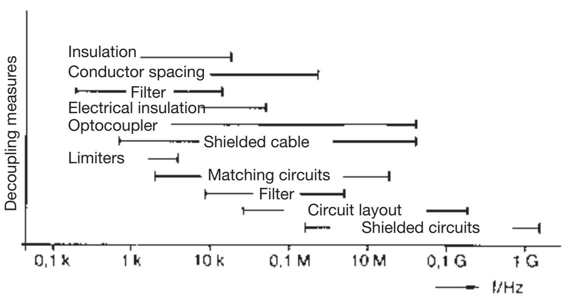


Fig. 5-22

Effectiveness trend of decoupling measures with respect to preferred frequency ranges

Bonding system

The basis of decoupling measures between the parts of an installation and its environment is an equipotential bonding system with good conductive properties.

In this system, all the relevant electrically conductive parts of an installation are connected to a reference potential (chassis earth). For operation of the installation as intended, current-carrying parts of the installation are conductively connected together and to that reference potential (bonding). If the reference potential is conductively connected to an earthing electrode, this constitutes either functional earthing (telecommunications engineering, DIN VDE 0300, 0804) or operational earthing (low voltage systems). Functional earthing can also be applied with a protection function (in connection with low voltage) and must then satisfy the relevant requirements set out in Section 5.1. Equipment enclosures which belong to the reference potential system can be designed in such a way as to constitute an equipotential envelope which shields the device from the emergence and ingress of electrical interference fields.

Telecommunications equipment in particular can be operated with functional earthing. In this case, the earthing has the purpose of enabling the required function of an electrical system. The functional earthing also includes operating currents of those electrical systems that use the earth as a return. An equipotential bonding between system parts intended not only for protection against unacceptably high touch voltages but also for electromagnetic compatibility must have sufficiently low resistivity even in the high frequency range in which the line inductance is dominant. This can be done by designing the bonding system as a mesh configuration, which reduces the inductance by up to 5 times more than linear systems. The effectiveness of this measure for high frequencies is limited by the width of the meshes of the grid (see Table 5-17).

The leakage currents from limiters, filters and shields must be considered in the design of a bonding system and coupling must be avoided in signal circuits. Extended conductors, which of course include conductors for equipotential bonding, are also subject to electromagnetic interference quantities. Coupling of a conductor-borne electromagnetic wave is reduced as the effective area of the receiving conductor increases. The inductive coupling with meshed conductors is reduced by generating opposing fields around the conductors of the mesh. Therefore, meshed systems, combined with their effective capacitance, particularly with the influence of the enclosure earths installed over them, have an excellent stable potential in whose vicinity the influence on the signal lines is low, similar to laying them in natural soil with its natural electrical conductivity.

The more extended a system, the more difficult is it to implement a continuous ground plane. For this reason, such grounds are only hierarchical, corresponding to the EMC zones, and must be consistently linked to the entire bonding system with consideration of their limit frequency.

The bonding system is to be set up in accordance with the following specifications:

- EN 50178 (VDE 0160) for power installations with electronic equipment
- DIN VDE 0800 ff. for the installation and operation of telecommunications systems including data processing systems
- EN 41003 (VDE 0804-100) for special safety requirements of devices for connection to telecommunications networks

In this case, a hierarchical, radial earthing design offers advantages for decoupling the subsystems and systems with respect to interference.

DIN VDE 0800 and 0804 deal with the requirements of more extended data processing systems where the levels handled are generally of the same order of magnitude, and interference by common conductors is not anticipated.

For more general reasons, for installation of systems structures intended (radial or mesh) may be specified for the bonding system. It is possible to use radial substructures in a meshed bonding system with no further special action.

If a radial bonding system is specified (Figure 5-23), the earths of the subsystems must only be connected together over the common equipotential bonding. This means that the following configurations are not permitted when signals are exchanged between subsystems:

– Shielding connected at both ends.

– Signal exchange with reference to a common signal reference conductor connected to the earth at both ends.

– Signal exchange over coaxial cable connected to earth at both ends.

This means that signal connections between subsystems in a radial bonding system must always be isolated.

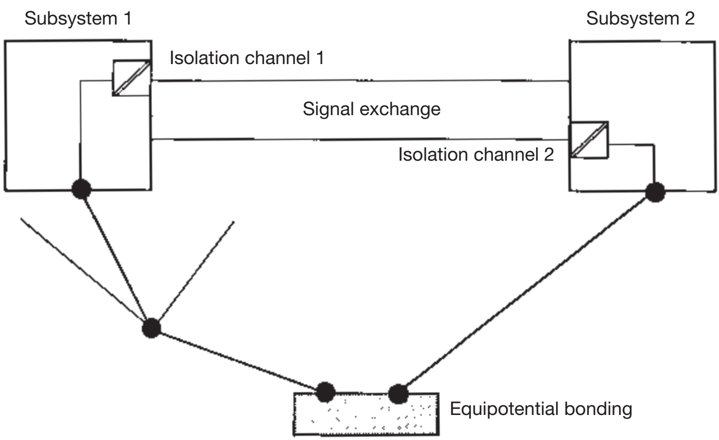


Fig. 5-23

Two subsystems in a radial bonding system

Shielding

On design of the shield, it must first be clarified whether the shielding is to block only electrical fields or also magnetic fields. Magnetic shields must be of material with a high conductivity and sufficient material thickness. The functional principle is based on two effects: The penetrating field induces currents which work to counteract their cause (the penetrating field) and thus partly compensate for it. There is also reflection of incoming field waves. The damping thus comprises absorption and reflection damping, and is dependent on the frequency, the conductivity, the permeability, the wall thickness and the geometry.

With respect to its effect, the shielding must initially be considered as the influenced conductor. Coupling interference quantities into this conductor yields a current that generates a voltage between the inner conductor and shield as a product of the shield current and the complex shield resistance. The complex shield resistance is identical to the shield-coupling resistance. The lower the shield resistance, the greater the decoupling effect of the shield.

In practice, it is essential to include the resistance of the entire shield circuit, i.e. also the shield connection, in the calculation. A shield that is connected to reference earth at just one end only acts against the capacitive interference. It then forms a distributed low-pass filter whose full capacitance acts at the end of the line to which the shield is connected. The interference coupling tends to increase at the open end of the shield, which becomes particularly evident at high interference frequencies.

If a shield can only be earthed at one end, this should always be the point of lower interference immunity. This is often the receiver, amplifier or signal processor side.

A shield earthed at both ends closes the current circuit around the area carrying a magnetic flux. A current that acts against the interference field according to Lenz's law is induced and so has a decoupling effect on the conductors of the shielded cable. This effect can also be achieved with non-shielded lines by using free wires or closely parallel earth conductors as substitute shields. The assumption here is that the shielded conductor is not influenced by low frequency shield currents resulting from equipotential bonding. This requirement is met by a bonding system that has sufficiently low impedances at the relevant frequencies. For frequencies where the external inductive component of the shield resistance is sufficiently large compared to its real component, i.e. at high frequencies, a coupling caused by potential difference is reduced to a value only induced by the coupling impedance. The upper limit frequency of the shield effect depends on the length of the shield between its connections to earth. Therefore, the higher the limit frequency of a shield's effectiveness should be, the shorter the intervals at which it must be connected to earth. Figure 5-24 shows typical methods of connecting shields for control cables.

There are, for example, fully insulated devices with no connection to a protective conductor system. However, they have an inner shield for connection to the shield of the signal lines. It should be noted that this shield may carry interference voltages relative to its environment („remote earth").

The manufacturer's directions for installation of all types of devices must be observed, irrespective of the structure of the bonding system. The ground connection between the subsystems to be connected with the shielded cable should have a lower resistance than the shield circuit. This is sufficient to prevent interference from bonding currents on the shield.

a)

b)

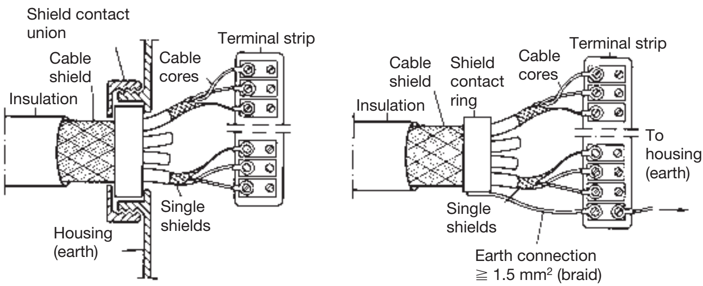


Fig. 5-24

Methods of connecting shielded control cables: a) coaxial (preferred) b) braided (less effective)

The relevant equipment can have a shield conductor rail (to DIN VDE 0160) or special shield conductor terminals (to DIN VDE 0800). Design in accordance with DIN VDE 0800 should be preferred for data processing systems when considering the possibility of interference. Where several systems interact, both bonding principles can be applied independently with reference to their shield connections, as shown in figure 5-25.

Cable routing

Signal cables of control systems must always be laid separately from the general installation network. However, power supply cables leading from a central distribution point to subsystems (e.g. peripheral devices) should be laid with the signal cables. A clearance of more than 0.3 m between the cables is sufficient for separate cable laying.

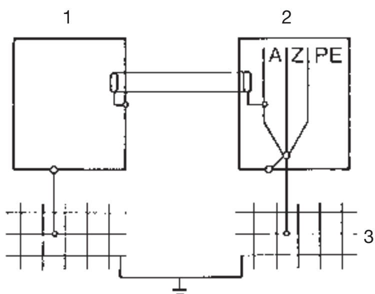


Fig. 5-25

Shielding of systems to DIN VDE 0160 and 0800:

1 Shielding to DIN VDE 0800, 2 Shielding to DIN VDE 0160 with busbars A for connection of the shield conductors, Z for connection of the signal reference conductors, and PE for connection of the protective conductors, 3 equipotential bonding system(s)

In the equipment rooms, the power supply lines are laid in a radial pattern from the low voltage distribution boards to the various devices or subsystems. They are laid in appropriate frames along the conductors of a bonding system that is meshed wherever possible.

Filters

Filters for damping of interference voltages require a sufficient spacing between the useful frequency and interference frequency. The filter provides for damping at selected frequencies, with the insertion loss of the filter being dependent not only on the filter impedance, but also on the impedances of the interference sources and sinks. Catalogue data are generally relative to source and sink impedances of 50 Ω. Source and sink impedances have an influence on the damping behaviour, and therefore different filter topologies are used, depending on the ratio of the impedances. Filter elements are not ideal: The connecting wires of a capacitor act as (low) inductances and (low) capacitances act between the windings of an inductor. On account of these „parasitic" properties, filters have resonance points at which their impedance drops to minimum levels. In practice, this means that the effect of a filter can deteriorate at high frequencies. The filter structure is determined by the source and sink impedances, the nature of the interference to be suppressed (symmetrical or asymmetrical), the filter direction (avoidance of penetration or emission of interference) and the rated current.

Filters for reduction of harmonic currents in networks are also termed filter circuits, series resonant circuits or absorber circuits. They consist of an inductance and a capacitance. The functional principle is that they practically represent a short-circuit for the harmonic to be reduced. A series resonant circuit set, for example, to 250 Hz, has its resonant frequency at 250 Hz. At frequencies below that resonant frequency, the circuit acts capacitively, and can compensate (partly) for existing lagging (inductive) reactive power. It must however be noted that in such a case an parallel resonant circuit with possibly undesirable oscillations is formed together with the network inductance and other filter circuits where present. At frequencies above the resonant frequency, the filter circuit functions inductively.

Switch cabinets

The following information applies to proper design of switchbays with respect to EMC:

– Wide-area, metallic conductive equipotential bonding of all metallic components of the panels and switchboards is essential.
– Use mounting plates, rails and racks of galvanized sheet steel only. Note: Painted, anodized or gold passivated components in some cases have very high resistance values for the 50 Hz frequency.
– Metallic components and parts inside the switchboard must be reliably connected over a wide area to ensure conduction. Ensure that appropriate contact material (screws and accessories) is selected.
– Wide-area, low-resistance earthing of interference sources (equipment) on mounting plates and racks prevents unwanted radiation.
– The cable layout inside the cabinet should be as close as possible to reference potential (chassis earth). Note: freely suspended cables tend to act as active and passive antennas.
– Unused wires, particularly those of motor and power cables, should be connected to protective conductor potential (PE) at both ends.

- Unshielded cables and wires of a circuit – i.e. feed and return – should be twisted together because of symmetrical interference.
- Relays, contactors and solenoid valves must be shunted by spark suppressor combinations or by overvoltage-limiting components. Line filters or interference suppression filters increase the interference immunity of the switchgear installation depending on the interference frequency at the system terminals.

5.6 Partial discharge measurement

Partial discharge measurement is an important tool for assessing the status of high-voltage insulation. It is a proven technique for diagnosing errors in the laboratory, for quality assurance in production and on-site for all high-voltage equipment, such as transformers, instrument transformers, cable systems, insulating bushings and gas-insulated switchgear.

Partial discharges may be symptoms of damages of the insulating materials caused for instance by thermal, mechanical or electrical over stressing or ageing.

Partial discharges can damage solid insulation materials in the interior and on the surface and may result in breakdown of the insulation. Partial discharges can decompose fluid and solid insulation.

Technical interpretation of the results obtained from the partial-discharge measurements enables detection of weak points at or in insulation systems and provides information on the continuing availability of the equipment.

Partial discharges (PD) are low-energy electrical discharges, which bridge only part of the insulating clearance. They occur when the electrical strength between electrodes of different potential is exceeded at a localized point and result in brief discharges of partial capacities within insulation. These fleeting phenomena result in high-frequency interference fields. In practice, the operator should be aware of possible damage to insulation, emission of electromagnetic interference fields (EMC) and the development of noise (corona).

Partial discharges may occur as follows:

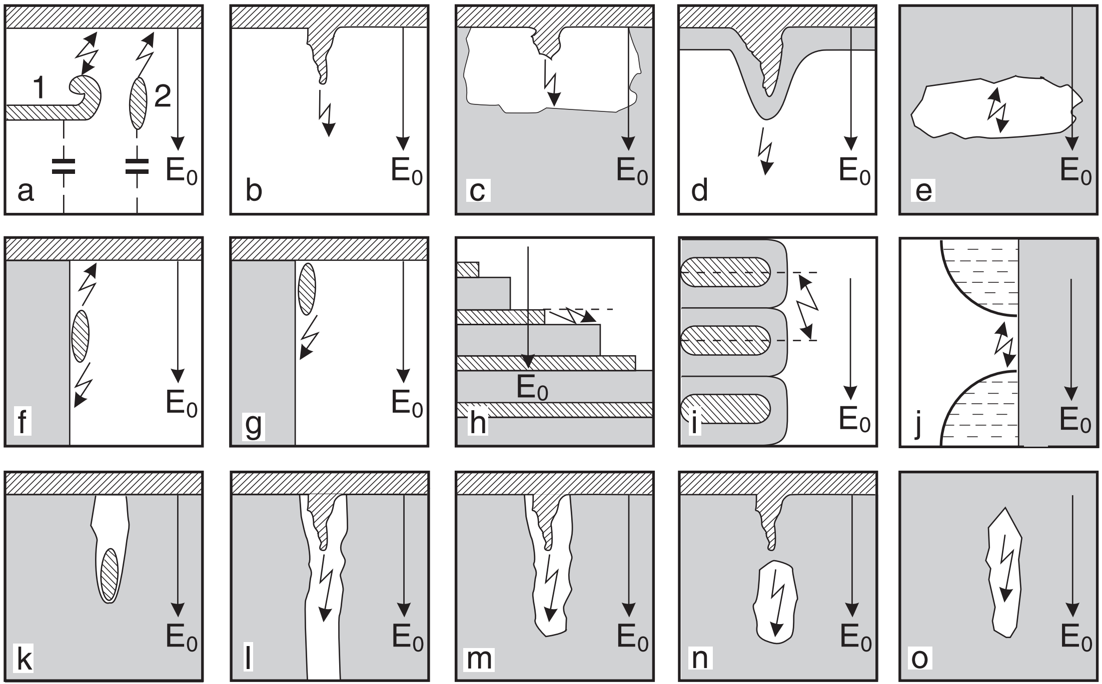
- in cavities inside solid insulation materials,
- at unhomogenous points of the electrical field in solid, fluid and gas insulation materials
- in conductors without fixed potential and stray particles in the area of electrical fields.

Some typical sources of partial discharges are shown in Fig. 5-26.

Partial discharges are verified by

- electrical partial-discharge measurement,
- acoustic partial-discharge measurement,
- optical partial-discharge measurement,
- chemical tests.

Electrical partial-discharge measurement is discussed below.



E_0=field intensity vector ▨ = Metal or conductive material ▭ = solid insulation material

Fig. 5-26
Sources of partial discharge at electrodes, insulation and in gas

5.6.1 Partial discharge processes

There is a basic distinction between internal and external partial discharges.

Internal partial discharges

Internal partial discharges are gas discharges that occur in separations, in cracks and in cavities inside of solid insulation material and in gas bubbles in fluid insulation material. This includes discharges in cavities between insulation and electrode (Fig. 5-26 c) and within an insulating body (Fig. 5-26 e).

Fig. 5-27 a shows a faulty insulating body with a cavity inside. The non-faulty dielectric is formed by the capacitances C'_3, the gas-filled cavity by C_1 and the element capacitances above and below the fault position by C'_2. The replacement configuration of the insulating body is shown in Fig. 5-27 b. A spark gap F is placed parallel to the cavity capacitance C_1. If the disruptive discharge voltage of the gas-filled fault cavity is exceeded, a flash-over will occur and the capacitance C_1 will be discharged.

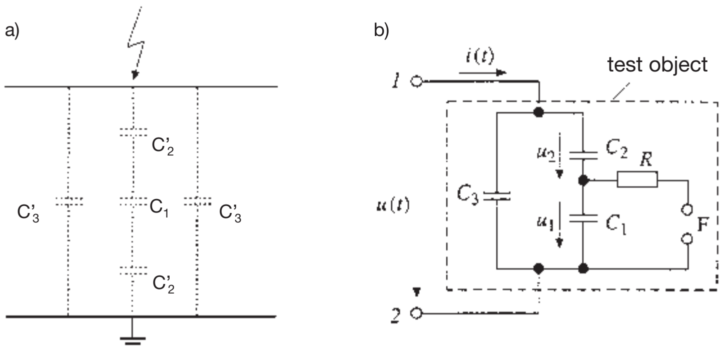


Fig. 5-27

Replacement configuration with internal partial discharges
a) configuration of equivalent components b) equivalent circuit

If alternating voltage u(t) is applied at the terminals of the equivalent circuit, the voltage at the capacitance of the cavity is found

$$u_{10}\,(t) = \frac{C_2}{C_1 + C_2}\,\hat{U} \cdot \sin(\omega\, t)$$

Fig. 5-28 a shows the two voltage processes. If voltage $u_{10}(t)$ exceeds igniting voltage U_Z of the gas-filled cavity, the spark gap F breaks down and the capacitance C_1 discharges. The persistent voltage value on the test object is referred to as partial discharge (PD) inception voltage. If the voltage on the test object u(t) exceeds this value, the internal discharge will spark several times during a half-wave.

When C_1 is discharged via F, pulse-shaped capactive charging currents i(t) – only partially fed from C_3 but primarily from the external capacitances of the circuit – are superimposed on the network-frequency alternating current (Fig. 5-28 b). The

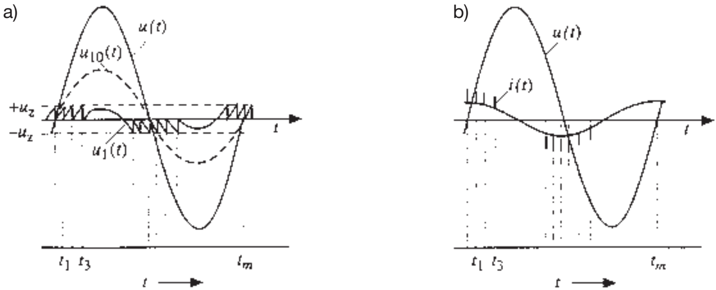


Fig. 5-28

a) voltage characteristics in the equivalent-circuit diagram for pulse-type internal partial discharges
b) current characteristics in the equivalent-circuit diagram for pulse-type internal partial discharges

accumulation of impulses in the area of the zero crossings of voltage u(t) – generally overwhelmingly in the area after the zero crossings – is an indicator for discharges in the cavities of solid insulation materials.

External partial discharges

If the field intensity at air-insulated electrode configurations (e.g. outdoor fittings) – such as in the area before the sharp edges – exceeds the electrical strength of air as a result of impulse ionization in the heavily loaded gas space electron avalanches and photoionization will occur, ultimately resulting in partial breakdown of this area (trichel impulses).

Figs. 5-29 a and b shows a simplified view of the processes with the associated equivalent circuit. In the diagram, C_1 represents the gas space through which the partial discharge breaks down and resistance R_2 represents the charge carriers formed before the peak, which move around in the field cavity and result in a degree of conductivity.

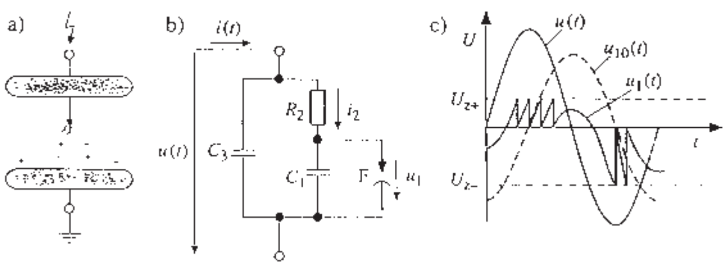


Fig. 5-29

Configuration with external partial discharges: a) peak plate configuration b) equivalent-circuit diagram c) voltage characteristics in the equivalent-circuit diagram for pulse-type external partial discharges.

The associated voltage characteristics of the configuration are shown in Fig. 5-29c.The voltage characteristic $u_{10}(t)$ at C_1 before the beginning of the first partial discharge follows the equation

$$u_{10}(t) = \frac{\hat{U}}{\omega C_1 R_2} \sin(\omega t - \frac{\pi}{2})$$

The response of the spark gap F in the equivalent-circuit diagram shows the pulse-shaped partial breakdown. If the voltage at the test object is sufficiently high over a time range, the result is a number of PD impulses per half-wave. An indication of external partial discharges on sharp-edged electrodes is the accumulation of impulses in the range of the peak values of the external voltage u(t) applied at the fittings.

5.6.2 Electrical partial discharge measurement procedures

Electrical partial discharge measurement according to IEC 60270 (DIN VDE 0434)

In the course of almost 40 years of use with simultaneous intensive development of the procedures, this procedure, which is based on the measurement of the apparent charge of the PD impulses at the test object terminals, has become very widespread in the area of high-voltage installations and devices.

Three different test circuits can be used (Fig. 5-30). The coupling capacitor C_K and the four-terminal coupling circuit Z_m (and Z_{m1}) are required for partial-discharge measurement. Impedance Z protects the high-voltage test source and acts as a filter against interference coupled from the network.

The high-frequency high-capacity charging current resulting from the partial discharges in the test object feeds the test object capacitance C_a from the coupling capacitance C_K. Therefore, ratio C_K/C_a determines which charge component at four-terminal coupling circuit Z_m can be measured, i.e., C_K determines the sensitivity of the PD measurement. The quantitative evaluation of the partial-discharge measurement is based on the integration of the high-capacity charging current. This is integrated in the partial discharge instrument within a fixed frequency band.

With respect to the strong influence of the test object and the instrumentation on the result, the test circuit must be calibrated before every test cycle with the test object connected. During this process, a calibration pulse generator feeds defined charge impulses to the terminals of the test object.

The partial discharge instrument gives the apparent charge as a numerical value with the dimension pC (pico-coulomb) as the result of the measurement. The phase angle of the partial charge impulses based on the applied test voltage is also significant. Different displays are shown on monitors for this purpose. Modern devices show the amplitude, rate of occurrence, frequency and phase angle at a specific voltage in a colour image (Fig. 5-31).

The test circuit as shown in Fig. 5-30a is preferred for measurements in practice. In the case of laboratory measurements where the test object is isolated from ground, the test circuit as shown in Fig. 5-30b is suitable.

The partial-discharge measurement technology distinguishes between narrow-band and broad-band partial-discharge measurement. This classification is based on the frequency segment in which the partial discharges are recorded. While measurement with the narrow-band measurement in an adjustable frequency band is done with selected mid-frequency, the broad-band method covers a frequency range of 40 kHz to 800 kHz. Interference couplings are a particular problem, as they tend to occur in

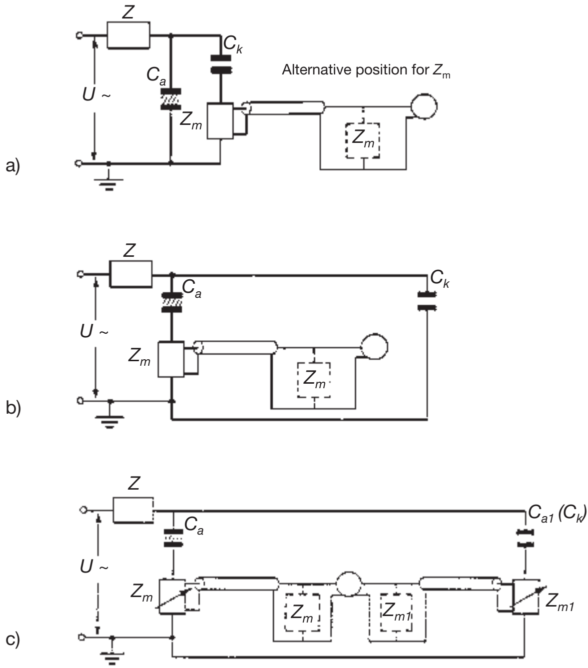


Fig. 5-30

Basic circuit from IEC Publication 60270:
a) + b) direct measurement c) bridge measurement

measurements on site as a result of a lack of shielding. There are now a number of countermeasures for this, such as narrow band measurements and active gate circuits. Another method is to use the bridge test circuit shown in Fig. 5-30 c.

Partial discharges within encapsulated switchgear installations are frequently located by acoustic partial-discharge measurement in addition to electrical partial-discharge measurement. It reacts to the sound energy that is generated by partial-discharge activity. Sensitive sensors, such as parabolic mirrors and structural sound pickups, detect these sounds in the frequency range between 20 kHz and 100 kHz.

UHF measurement

The PD impulse in SF_6-isolated high-voltage installations has a wide frequency spectrum up to the GHz range. The electromagnetic waves generated in this process

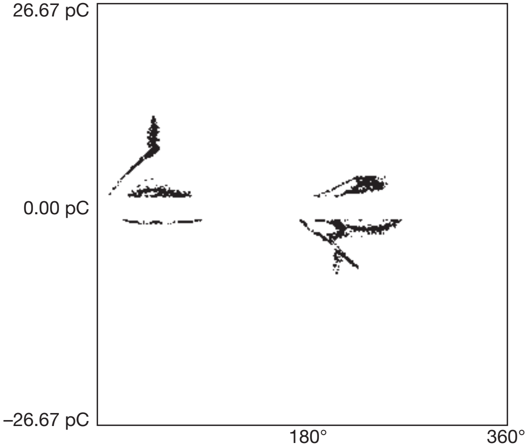


Fig. 5-31

PD characteristic quantities, in coordination with the voltage applied

spread inside the encapsulation in the form of travelling waves. They can be detected using capacitive probes integrated into the encapsulation (Fig. 5-32) and used to locate the fault positíon.

However, this requires several probes in one installation, and also the laws of travelling wave propagation, including the effects of joints (such as supports) and branching must be taken into account in the interpretation.

The characteristic partial-discharge images formed with UHF measurement are similar

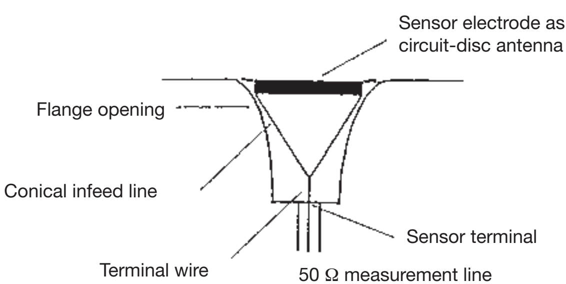


Fig. 5-32

Cone sensor in the flange of a GIS

to those formed by conventional measurement. The measurement sensitivity is not determined with a calibration pulse generator but by applying a voltage to one of the UHF PD probes to determine the transmission function of the installation, including the other PD probes.

One great advantage of the UHF measurement (Ultra High Frequency, 300 MHz to 3 GHz) is the significant decrease of external interference in this frequency range.

UHF measurement by permanently installed probes is particularly suited for monitoring high-voltage installations during operation. Measurements can be made continuously while storing the measured values or at regular intervals (monitoring).

5.6.3 Assessment of partial discharges

There are essentially two parameters important for assessing partial discharges:

– the frequency distribution of the discharge amplitude and

– the dependency of the discharge performance on the voltage applied.

The former provides information about the kind of insulation defect which is responsible for the occurrence of partial discharges, while the latter indicates whether partial discharges are boosting or accelerating the damaging process. Base for the amplitudes frequency distribution diagrams (PD images) is the analysis of the statistic performance and the correlation with well known and proven physical influences. Essentially the process of creating initial electrons is playing an important part.

In the classic PD measurement procedure as per IEC 60270 the evaluation of the individual PD impulses is based on the recharge current measured at the coupling capacitor and the results are compared with the limit values specified in the relevant product standards. This procedure is preferably suitable for development and production tests.

When monitoring installations in service the main concern is to detect variations in the performance of the insulating material. Evaluation and attaching the effects to types of defects are of secondary importance. To detect the occurrence of limiting performance values possibly by means of single-parameter measurement is regarded the main task of PD monitoring systems. For reason of convenience the diagrams of amplitude frequency distribution are replaced by an integral measurement of the discharge impulses and dynamic peak value records. Fig. 5-33 shows these monitoring records. In case of the occurrence of high values of the discharge integral the device concerned is detected by evaluating the peak value profile of all probes distributed over the installation observed. This works since damping and reflection of PD travelling waves at insulating partitions, elbows or tee-offs result in amplitudes decaying with rising distance from the point of origin.

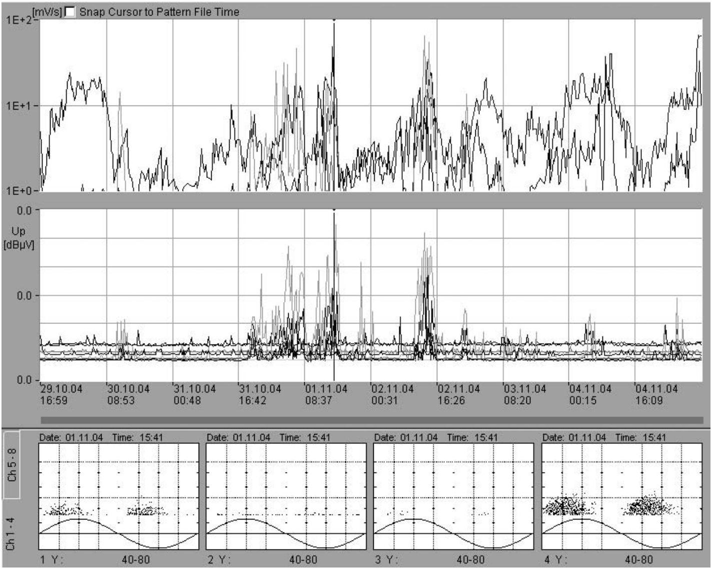


Fig. 5-33

Typical indication of PD monitoring

5.7 Effects of climate and corrosion protection

The operational dependability and durability of switchgear installations and their components are strongly influenced by the climatic conditions at their place of installation.

There are two aspects to the demand for precise and binding specifications for these problems:

– The description of the climatic conditions to be expected in service and also during storage, transport and assembly.

– The specification of the test conditions or design requirements that ensure reliable functioning under defined climatic conditions.

5.7.1 Climates

The standard DIN EN 60721-3, „Classes of environmental influence quantities and their limit values", is a comprehensive catalogue of classes of interconnected environmental factors. Every class is identified with a three-character designation as follows:

1st place: type of product use
(1 = storage, 2 = transport, 3 = indoor application, 4 = outdoor application etc.)

2nd place: type of environmental influence

(K = climatic conditions, B = biological conditions, C = chemically active substances etc.)

3rd place: assessment of the severeness of the environmental influences (higher figures = more difficult conditions)

For example, class 3K5 can be considered for applications of indoor switchgear installations in moderate climate zones. It indicates a total of 16 parameters of different climatic conditions. The most important are summarized in Fig. 5-34 in the form of a climatic diagram.

It must not be assumed that one or even more of the given limit values will occur in service continuously; on the other hand it is also assumed that they will be exceeded for a short period or in rare cases, but with a probability of < 0.01.

The classification of environmental conditions only provides manufacturers and users of electrotechnical products with an orientation and a basis for dialogue. The IEC committees responsible for the product groups are expected to use them as a basis for unified specifications for normal and special service conditions. Tables 5-18 and 5-19 show the corresponding specifications in the product standards IEC 60694 (VDE 0670 Part 1000) – High-voltage switchgear and controlgear[1)] – and DIN EN 60439-1 (VDE 0660 Part 500) – Low-voltage switchgear assemblies.

These standards also include specifications regarding additional environmental conditions such as contamination, oscillations caused by earthquakes, technically originated external heat, electromagnetic influence etc.

Switching devices, including their drives and auxiliary equipment, and switchgear installations must be designed for use in accordance with their ratings and the specified normal service conditions. If there are special service conditions at the installation site, specific agreements are required between manufacturer and user.

1) Compare the climatic diagram (Fig. 5-36).

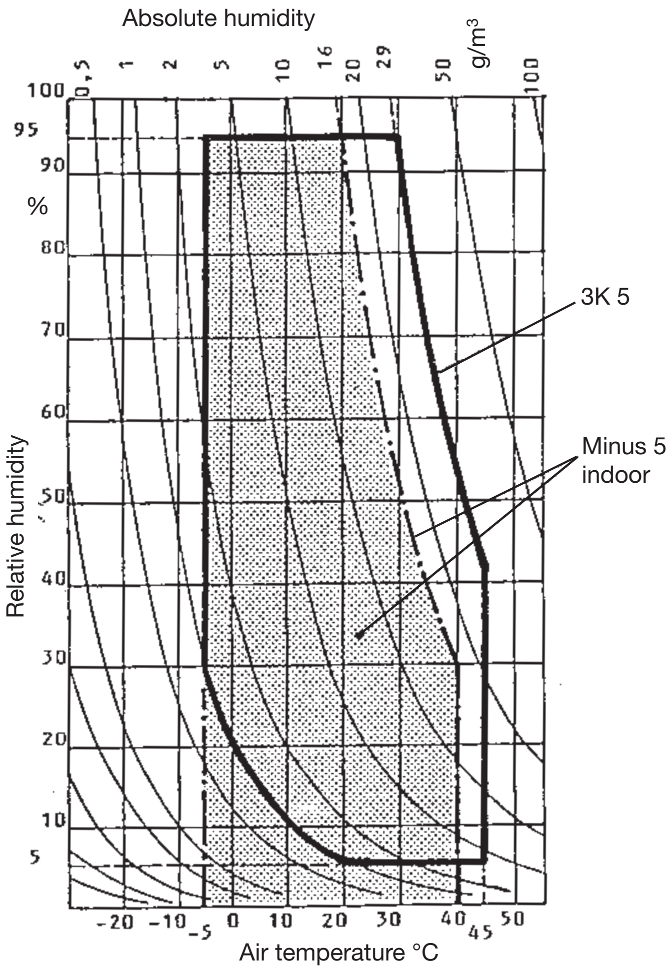


Fig. 5-34

Climatic service conditions for indoor switchgear
Climate diagrams as per DIN EN 60721-3 for class 3K5
and as per DIN EN 60694 for class „Minus 5 indoor"

Table 5-18

Normal and special climatic service conditions for indoor application
N = normal service conditions (with variations N_1, N_2 etc.)
S = special service conditions

Environmental influence	High-voltage switchgear and controlgear IEC 60694 (VDE 0670 Part 1000)	Low-voltage switchgear assemblies IEC 60439-1 (VDE 0660 Part 500)
Minimum temperature	N_1: – 5°C N_2: – 15°C N_3: – 25°C S: – 50°C/+ 40°C	N: – 5°C
Maximum temperature	N_1: + 40°C N_2: + 35°C (24h average) S: + 50°C/– 5°C	N_1: + 40°C N_2: + 35°C (24h average)
Relative humidity	N: 95% (24h average) N: 90% (monthly average) S: 98% (24h average)	N: 50% at 40°C N: 90% at 20°C
Water vapour partial pressure[1)]	N: 2.2 kPa (24h average) N: 1.8 kPa (monthly average)	
Condensation	occasional	occasional
Solar radiation	negligible	N: none S: present, caution!
Installation height	N: ≤ 1000 m S: > 1000 m (with dielectric correction)[3)]	≤ 2000 m[2)]

[1)] 2.2 kPa = 22 mbar = 16 g/m3
1.8 kPa = 18 mbar = 12 g/m3
[2)] > 1000 m special agreement for electronic equipment
[3)] For high voltage switchgear withstand voltage values are specified according IEC 60694 in form of standard insulation levels which are to be proven by dielectric withstand tests. These proving tests must be carried out under ambient conditions corresponding to the standard reference conditions (20°C, 101,3kPa, 11g/m² humidity content). Installations and apparatus with these standard insulation levels are regarded to be suitably dimensioned for application in heights up to 1000m. When used in a place higher than 1000m above sea level the insulating withstand voltages must be adjusted accordingly by calculation applying the atmospheric correction factor K_a in a modified version.

$$K_a = e^{m \frac{H-1000}{8150}}$$

H Height of the place of installation above sea level

See also Section 4.1.1.

Table 5-19

Normal and special climatic service conditions for outdoor application
N = normal service conditions (with variations N_1, N_2 etc.)
S = special service conditions

Environmental influence	High-voltage switchgear and controlgear DIN EN 60694 (VDE 0670 Part 1000)	Low-voltage switchgear assemblies DIN EN 60439-1 (VDE 0660 Part 500)
Minimum temperature	N_1: –10 °C N_2: –25 °C N_3: –40 °C S: –50 °C/+ 40 °C	N_1: –25 °C N_2: –50 °C
Maximum temperature	N_1: +40 °C N_2: +35 °C (24h average) S: +50 °C/–5 °C	N: +40 °C +35 °C (24h average)
Condensation and Precipitation	are to be considered	100 % rel. humidity at +25 °C
Solar radiation	1000 W/m²	N: –– S: If present, caution!
Ice formation	N_1: 1 mm thickness N_2: 10 mm thickness N_3: 20 mm thickness	
Installation height	N: ≤ 1000 m S: > 1000 m (with dielectric correction)[2]	≤ 2000 m[1]

[1] above 1000 m special agreement for electronic equipment
[2] See also note [3] of Table 5-18.

5.7.2 Effects of climate and climatic testing

Fig. 5-35 uses examples to indicate the variety of influences possible on switchgear in service resulting from climatic conditions. The development and manufacture of devices and installations that resist these influences require considerable experience. Additional security is provided by conducting appropriate tests based on the relevant product standards. The following are some examples:

– Wet-test procedure of the external insulation of outdoor switchgear as per IEC 60060-1 (VDE 0432 Part 1)
– Limit temperature tests of high voltage circuit-breakers as per IEC 62271-100 (VDE 0671 Part 100)
– Switching of disconnectors and earthing switches under severe icing conditions as per IEC 62271-102 (VDE 0671 Part 102)
– Testing of indoor enclosed switchgear and controlgear (1 kV to 72.5 kV) for use under severe climatic conditions (humidity, pollution) as per IEC Report 60932.

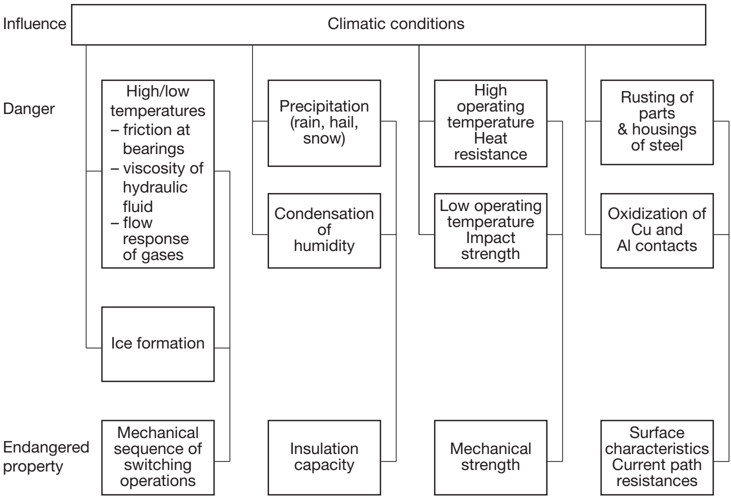


Fig. 5-35

Ways that switchgear and installations are affected by climatic conditions

5.7.3 Reduction of insulation capacity by humidity

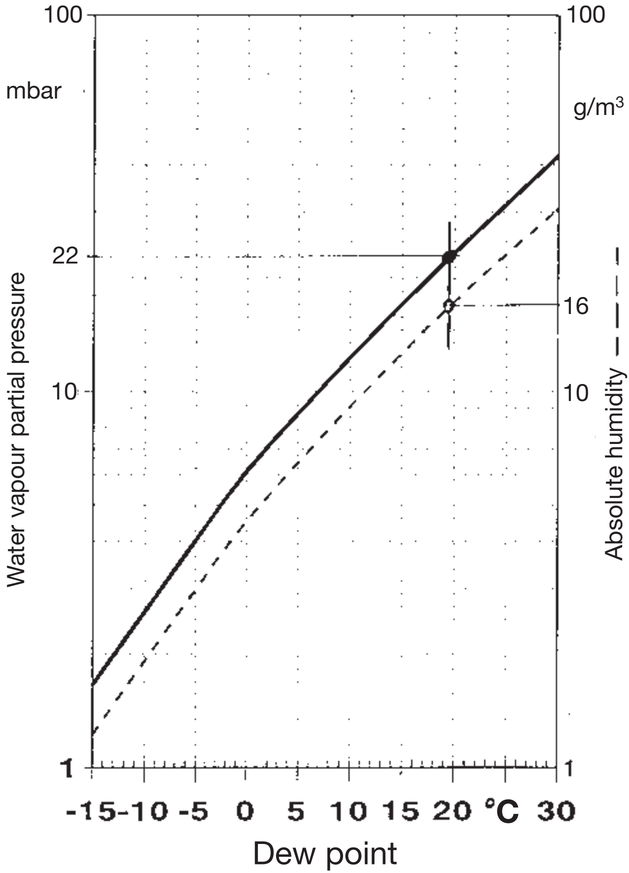
The reduction of insulation capacity by humidity is particularly significant on the surface of insulators. With outdoor devices, humidity results primarily from precipitation, such as rain, hail, snow, while in the case of air-insulated indoor switchgear and inside gas-insulated installations (GIS), the problem is condensation from moisture that was previously a component of the ambient gas or the atmosphere.

The moisture content of a gas mixture can be expressed in different ways. From the physicist's point of view, the scale for the fractions of the components of a gas mixture is the partial pressures. The partial pressure of a component is the pressure that is measured at a given temperature if this component is the only constituent of the total volume of the mixture. In the event of unintended admixtures, as observed here, the partial pressure of water vapour varies in the mbar range or when considered as absolute moisture in the range of a few g/m^3. Another possibility of expressing the moisture content quantitatively is to determine the „dew point", i.e. the temperature at which condensation occurs. This information is the most meaningful for the switchgear operator. Fig. 5-36 shows the relations.

The sequence of the reduction of insulation capacity by moisture is the same for all three types of insulator surfaces: Initially only a very slight current flows over the humidity film along the insulator surface because of the very low conductivity of the pure water of the film. Partial discharges along the current path yield decomposition products that continually increase the conductivity until the insulator surface is permanently damaged or a flashover occurs. Any outside contamination that is present already in the beginning significantly accelerates the deterioration process.

Countermeasures for outdoor switchgear are limited to the selection of material (ceramic, glass, cycloaliphatic resins, silicone rubber) and the selection of the creepage distance (cf. IEC 60071-2 (VDE 0111 Part 2)). Usage of specific minimum lengths for creepage paths and also material selection are also very important for indoor insulation in atmospheric air. However, condensation can also be prevented if required by the use of air-conditioning or by raising the temperature slightly inside switchbays and cubicles with small anticondensation heaters.

In the case of gas-insulated switchgear (GIS), the problem is different. The moisture content of the insulating gas is not due to climatic conditions but is primarily brought in as the moisture content of solid insulation materials and only gradually transferred to the insulation gas. The installation of drying filter inserts with sufficient moisture-absorbing capacity has been found to be a suitable means of keeping the moisture content of the gas or the dew point low (≤ –5°C).



Relation between water-vapour partial pressure, absolute humidity and dew point
10 mbar = 1 kPa

5.7.4 Corrosion protection

Design regulations for preventing corrosion are not included in national and international standards. They are a part of the manufacturer's experience and can be found in internal documents and also occasionally in the supply regulations of experienced users. The following are examples of proven measures:

- Painting and galvanizing sheet metal and sections of steel, aluminium and stainless steel (Fig. 5-37)
  Note: Top-coat varnishing can be done in one pass with the powder-coating process applied to the appropriate thickness instead of several wet-coating passes.
- Structural components of mechanical drives and similar of steel, which are required to meet close tolerances or antifriction properties, such as shafts, latches and guideways, can be effectively protected from corrosion for use indoors by manganese or zinc phosphor treatment (5-8 μm) concluded by an oil bath.
- Structural components of steel which are not subjected to any specific mechanical demands and standard parts are generally galvanized with zinc (12 μm) and then chromatized (passivization).
- Conductor materials such as copper and aluminium must be silver galvanized (20 μm) in contact areas with spring-loaded contacts. Aluminium requires application of a copper coating (10 μm) before the silver is applied. A silver coating of about 20 μm has the optimum resistance to mechanical friction.
  The appearance of dark patches on silver surfaces is generally no reason for concern, because the oxidation products of silver are conductive and this will not greatly affect the conductivity of the contact. The oxidation products of copper are non-conductive, so oxidation on copper surfaces can easily result in an increase in the temperature of the contact and then result in serious problems.
  Oxidation gradually reduces the thickness of the silver coating. Under normal indoor conditions, climatic influences will not generally result in complete loss of the silver coating. However, this must be taken into consideration in industrial premises with particularly chemically aggressive atmospheres. Under these circumstances it may be necessary to use partially gold-plated contacts, even in the area of power engineering.

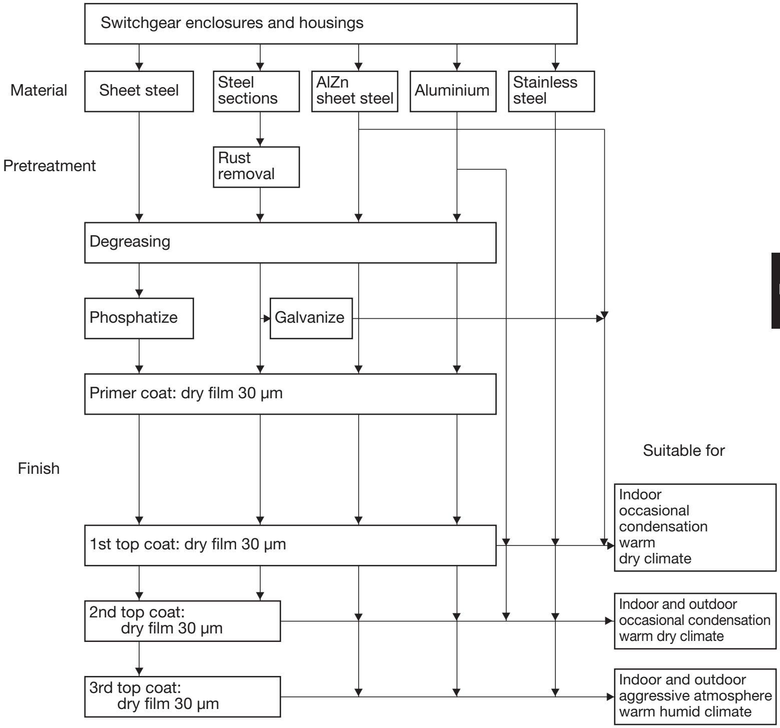


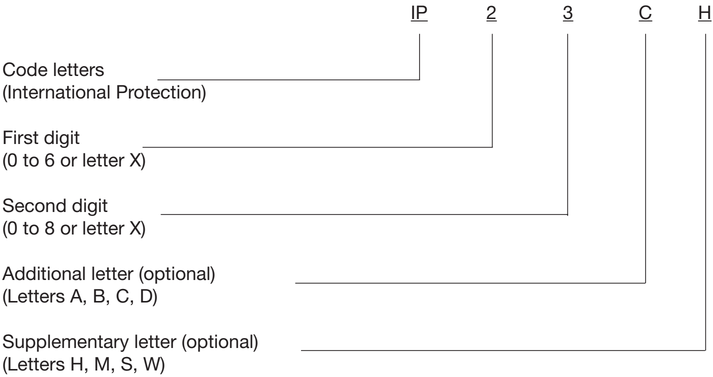
Fig. 5-37

Surface treatment and coating for switchgear installations

5.8 Degrees of protection provided by enclosures for electrical equipment of up to 72.5 kV according IEC 60529 (VDE 0470 Part 1) - IP code

The IP-code is a designation code applied to indicate the degree of protection by enclosures against the access of persons to hazardous parts and against the ingress of solid foreign objects and of water and to give additional information with respect to this kind of protection.

Layout of the IP Code



The degrees of protection provided by enclosures are identified by a symbol comprising the two letters IP (International Protection), which always remain the same, and two digits indicating the degree of protection. The term "degree of protection" must be used to indicate the full symbol (code letters, code digits).

If a code digit is not required, it must be replaced by the letter „X" („XX", if both digits are not used).

The „additional letter" states the degree of protection of persons against the access to hazardous parts

– if this protection is of a higher degree than the protection indicated by the first digit or
– if only the protection against the access to hazardous parts is specified and the first digit is replaced by „X"

An additional information may be given by the „supplementary letter" placed either behind the second digit or after the additional letter. The technical committees of IEC are expected to designate further supplementary letters in product standards so far needed.

Table 5-19

IP - degrees of protection

Component	Digits or letters	Significance for protection of the **equipment**	Significance for protection of **persons**
Code letters	IP	–	––
First digit	0	not protected	
		Protection against ingress of solid bodies	Protection against access to hazardous parts with
	1	≥ 50 mm diameter	back of the hand
	2	≥ 12.5 mm diameter	fingers
	3	≥ 2.5 mm diameter	tools
	4	≥ 1.0 mm diameter	wire ≥ 1.0 mm Ø
	5	dust-protected	wire ≥ 1.0 mm Ø
	6	dustproof	wire ≥ 1.0 mm Ø
Second digit	0	not protected	
		Protection against ingress of water with harmful effects by	
	1	vertical drops	
	2	drops (15 ° angle)	
	3	spray water	
	4	splash water	
	5	jet water	
	6	strong jet water	
	7	temporary immersion	
	8	continuous immersion	
Additional letter (optional)			Protection against access to hazardous parts with
	A		back of hand
	B		finger
	C		tool
	D		wire (1.0 mm Ø, 100 mm long)
Supplementary letter (optional)		Supplementary information especially for	–
	H	High-voltage devices	
	M	Movement during water test	
	S	Stationary during water test	
	W	Weather conditions	

Examples for application of letters in the IP code

The following examples are intended to explain the application and the configuration of letters in the IP code.

IP44 – no letters, no options
IPX5 – first digit omitted
IP2X – second digit omitted
IP20C – use of additional letters
IPXXC – omission of both digits, use of the additional letter
IPX1C – omission of the first digit, use of the additional letter
IP2XD – omission of the second digit, use of the additional letter
IP23C – use of the supplementary letter
IP21CM – use of the additional letter and the supplementary letter
IPX5/IPX7 – indication of two different protection classes by one housing against jet water and against temporary immersion for „versatile" application.

6 Power system planning and switchgear engineering

6.1 Planning of switchgear installations

6.1.1 Concept, boundary conditions, pc calculation aid

The process of planning switchgear installations for all voltage levels consists of establishing the boundary conditions, defining the plant concept and deciding the planning principles to be applied.

The planning phase is a time of close cooperation between the customer, the consulting engineer and the contractor.

The boundary conditions are governed by environmental circumstances (plant location, local climatic factors, influence of environment), the overall power system (voltage level, short-circuit rating and arrangement of neutral point), the frequency of operation, the required availability, safety requirements and also specific operating conditions.

Table 6-1 gives an indication of the boundary conditions which influence the design concept and the measures to be considered for the different parts of a switchgear installation.

In view of the equipment and plant costs, the necessity of each measure must also be examined from an economic standpoint.

Taking the busbar concept as an example (Table 6-3), the alternatives are evaluated technically and economically. The example is valid for h.v. installations, and to some extent m.v. installations as well.

PC calculation aid

Numerous computer programs are available for use in planning switchgear installations, particularly for design calculation. Sections 6.1.6 and 6.1.7 deal with computer-aided methods for:

– short-circuit current
– cable cross sections.

Table 6-2 summarizes the computer programs used in planning switchgear installations, together with their fields of application and contents.

Table 6-1

Choice of plant concept and measures taken in relation to given boundary conditions

Boundary conditions	Concept and measures
Environment, climate, location:	Outdoor/indoor Conventional/GIS/hybrid Equipment utilization Construction Protection class of enclosures Creepage, arcing distances Corrosion protection Earthquake immunity
Network data,network form:	Short-circuit loadings Protection concept Lightning protection Neutral point arrangement Insulation coordination
Availability and redundancy of power supply:	Busbar concept Multiple infeed Branch configuration Standby facilities Uninterruptible supplies Fixed/drawout apparatus Choice of equipment Network layout
Power balance:	Scope for expansion Equipment utilization Instrument transformer design
Ease of operation:	Automatic/conventional control Remote/local control Construction/configuration
Safety requirements:	Network layout Arcing fault immunity Lightning protection Earthing Fire protection Touch protection Explosion protection

Table 6-2

PC programs for project planning and calculations for switchgear installations

Program name	Applications	Testing, calculation and dimensioning
EMTP/ATP	Calculation of transient processes in any meshed multiphase electrical systems	– Internal and external overvoltages – Interference voltage affecting telecommunications cables – Transient voltage boost in earthing systems on lightning strike – Operational response of battery power systems
ERSO2005	Calculation of earthing systems	– Determination of the propagation resistance – Determination of step and touch voltages
PRESSURE	Calculation of the pressure characteristic in switchgear rooms on arcing	– Verification of the pressure with stand capability of medium voltage switchgear – Dimensioning of pressure relief equipment
NEPLAN®	Program system for network calculation with the following modules:	
	Phase fault current calculation Calculation of symmetrical and non-symmetrical fault currents to – IEC 60909 (VDE 0102) – Superposition method	– Switchgear installations (busbars, connections) – Equipment (switches, transformers)
	Load flow calculation	– Protection systems – Switchgear installations – Equipment and power – Minimum loss system operation methods – Critical system states – Useful switchovers on equipment failure
	Load curve simulation	– Voltage drop on motor start-up – Load behaviour against time
	Optimized load flow – Distribution network – Transmission network	– Load prediction – Minimization of losses – Voltage stability
	Transient stability	– Power plant use – Study of network behaviour in dynamic processes – Generator and turbine control – Faults and switching processes

(continued)

Table 6-2 (continued)

Computer programs for project planning and calculations for switchgear installations

Program Name	Application area	Testing, determination, dimensioning
NEPLAN®	Motor start-up Harmonic analysis	Simulation in time range – Harmonic currents and voltages in networks with converters – Filtering and compensation equipment – Propagation of audiofrequency ripple control signals
	Selectivity analysis (overcurrent-time protection)	– Protection coordination in MV and LV networks – demonstration of selectivity – Checking of switch-off conditions
	Distance protection	– Compilation of selective tripping schedules
	Dimensioning of medium and low voltage cables	– Optimum cable cross-section – Protection from overload – Protection on short-circuit – Voltage drop
	Reliability analysis	– Determination of reliability characteristics in networks
	Maintenance	– Determination of an optimum maintenance and replacement strategy for systems and equipment

6.1.2 Planning of high-voltage installations

The following criteria must be considered when planning high-voltage switchgear installations:

Voltage levels

High-voltage installations are primarily for power transmission, but they are also used for distribution and for coupling power supplies in three-phase and HVDC systems. Factors determining their use include network configuration, voltage, power, distance, environmental considerations and type of consumer:

Distribution and urban networks	> 52 – 245 kV
Industrial centres	> 52 – 245 kV
Power plants and transformer stations	> 52 – 800 kV
Transmission and grid networks	245 – 800 kV
HVDC transmission and system ties	> 300 kV
Railway substations	123 – 245 kV

Plant concept, configuration

The circuitry of an installation is specified in the single-line overview diagram as the basis for all further planning stages. Table 6-3 shows the advantages and disadvantages of some major station concepts. For more details and circuit configurations, see Section 11.1.2.

The availability of a switching station is determined mainly by:

– circuit configuration, i. e. the number of possibilities of linking the network nodes via circuit-breakers and disconnectors, in other words the amount of current path redundancy,

– reliability/failure rate of the principal components such as circuit-breakers, disconnectors and busbars,

– maintenance intervals and repair times for the principal components.

Table 6-3

Comparison of important busbar concepts for high-voltage installations

Concept configuration	Advantages	Disadvantages
Single busbar	– least cost	– BB fault causes complete station outage – maintenance difficult – no station extensions without disconnecting the installation – for use only where loads can be disconnected or supplied from elsewhere
Single busbar with bypass	– low cost – each breaker accessible for maintenance without disconnecting	– extra breaker for bypass tie – BB fault or any breaker fault causes complete station outage
Double busbar with one circuit-breaker per feeder	– high changeover flexibility with two busbars of equal merit – each busbar can be isolated for maintenance – each feeder can be connected to each bus with tie breaker and BB disconnector without interruption	– extra breaker for coupling – BB protection disconnects all feeders connected with the faulty bus – fault at branch breaker disconnects all feeders on the affected busbar – fault at tie breaker causes complete station outage
2-breaker system	– each branch has two circuit-breakers – connection possible to either busbar – each breaker can be serviced without disconnecting the feeder – high availability	– most expensive method – breaker defect causes half the feeders to drop out if they are not connected to both bus bars – feeder circuits to be considered in protection system; applies also to other multiple-breaker concepts

(continued)

Table 6-3 (continued)

Comparison of important busbar concepts for high-voltage installations

Concept configuration	Advantages	Disadvantages
Ring bus	– low cost – each breaker can be maintained without disconnecting load – only one breaker needed per feeder – no main busbar required – each feeder connected to network by two breakers – all changeover switching done with circuit-breakers	– breaker maintenance and any faults interrupt the ring – potential draw-off necessary in all feeders – little scope for changeover switching
1½-breaker system	– great operational flexibility – high availability – breaker fault on the busbar side disconnects only one feeder – each bus can be isolated at any time – all switching operations executed with circuit-breakers – changeover switching is easy, without using disconnectors – BB fault does not lead to feeder disconnections	– three circuit-breakers required for two feeders – greater outlay for protection and auto-reclosure, as the middle breaker must respond independently in the direction of both feeders

Dimensioning

On the basis of the selected voltage level and station concept, the distribution of power and current is checked and the currents occurring in the various parts of the station under normal and short-circuit conditions are determined. The basis for dimensioning the station and its components is defined in respect of

– insulation coordination
– clearances, safety measures
– protection scheme
– thermal and mechanical stresses

For these, see Sections 3, 4, and 5.

Basic designs and constructions

The basic designs available for switching stations and equipment together with different forms of construction offer a wide range of possibilities, see Table 6-4. The choice depends on environmental conditions and also constructional, operational and economic considerations.

For further details, see Sections 10 and 11.

Table 6-4

The principal types of design for high-voltage switchgear installations and their location

Basic design	Insulating medium	Used mainly for voltage level (kV)	Location Outdoor	Location Indoor
Conventional	Air	>52 – 123	×	×
Conventional	Air	123 – 800	×	
GIS	SF_6	>52 – 800	× 1)	×
Hybrid 2)	Air/SF_6	245 – 500	×	

1) GIS used outdoors in special cases
2) Hybrid principle offers economical solutions for station conversion, expansion or upgrading, see Section 11.4.2.2.

There are various layouts for optimizing the operation and space use of conventional outdoor switchgear installations (switchyards), with different arrangement schemes of busbars and disconnectors, see Section 11.3.3

6.1.3 Planning of medium voltage systems

Medium voltage networks are networks with rated voltages of over 1 kV and up to 36 kV. Medium voltage switchgear is used in transformer substations and switching substations, and in secondary unit substations and customer substations (in public utility networks only). This section is exclusively concerned with medium voltage switchgear for transformer substations and switching substations.

On account of the widely differing structures which result from the demands placed upon them, a distinction is made between industrial and power station service networks on the one hand, and public utility networks on the other hand.

The most frequent network voltages in Germany are

Public utility networks:	10 kV and 20 kV
Industrial and power station service networks:	6 kV, 10 kV and 30 kV.

While the load density in public utility networks ranges from 10 kW/km^2 or less in rural areas to 20 MW/km^2 or more in major cities, it often reaches even much higher levels in industrial and power station service networks.

Apart from the high load density, industrial and power station service networks are frequently characterized by:

– high demands for reliability of supply,
– high demands for voltage quality,
– a high proportion of motor loads, and
– high short-circuit powers.

As a consequence, the structure of industrial and power station service networks is strongly influenced by the requirements of the relevant production process. The requirements for configuration and the rated data of the medium voltage switchgear installations are to be deduced individually from the network structure concerned. It is normally essential to perform a network calculation (e.g. with NEPLAN®, cf. Table 6-2) in order, for example, to take account of the contribution of motor loads to the short-circuit current or to be able to formulate requirements for network protection.

The function of public utility networks is primarily to provide blanket supply of electrical energy while fulfilling the following conditions:

– Appropriate reliability of supply
– Adequate voltage quality
– Cost-effectiveness

As there are no restrictive planning criteria with regard to the appropriate reliability of supply, a number of standard network concepts which provide a level of reliability generally accepted as appropriate have become established in the course of time.

The demands placed on the medium voltage switchgear differ with the different network concepts. The choice of suitable system configuration is therefore always associated with the network planning, which matches the network concepts to the supply functions of the relevant network operator. The fundamental functions of network planning and the most important standard network concepts are therefore presented in the following section.

Planning and optimization of medium voltage networks for public power supply

The function of network planning is nowadays less that of planning the network configuration than rather questioning and optimizing the existing, in many cases historically determined, network structures when replacement investments are impending. Frequently, the background conditions dictated by the network operator's supply function no longer correspond to the background conditions against which the medium voltage networks were established and expanded. Typical changes which can have feedback effects on the network structure and provide occasion for fundamental replanning or target network planning comprise the following:

– changed supply areas, for instance as a result of corporate mergers,
– New or shifted load centres, with total load nearly stagnating or only rising slightly,
– inaccurate load forecasts,

– integration of decentralized generation facilities,

and also

– increased pressure on costs,
– increased equipment reliability,
– improved network management.

Fundamental planning comprises the following aspects and focal points:

– analysis of the actual situation,
– definition of planning principles and criteria,
– load forecast,
– development of target network variants,
– technical and commercial comparison of the network variants, and
– definition of the target network.

The target network defines not only the network structure, but also the locations and sizes of transformer substations and switching substations and the requirements for the medium voltage switchgear.

Network calculations (e.g. with NEPLAN®, cf. Table 6-2) are performed in the course of analysis of the actual situation and to assess the target network variants. In that process, load flow and phase fault current calculations are accompanied above all by probability calculations to estimate reliability.

Probability calculations on reliability facilitate quantification of the reliability of supply in distribution networks. The influence of different network and system configurations on service reliability can be quantified in this way on the basis of reliability characteristics.

Examples of reliability characteristics include interruption frequency (stated as 1/a), i.e. the expected value for the frequency with which interruptions are to be expected by consumers in the network, and non-availability (stated in min/a), i.e. the probability of finding a consumer without supply.

The reliability calculations are based on models of characteristic disturbance sequences, which are applied to the equipment in a specified network.

All significant contributions to failure events in the network are examined on the basis of the reliability characteristics of the equipment and the failure models, and the effects of these failures on the service to consumers are determined. The reliability characteristics then describe the cumulative effects of all failures in the network. Furthermore, if the costs of interruptions are known, details of the annual costs caused by interruptions to supply can be presented.

The results of the reliability calculations for each consumer are as follows:

– $H_{\underline{U}}$: Expected interruption frequency (in 1/a)
– $Pr_{\underline{U}}$: Expected non-availability (in min/a)
– $T_{\underline{U}}$: Expected average interruption duration (in min or h)
– $W_{\underline{U}}$: Expected energy not supplied on time (in MWh/a)

Those for the system as a whole are as follows:

– SAIFI (System Average Interruption Frequency Index): Expected average interruption frequency (in 1/a)
– SAIDI (System Average Interruption Duration Index): Expected average non-availability (in min/a)
– $W_{\underline{U},total}$: Expected energy not supplied on time (in MWh/a)

In addition, the contributions of the individual pieces of equipment to the "unreliability" of the network can be quantified. This allows the importance of the equipment for the function of the network to be determined and, for example, priorities to be deduced for maintenance and replacement work.

a) Ring network
b) Network with opposite station
c) Network with load-centre substation

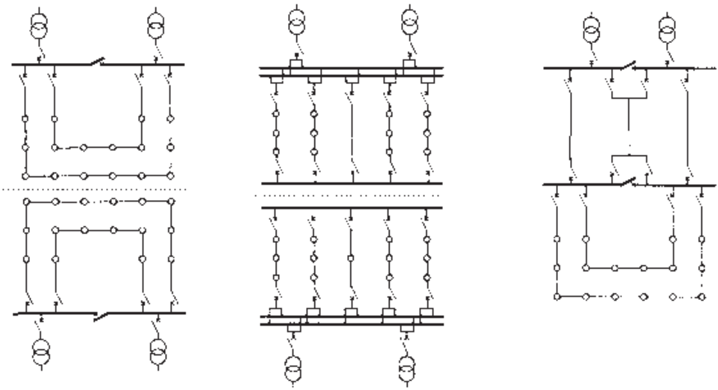


Fig. 6-1:

Networks in which the individual transformer substations are not interconnected on the medium voltage side

a) Corresponding transformer substations
b) Corresponding transformer substations with opposite station

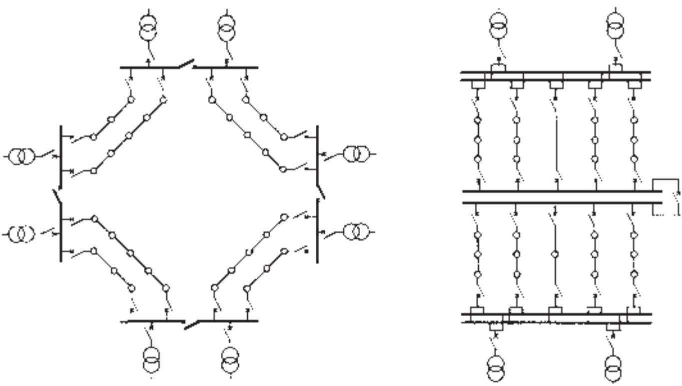


Fig. 6-2:

Networks in which the individual transformer substations are interconnected on the medium voltage side

It is impossible to say in general which network concept provides the most efficient ratio of network costs to service reliability for which supply job, as the forms of the higher level high voltage networks and the subordinate low voltage networks and, last but not least, the rated system voltage which is usually specified, also have to be taken into account.

For transformer substations in explosion-proof design, there are no medium voltage connections between the substations. In these cases, the simple ring network concept as shown in fig. 6-1 a) is usually preferred. In extensive catchment areas with low load density, it is often more economical to implement a concept with opposite stations as shown in fig. 6-1 b). The opposite stations can be designed as switch-disconnector systems. When load centres far from the transformer substations are to be supplied, it is useful to provide a load centre substation as shown in fig. 6-1 c). This is connected to the transformer substation by feed cables and supplies power close to the load, for example via a ring network. Load centre substations are to be designed as circuit-breaker systems.

Networks in which the transformer substations are connected on the medium voltage side are used when those substations are not in intrinsically safe design. Back-up supply is then effected through the medium voltage network. The transformer substations are connected together either directly by distribution cables (fig. 6-2 a)) or by feed cables as in the opposite station concept shown in fig. 6-2 b). These network concepts can provide an economical alternative when the construction of an additional transformer substation is to be avoided, or initially implemented with one transformer only. The cost-effectiveness is however to be checked for the individual case concerned. Operational management of these network concepts is more complex, as coupling of the transformer substations through the medium voltage network has to be avoided when switching operations are performed in the network. Otherwise, for example, high circulating currents could flow or the short-circuit withstand capability of equipment could be exceeded.

In practice, the load density within the supply territory of a distribution network operator frequently varies over quite a large range, and the higher and lower level networks are not uniform. This means that the network concepts presented are mostly not encountered in their pure form, but as hybrids.

A common feature of all the network concepts presented is the radial operating mode of the distribution cables, which not only facilitates simple operational management (apart from the exception mentioned above) but also a simple protection strategy and troubleshooting, particularly with single phase faults (earth faults / short-circuits to earth).

Planning of medium voltage switchgear

The standard structure of medium voltage switchgear today is the factory-assembled type-tested switchgear installation conforming to IEC 60298 (VDE 0670 Part 6). The most common structural types are described in Section 8.2.

The most important distinguishing characteristics of the currently available structural types and the associated decision-making criteria are:

Distinguishing characteristics		Technical decision-making criteria
Low costs	Higher costs	–
Single busbars	Double busbars	Network concept
Air-insulated	Gas-insulated	Dimensions of the installation Environmental conditions (contamination, moisture, service requirements, cleaning)
Cubicle	Metal-partitioned	Personnel safety during wiring work Restriction of damage in the event of internal arcing (if compartmentalization is designed for this)
Switch disconnector system	Circuit-breaker system	Rating data – Short-circuit currents – Operating currents – Switching frequency Protection concept

6.1.4 Planning of low-voltage installations

Low-voltage installations are usually near the consumer and generally accessible, so they can be particularly dangerous if not installed properly.

The choice of network configuration and related safety measures is of crucial importance. The availability of electricity is equally dependent on these considerations.

Table 6-5 compares the advantages and disadvantages of commonly used network configurations, see also Section 5.1.

Another important step in the planning of low-voltage switchgear installations consists of drawing up a power balance for each distribution point. Here, one needs to consider the following:

– nominal power requirement of consumers,
– short-time power requirement (e.g. motor startup),
– load variations.

The IEC recommendations and DIN VDE standards give no guidance on these factors and point out the individual aspects of each installation.

For power plants and industrial installations, the circumstances must be investigated separately in each case.

The following Tables 6-5 and 6-6 are intended as a planner's guide. The planners can use the information in Table 6-6 for reference.The total power is derived from the sum of the installed individual power consumers multiplied by the requirement factor with the formula:

$$P_{max} = \Sigma Pi \cdot g$$

P_{max} = power requirement
Pi = installed individual power producer
g = requirement factor

Table 6-5

Summary of network configurations and protection measures for low-voltage installations

System[1)]	Advantages	Disadvantages	Main application
TN system	Fast disconnection of fault or short circuit. Least danger for people and property.	High cost of wiring and cable due to protective conductors. Any fault interrupts operations.	Power plants, public power supply and networks.
TT system	Less wiring and cable required. Zones with different touch voltages permitted. Can be combined with TN networks.	Complex operational earthing ($\leq 2\ \Omega$). Equipotential bonding necessary for each building.	Livestock farming.
IT system	Less expensive in respect of wiring and cables. Higher availability: 1st fault is only signalled, 2nd fault is disconnected.	Equipment must be insulated throughout for the voltage between the outside conductors. Equipotential bonding necessary.	Hospitals Industry.
Total insulation	Maximum safety. Can be combined with other networks.	Equipment doubly insulated, economical only for small consumers. With heat-generating loads, insulation constitutes fire hazard.	Residential, small-scale switchboards and equipment
Safety/extra-low voltage Functional extra-low voltage	No dangerous touch voltages.	Limited power with cost-effective equipment use. Special requirements for circuitry.	Small apparatus.

[1)] For definitions and block diagram of the systems, see Section 5.1.2

Table 6-6

Demand factor g for main infeed of different electrical installations

Type of installation or building	Demand factor *g* for main infeed	Remarks
Residential buildings		
Houses	0.4	Apply *g* to average use per dwelling.
Blocks of flats		Total demand = heating + a.c. + general.
– general demand (excl. elec. heating)	0.6 typical	
– electric heating and air-conditioning	0.8 to 1.0	
Public buildings		
Hotels, etc	0.6 to 0.8	Power demand strongly influenced by climate, e.g.
Small offices	0.5 to 0.7	– in tropics high demand for air-conditioning
Large offices (banks, insurance companies, public administration)	0.7 to 0.8	– in arctic high heating demand
Shops	0.5 to 0.7	
Department stores	0.7 to 0.9	
Schools, etc.	0.6 to 0.7	
Hospitals	0.5 to 0.75	
Places of assembly (stadiums, theatres, restaurants, churches)	0.6 to 0.8	
Railway stations, airports, etc.	no general figure	Power demand strongly influenced by facilities
Mechanical engineering		
Metalworking	0.25	Elec. drives often generously sized.
Car manufacture	0.25	
Pulp and paper mills	0.5 to 0.7	*g* depends very much on standby drives.
Textile industry		
Spinning mills	0.75	
Weaving mills, finishing	0.6 to 0.7	
Miscellaneous Industries		
Timber industry	0.6 to 0.7	
Rubber industry	0.6 to 0.7	
Leather industry	0.6 to 0.7	
Chemical Industry **Petroleum Industry** }	0.5 to 0.7	Infeed must be generously sized owing to sensitivity of chemical production processes to power failures.
Cement works	0.8 to 0.9	Output about 3500 t/day with 500 motors. (Large mills with h.v. motor drives.)
Food Industry	0.7 to 0.9	
Silos	0.8 to 0.9	
Mining		
Hard coal		
Underground working	1	
Processing	0.8 to 1	
Brown coal		
General	0.7	
Underground working	0.8	

(continued)

Table 6-6 (continued)

Demand factor g for main infeed of different electrical installations

Type of installation or building	Demand factor *g* for main infeed	Remarks
Iron and steel industry		
(blast furnaces, convertors)		
Blowers	0.8 to 0.9	
Auxiliary drives	0.5	
Rolling mills		
General	0.5 to 0.8[1)]	[1)] *g* depends on number of standby drives.
Water supply, Ventilation	0.8 to 0.9[1)]	
Aux. drives for		
– mill train with cooling table	0.5 to 0.7[1)]	
– mill train with looper	0.6 to 0.8[1)]	
– mill train with cooling table and looper	0.3 to 0.5[1)]	
Finishing mills	0.2 to 0.6[1)]	
Floating docks		
Pumps during lifting	0.9	Pumping and repair work do not occur simultaneously.
Repair work without pumps	0.5	
Lighting for road tunnels	1	
Traffic systems	1	Escalators, tunnel ventilation, traffic lights
Power generation		
Power plants in general		
– low-voltage station services	no general figure	
– emergency supplies	1	
Nuclear power plants		
– special needs, e.g. pipe heating, sodium circuit	1	
Cranes	0.7 per crane	Cranes operate on short-time: power requirements depend on operation mode (ports, rolling mills, ship-yards) .
Lifts	0.5 varying widely with time of day	Design voltage drop for simultaneous startup of several lifts

The *type of construction* depends on the station's importance and use (required availability), local environmental conditions and electromechanical stresses.

Construction	Main application
Type-tested draw-out switchgear	Main switching stations Emergency power distribution Motor control centres
Type-tested fixed-mounted switchgear	Substations a.c./d.c. services for h.v. stations Load centres
Cubicles or racks	Light/power switchboards Load centres
Box design	Local distribution, Miniature switchboards

The short-circuit currents must be calculated in terms of project planning activity, the equipment selected in accordance with thermal stresses and the power cable ratings defined. See also Sections 3.2, 7.1 and 13.2. Particularly *important is the selectivity* of the overload and short-circuit protection.

Selective protection means that a fault due to overloading or a short circuit is interrupted by the nearest located switchgear apparatus. Only then can the intact part of the system continue to operate. This is done by suitably grading the current/time characteristics of the protection devices, see also Sections 7.1.4,14.3 and 15.4. The choice of relays can be difficult if account has to be taken of operating conditions with powerful mains infeeds and comparatively weak standby power sources. In some cases changeover secondary protective devices have to be provided.

6.1.5 Station services switchgear in power plants

In a power plant, the electrical station services (abbreviated to SS in the following) consists of all the d.c. facilities from 24 to 220 V and a.c. facilities up to about 20 kV for controlling and supplying power to the equipment needed to keep the plant running.

Hence, these auxiliary services clearly play a vital role in assuring the plant`s reliable operation. Close attention must therefore be paid to requirements affecting the particular plant and the safety considerations, such as the provision of backup systems.

Alternating current (a.c.) station services

The a.c. services for a generating plant unit consist essentially of the SS power transformer, in most cases a medium-voltage distribution net, and low-voltage distribution facilities. They may include a power transformer and the necessary distribution gear fed from separate m.v. network for supplying general loads, i.e. not directly related to the generating unit, and possibly for starting the units and shutting them down. Standby power supplies are dealt with in Chapter 15.

The basic SS arrangement in a so-called unit-type system for a power plant composed of separate units is shown in Fig. 6-3, and corresponding layout for a bus-type system in Fig.6-4. The advantages of the unit-type configuration are that the ratings for the SS distribution facilities are lower, making it easier to cope with short-circuit currents, and that the units are self-contained, so enhanced availability.

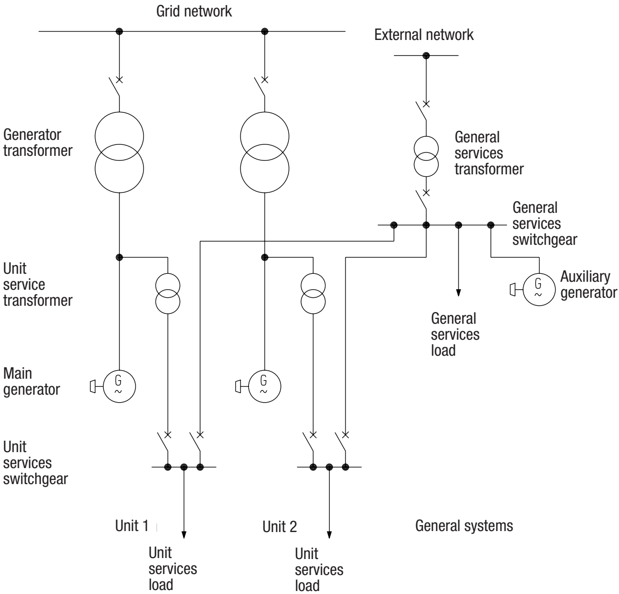


Fig. 6-3:

Basic diagram of SS power supply for a unit-type generating plant

Bus-type system configurations are employed in plants with smaller generators and hence reduced SS power requirements, and have the advantage of lower capital cost. The station services of all power plants are based on these two principal arrangements.

Redundancy in the form of double busbars, cross-links between generating units, etc are possible, giving rise to a grat many alternative layouts.

Special requirements of auxiliary systems for different types of power plants are described on the following pages.

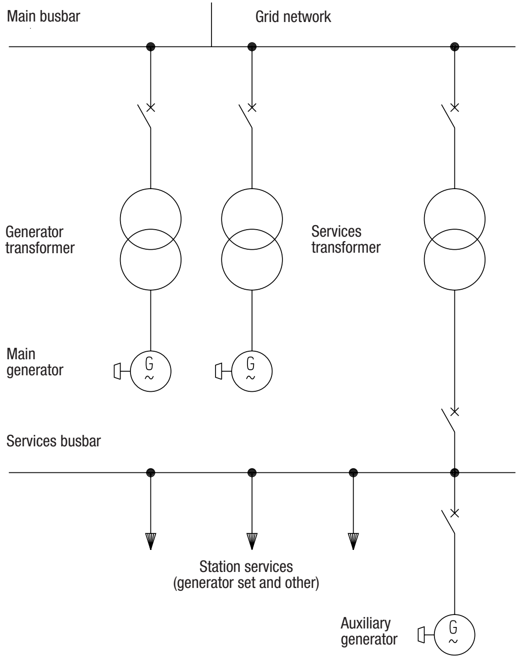


Fig 6-4:

Basic diagram of bus-type SS power supply

Hydro power plants

In hydro power plants the station services require 1-3% of the generators rated power, depending on type and size. Most of the individual motor ratings are below 50 kW. Often the only exceptions to this are ratings of the power house crane, governor oil pumps and dewatering pumps. For this reason, medium-voltage distribution can be dispensed with. Only in the case of long distances to outside installations such as water intake stations, or very extensive power house, is medium- voltage switchgear required.

The unit-type layout is preferred with unit ranges >50MW. An uninterruptible SS power supply is not an absolute necessity. A brief interruption of up to a few minutes does not cause the turbines to trip out because the governor oil pumps are either fed from the station battery, or the governor system has an oil accumulator tank. Nevertheless, standby power facilities (usually a diesel set) or an external supply from a separate medium-voltage network cannot be omitted, since the energy sources mentioned above are available for only a short time and power must be secured for the gates and valves.

Diesel power plants

The SS power requirement in relation to generator output lies between 1% in the case of small sets and 3% for heavy-oil plants. Few of the auxiliaries have ratings above 50 kW. There is therefore no need for medium-voltage equipment. Much of the services power is determined by the number of auxiliaries, which with large heavy-oil engines (> 10 MW) can amount to 100 separate drives per set.

The failure of auxiliary systems such as fuel supply or lube oil causes the generating set to trip within a few seconds. Redundancy with automatic selection is hence necessary both for the auxiliaries and their power feeds. In the case of diesel plants burning heavy fuel oil, facilities should be provided for switching from heavy to light diesel oil if the main services supply fails, to prevent the heavy fuel oil from thickening and so clogging the pipes.

Diesel power plants are chiefly used in "island” networks. Consequently, there is often no secure external supply available and one has to resort to standby power units. With relatively small sets, auxiliaries fed from the station battery (possibly through inverters) can be used in the event of emergency shutdowns. This also applies to starting if the a.c. supply falls, which is more frequently the case with plants running isolated.

Gas turbine / combined-cycle power plants

In pure gas turbine plants, i.e. where the heat in the exhaust gases is not utilized, the SS power of the set when running is about 1% of the unit range. The auxiliaries are usually fairly small, so a medium-voltage level can be dispensed with. This is not so with the starting gear, where gas turbines of any substantial size will need a medium-voltage supply. Widely used are starting systems with static frequency changers, which provide the variable frequency necessary for starting.

Unit-type system is the preferred arrangement. On economy grounds, one starting facility is commonly provided for several units.

In the case of combined-cycle plants, where the exhaust from a gas turbine passes to a heat recovery boiler to raise steam for a turbine set, the proportion of supply power rises to some 3% because of the additional loads in the stream cycle , the cooling-water loop and for the steam turbine-generator.

Conventional steam power plants

The power needed fort he services in coal-fired steam plants amounts to about 7-10% of the unit rated output, and some 5-6% in oil-fired stations. In conventional steam plants the station services are predominantly arranged on the unit-type principle. A medium-voltage level is required chiefly because of the large feedwater drives. A general power supply system is usually provided for starting and shutting down the generator units, but also as a provisional source if a unit`s own supply falls, and to feed loads that are separate from the units. In view of the extended size of such plants there may be several distribution centres for this general supply.The latter obtains its power either from the utility network or, if this cannot be relied on, from the station`s own diesel or gas turbine generating set.

Combined heat and power stations

While the station services for the different types of power plants are to a large extent standardized, the remarkable feature of the SS facilities for combined heat and power

(CHP) stations is their wide variety. The reason is that CHP stations produce such diverse commodities as electricity and heat.

The design of these power plants, and hence of their SS systems, is governed by which of their products has priority.

If the main emphasis is on producing heat, the station services are more likely to be fed from a separate network than by the turboset itself. On the steam side, CHP stations are usually operated in a busbar configuration, in which case this arrangement is also applied on the electrical side. If, in addition to the boilers providing steam for the turbines, peak heating loads call for the use of back-up boilers, these will require power from the station power supply, as will the pumps for circulating hot water if the chosen heating medium is water.

In the event of a boiler or turbine outage, it is rarely possible to draw heat from another network to make up the deficit, a situation that is usually no problem with electricity. The aim is therefore to operate smaller units in parallel, with redundancy.

Direct current (d.c.) station services

Direct-current systems are used for control and monitoring purposes, but also for supplying power to d.c. drives and, as part of an emergency (UPS) system, via inverters to alternating-current drives. The required energy is stored in batteries, with conversion by means of rectifiers and inverters. In normal operations the d.c. loads are fed via the rectifiers. The batteries serve only as a buffer in the event of shortlived high load currents or to brief interruptions in the a.c. supply, particularly to ensure that the generating units are shut down safely.

The d.c. systems employed in generating stations for providing power and for control purposes have voltages of 110 or 220 V, while the increasing use of electronics has also led to self-contained rectifier-battery systems of 24 or 48 V.

As with a.c. station services systems, both unit-type and busbar arrangements are possible, or a mixture of the two (e.g. 220 V as a unit system and 24 V as a busbar system for higher-level control facilities. Redundancy needs to be provide in order to achieve the required reliability.

Automatic station service power transfer

Reliability is greatly enhanced by duplicating parts of an station service system, the power supply for instance. Automatic transfer facilities are therefore needed to ensure trouble-free operation or to guarantee secure startup (see also section 15). Their purpose is to switch the station service loads to another power feed quickly and as far as possible without upsetting the running of the power plant.

6.1.6 Computer-aided calculation of short-circuit currents

A knowledge of the expected short-circuit currents in an installation is essential to the correct selection of the switchgear and the line-side connected networks. The methods of calculation are described in chapter 3.

The upper limit value of these fault currents determines
- the power ratings of the switching devices,
- the mechanical design of the installation,
- the thermal design of the equipment,
- the electrical design and configuration of earthing systems,
- the maximum permissible interference in telecommunications systems.

The lower limit value of these fault currents determines
- overcurrent protection relays and their settings.

The calculation of short-circuit currents therefore helps to solve the following problems:
- Dimensioning of equipment on the basis of (dynamic) stresses on closing and opening and also thermal stresses.
- Design of the network protection system.
- Questions of compensation and earthing.
- Interference problems (e.g. in relation to telecommunications lines).

The NEPLAN® computer program enables simple but comprehensive calculation of short-circuit currents. It takes account of
- different switching conditions of the installations,
- emergency operation,
- cold and hot states of the cable network,
- contribution of motors to short-circuit currents.

The program output provides the short-circuit currents at the fault location and in the branches

a) for the transient phase after occurrence of the fault:
   - Initial symmetrical short-circuit current I''_k
   - Peak short-circuit current i_p
   - Symmetrical short-circuit breaking current I_a

b) for the steady-state phase after occurrence of the fault:
   - Sustained short-circuit current I_kk
   - Short-circuit powers S''_k
   - Voltages at the nodes

The results can be printed out both as phase values (L1, L2, L3) and as component values (positive-sequence, negative-sequence, zero-sequence system).

The comprehensive graphics functions provided by NEPLAN® allow not only the network topology but also phase fault results to be displayed on screen and plotted, see fig. 6-5. The user creates and edits the graphical network display interactively with the mouse. The calculations performed by the program strictly follow the method set out in IEC 60909 (VDE 0102) and described in section 3.3.

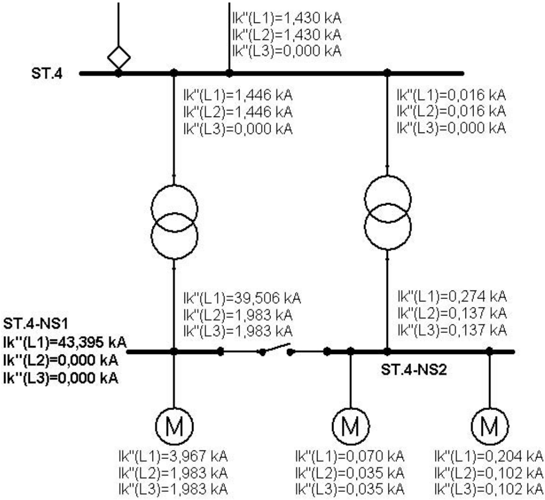


Figure 6-5:

Example of graphic output (plot) of a computer-aided short-circuit current calculation (partial section) by the NEPLAN® PC program.

6.1.7 Computer-aided calculation of cable cross-sections

Before the cross-sections of the cables between the equipment in the switchgear system and the connected loads are finalized, they are to be calculated in relation to the operating conditions and cable lengths.

Factors determining the cross-section in this calculation are as follows:

– Permissible load carrying capacity in normal operation, taking account of the ambient temperature and method of laying.

– Response of protective devices on overload and at the smallest possible short-circuit current to interrupt hazardous touch voltages.

– Permissible voltage drop along the cable line in normal operation and, where applicable, during the start-up phase of motors.

– Thermal short-circuit strength.

The NEPLAN® module developed at ABB makes it possible to carry out this comprehensive calculation for every circuit. By entering the circuit data, such as operating current, max. and min. short-circuit current, tripping currents/times of the protective devices and maximum permitted voltage drops, the program selects the appropriate minimum cross-section to be laid for the relevant cable length. The method of calculation is in accordance with DIN VDE 0100, DIN VDE 0276 and the respective cable manufacturer's data.

6.2 Planning of substations

6.2.1 Modular planning of substations

To deal with ever tighter project schedules, it is essential to continue to increase the degree of prefabrication of switchgear components, to support project management with computerized aids as much as possible, to reduce engineering during the project and to save as much time as possible in assembling and commissioning the equipment.

Efforts similar to the previously achieved progress in modularization and standardization in

- LV switchgear design using type-tested switchgear assemblies (TTA, PTTA) as modular LV switchgear system (ABB MNS system),
- MV switchgear design using type-tested switchbays with standard programs,
- high-current technology with modular structure of generator busducts and circuitbreakers,
- HV switchgear design with gas-insulated switchbay series in modular technology as preassembled, type-tested and pretested bays have been made with optimized primary and secondary technical design in the area of HV outdoor switchgear installations.

6.2.2 Definition of modules

More highly integrated modules and function groups as modules are required to reduce the project periods for switchgear installations.

A module in this sense is a unit or a function group,

- that can execute a self-contained function,
- that has a minimum of interfaces, which are as standardized as possible,
- whose complex function can be described with few parameters,
- that can be prefabricated and pretested to a great extent and
- that can be altered within narrow limits by the smallest possible degree of adaptation engineering for customer demands and requirements while adhering to standards as much as possible.

It is essential that any changes to modules do not detract from the rationalization and quality achieved by type testing, degree of prefabrication and pre-testing.

6.2.3 From the customer requirement to the modular system solution

The progressive deregulation in energy markets and the accompanying downward pressure on costs is resulting in new requirements on the project planning of transformer substations. In addition to the engineering of classical customized installations, the modular switchgear installation concept offers the chance of developing largely standardized and therefore more economical solutions. This is done by implementing a systematic pattern of thinking to yield products with high functionality and combined installation modules. This means that the interfaces are unified and also reduced in number by grouping products into modules.

For project planning and engineering, this means that system solutions are generated from a modular system of components in which the individual modules are precisely described as derived from the technical and economical requirements of a new substation in the network. The available CAD systems are ideally suited for quick and easy combination of complete station components from a catalogue of individual components. The current integrated enterprise resource planning (ERP) software also offer suitable databases and structures that enable quick access to descriptions, parts lists and prices.

The substation planner will have the greatest optimization effect when the customer provides requirements that describe functions only instead of detailed requirements in the form of comprehensive specifications. This gives the engineer the greatest possible freedom to bring the system requirements into conformity with the available modular solutions. In the modular concept, detailed installation requirements that go far beyond the description of functions result in expensive adaptation work, making the overall installation more expensive. Adaptation work in the modular concept is possible, but it always results in extra work in preparing the tender, project planning, engineering, processing and documentation of the installation.

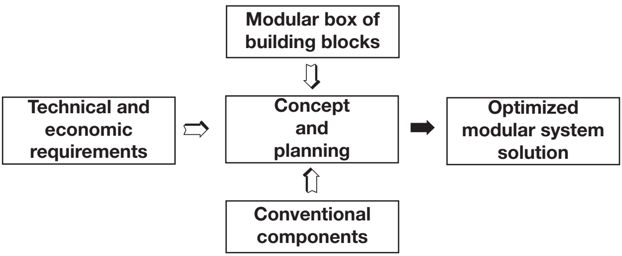


Fig. 6-6

From the functional requirements of the network to the modular system solution

6.2.4 IT tools for computer-aided project management

6.2.4.1 Terms and standards

Schedule of the most important IT terms

PDM Systems
(Product Data Management)
Supports product-related processes in product development, CAD integration, revision management, document management, etc.

SCM Systems
(Supply Chain Management)
The integrated, process-orientated planning and control of flows of goods, information and money throughout the chain of added value from the customer to the raw materials supplier.

E-procurement
Support of the procurement processes by information technology (Internet).

ERP Systems
(Enterprise Resource Planning)
Planning and control of the entire chain of added value in an enterprise. (Purchasing, materials management, production planning and control, quality assurance, warehouse management, personnel and financial management.)

DMS Systems
(Document Management System)
A document management system manages documents created electronically and non-electronically throughout their life cycle.

CAD Systems
(Computer Aided Design/Drafting)
Engineering development and design; compilation of drawings and calculation.
MCAD Mechanical design
ECAD Electrical design (circuit diagrams etc.)

CASE Systems
(Computer Aided Software Engineering)
Systems to support and verify software development.

Collaborative Engineering (CE)
Also known as "Simultaneous Engineering”. Individual steps in product development do not take place in chronological sequence, but simultaneously, using Internet technologies.

MRO Materials
Standard commercial consumable materials and products not relevant to production, which are as a rule procured in large quantities.

Tabelle 6-7

Schedule of the most important standards

Standard	Title
IEC 61346	Industrial systems, installations and equipment and industrial products - Structuring principles and reference designations
IEC 61355	Classification and designation of documents for plants, systems and equipment
IEC 61082	Preparation of documents used in electrotechnology
IEC 61360	Standard data element types with associated classification scheme for electric components
IEC 81714	Design of graphical symbols for use in the technical documentation of products
IEC 60617	Graphical Symbols (IEC database)
IEC 82045	Document management
IEC 61286	Information technology - Coded graphic character set for use in the preparation of documents used in electrotechnology and for information interchange
IEC 62023	Structuring of technical information and documentation
IEC 62027	Preparation of parts lists
IEC 61175	Industrial systems, installations and equipment and industrial products - Designation of signals
ISO 10303	Product data representation and exchange

6.2.4.2 Schedule of the most important file formats and interfaces

BMP (Bitmap Picture)
Raster image in bitmap format

JPEG (Joint Photographic Experts Group)
Image file

GIF (Graphics Image Format)
Image file

DGN
File format of the MicroStation CAD program from Bentley

DWG
Standard file format for saving vector graphics in AutoCAD

DXF (Drawing Exchange Format)
Drawing exchange format for vector data, originally for AutoCAD

EDIF (Electronic Design Interchange Format)
Mostly for digital and analog components

HPGL (Hewlett Packard Graphics Language)
Standard file format for vector graphics

IGES (Initial Graphics Exchange Specification)
Interface developed in the USA under the auspices of the National Bureau of Standards, orientated towards the transfer of geometry data between different CAD/CAM systems, mainly in the field of mechanical design.

PDF (Portable Document Format) Document format from Adobe
Texts and image data can be presented together in a uniform document. As PDF documents can be exchanged without problems between various software platforms, this format has achieved a certain popularity.

TIFF (Tagged image file format)
Raster data, pixel graphics

VNS (Verfahrensneutrale Schnittstelle für Schaltplandaten – Process-neutral interface for circuit diagram data)
Unofficial but widespread German interface for exchange of documentation for electrotechnical systems.

Interfaces for high quality data exchange are increasingly gaining in importance for CAD/CAE applications.

The familiar interfaces IGES and DXF are only suitable for the exchange of simple graphical information. Higher quality interfaces, such as VNS (**V**erfahrens-**N**eutrale Schnittstelle für Schaltplandaten to DIN V 40950 2^{nd} edition) provide opportunities on a significantly higher level to transfer graphical and logical information between electrical engineering systems and CAD systems. This interface is however only customary in Germany. A fully comprehensive exchange of information is, finally, achieved by STEP (**ST**andard for the **E**xchange of **P**roduct model data to ISO/IEC 10303). Data transfer via STEP presupposes the availability of STEP-compliant tools with object-orientated databases. The interface properties defined as application models for the various applications have been published as standards for mechanical engineering (AP 214) and for electrical engineering (AP 212).

VRML (Virtual Reality Markup Language)
Language describing 3D scenes and their geometry, lighting, animation and interaction features. Most 3D modelling tools facilitate import and export of VRML files, which has allowed this file format to become established as an exchange format for 3D models.

JT
JT is a file format from the UGS PLM Solutions company which facilitates product visualization, information distribution and common data use by various PLM programs. It is also used by CAD systems for open data exchange with PDM systems.

6.2.5 Computer-aided project management

As a result of the different viewpoints of those concerned with planning with regard to the trades involved in a switchgear installation and the sometimes lengthy planning stages between compilation of a bid and the construction of the system, project planning places extremely high demands on the computer-aided procedures and data management systems.

These procedures are predominantly aimed at facilitating and supporting the business models qualitatively (by reducing error and defect costs) and quantitatively (reducing costs by reuse). The basis of this is the modularization described in 6.2.1.

Current interest focuses especially on the data management and communication processes (Product Data Management and Collaborative Engineering).

As the persons involved in the planning process are often working together and communicating from different parts of the world, the need for processes to support information exchange and graphically display various views of the switchgear system has been continuously growing in recent years.

IT technologies to support a distributed work platform and communication in global projects with customers, their consultants and the subcontractors are of especial importance. These processes represent the backbone of rapid and effective project planning.

The widespread availability of the Internet has brought about major changes in the selection of and communication with suppliers in recent years (eCommerce).

In addition, the customers and future system operators now have increased demand for integration of the system supplied in their networks and information systems.

Internet technologies now permit the online use of product configuration tools in early phases of bid compilation.

This presupposes a clearly structured product portfolio and a modular product structure.

In method support, the trend is one towards modular product platforms which can be adapted to suit various markets and applications.

A virtual switchgear model assists in distributed planning and communication.

In recent years, the communication processes, technologies and protocols of the Internet have enriched our opportunities for access to product information and navigation. Improved configuration tools can also be developed on the basis of a clearly structured model. The trend towards standardization and modularization of the fundamental components in a system will therefore continue. Only in this way can complex systems be configured and the overall delivery periods and costs reduced.

The virtual, digitally available product model has an influence on the structuring of documentation in various phases of the design, procurement, production and operation of the switchgear system (Product Data Management). That is why the infrastructure and logistics of passing on information play such an important role in this application.

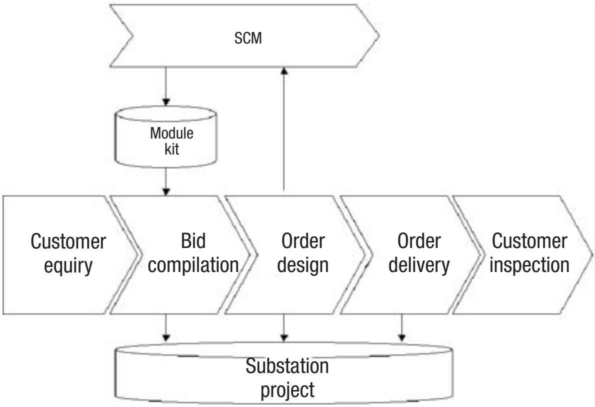


Figure 6-7 shows the planning phases which are most important here.

The individual phases/process steps are considered separately below.

SCM (Supply Chain Management)

Assures the quality and quantity of the information in the module kit, which forms the basis of reuse and the associated increases in productivity and efficiency addressed above.

Module kit

Represents the product portfolio, and is to be managed with a high quality standard as it is the basic requirement for the following processes.

Customer enquiry

The most important part of the entire process chain, as the requirements have to be defined and verified here both functionally and commercially, to be used as input for the following process steps.

Bid compilation

Compilation of the functional and commercial specification on the basis of the customer enquiry.

Importance must be attached here to high quality and short throughput times. This is ensured by a module kit. Special customer requirements are then defined in a further design step. It is important here to establish the product/project structure in such a way as not to incur additional revision work in subsequent steps.

Order design

On receipt of the order, the bid structure can be adopted and the detailed engineering of the system can begin. The planning is firmed up in this process step and all documents prepared and compiled for delivery.

In addition, the purchasing department has to order all the parts.

Order delivery

This process step is performed locally at site. In terms of information management this means that all the documents and information required must be available and, when amendments are made at site, these amendments are included accordingly in the project documentation, as this is the basis for customer inspection.

Customer inspection

Functional and commercial inspection and acceptance of the project/product delivered.

Transformer substation project

Protected software environment in which the project/product is virtually planned, specified and managed. Secure revision management is highly important for the performance of the project, and it is ensured that the persons responsible and involved are informed of the version and status of all revisions.

6.3 Reference designations and preparation of documents

Two important series of standards have guided the rules for the reference designation of equipment and the preparation of circuit documents for many years. The symbols for individual devices were specified in the DIN 40900 series, and the DIN 40719 series regulated reference designation and representation.

The two series of standards have been superseded in the context of international standardization in the IEC. DIN 40900 has been replaced by the IEC 60617 series. The changes are minor, because DIN 40900 was already based on an earlier version

of the international standard IEC 60617. The most important parts of DIN 40719 were superseded by IEC 61082 as early as 1996/97. The structure of reference designation systems has been fundamentally revised on an international level. IEC 61346-1 describes the general rules. With the publication of IEC 61346-2 containing the tables of code letters, the last part of DIN 40719, Part 2, was withdrawn.

The change from "item designations for electrical equipment” in accordance with DIN 40719-2 to the new standard IEC 61346, "Structuring principles and reference designations” took place only very hesitantly. The following section presents the structuring principles and reference designation system of IEC 61346. The most important designation tables from the old standard DIN 40719 are included once again in section 6.3.4.

6.3.1 Structuring principles and reference designations to IEC 61346

If, in the past, designations in electrical systems were determined by means of designation blocks and firmly assigned tables for specified data positions within those designation blocks, now, however, the focus is on a hierarchical structure with reference designations derived from that. Such structures are based on „component relationships". The elements in a lower order level of a hierarchical structure are always complete components of the next higher level. The structure established in this way can be represented as a tree structure with nodes and branches.

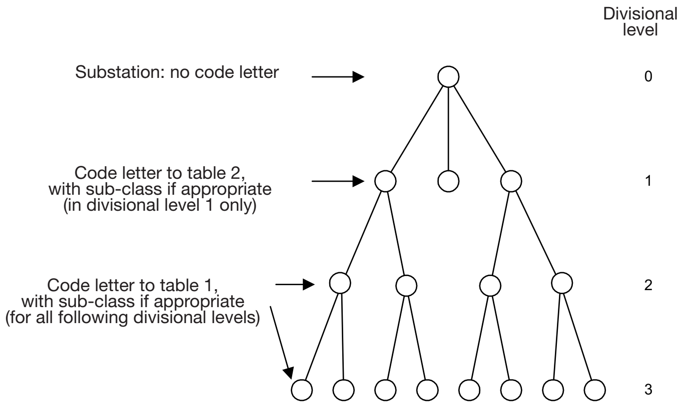


Figure 6-8 Assignment of classes to divisional levels

On divisional level 1 to figure 6-6, selection of code letters is performed on the basis of Table 2 of IEC 61346-2, „Classes of infrastructure objects". Table 6-8 below shows this table 2 from the standard in a specific version for the field of application of switchgear.

Table 6-8 Classes of infrastructure objects

	Code	Object class definition	Examples
Objects for common tasks	A	Objects related to two or more classes of infrastructure objects of classes B to Z.	Supervisory control system ripple control equipment PLC-equipment
Objects for main process facilities	B	Installations for > 420 kV	
	C	Installations for. ≤ 420 kV	
	D	Installations for 220 kV ... <380 kV	
	E	Installations for 110 kV ... <220 kV	
	F	Installations for 60 kV ... <110 kV	
	G	Installations for 45 kV ...<60 kV	
	H	Installations for 30 kV ...<45 kV	
	J	Installations for 20 kV ...<30 kV	
	K	Installations for 10 kV ...<20 kV	
	L	Installations for 6 kV ...<10 kV	
	M	Installations for 1 kV ...<6 kV	
	N	Installations for <1 kV	
	P	Objects for equipotential bonding	Earthing protection Lightning protection
	Q, R, S	Free	
	T	Transformer plants	
	U	Free	
	V	Objects for the storage of material or goods	Finished good stores Raw material stores Water tank plant Oil tank plant
	W	Objects for administrative or social purposes or tasks	Canteen Office Recreation area Garage
Objects not related to the main process	X	Objects for fulfilling auxiliary purposes or tasks outwith the main process (for example on a site, in a plant or building)	Air-conditioning system Alarm system, Clock system Lighting installation, Electric power distribution Fire protection system Security system Water supply Crane
	Y	Objects for communication and information tasks	Computer network Telephone system Video surveillance system Antenna system
	Z	Objects for housing or enclosing technical systems or installations like areas and buildings	Building Constructional facilities Factory site Road Wall, fence

Table 1 of IEC 61346-2 stipulates code letters for "Classification of objects by purpose or task”. Classification by these code letters is applied for all divisional levels following level 2 down to the necessary divisional depth. Table 6-9 shows examples of the classification of functions and products in electrical power distribution with the assignment of code letters and definitions to IEC 61346-2.

Table 6-9 – Examples for the classification of functions and products in electrical energy distribution.

Code -	Purpose or task of object (acc. IEC 61346-2)	Examples of terms describing purpose or task of objects and functions	Examples for products
A	two or more purposes This class is only for objects for which no main purpose can be identified		Bay/protection controller Touch screen
B	converting an input variable (physical property, condition or event) into a signal for further processing	detecting measuring* monitoring sensing weighing* *picking-up of values	Buchholz relay Detector Fire detector Gas detector Measuring element Measuring relay Measuring shunt Measuring transformer Microphone Movement detector Photocell Pilot switch Position switch Proximity switch Proximity sensor Protective relay Sensor Smoke sensor Tachogenerator Temperature sensor Thermal overload relay Video camera
C	storing of material, energy or information	recording storing	Buffer (store) Buffer battery Capacitor Event recorder (mainly storing) Hard disk Memory RAM Storage battery Tape recorder (mainly storing) Video recorder (mainly storing) Voltage recorder (mainly storing)

Code -	Purpose or task of object (acc. IEC 61346-2)	Examples of terms describing purpose or task of objects and functions	Examples for products
D	reserved for future standardization		
E	providing radiant or thermal energy	cooling heating lighting radiating	Boiler Fluorescent lamp Heater Lamp Lamp bulb Laser Luminaire Maser Radiator
F	protecting directly (selfacting) a flow of energy, signals, personnel or equipment from dangerous or unwanted conditions including: systems and equipment for protective purposes Schützen	absorbing guarding preventing protecting securing- shielding	Cathodic protection Anode Faraday cage Fuse Miniature circuit-breaker Surge diverter Sichern Thermal overload release
G	Initiating a flow of energy or material Generating signals used as information carriers or reference source Producing a new kind of energy, material or product	Assembling crushing disassembling generating material removing milling mixing producing	Dry cell battery Dynamo Fuel cell Generator Power generator Rotating generator Signal generator Solar cell Wave generator
H	Reserved for future standardization		
J	Reserved for future standardization		
K	Processing (receiving, treating and providing) signals or information (excluding objects for protective purposes, see class F)	Closing (control circuits), continuous controlling, opening (control circuits), switching, synchronizing	All-or-nothing relay Analogue integrated circuit Automatic paralleling device Binary integrated circuit Contactor relay CPU Delay element Delay line Electronic valve Electronic tube Feedback controller Filter Induction stirrer Microprocessor Process computer Programmable controller Synchronizing device Time relay Transistor
L	Reserved for future standardization		

Code -	Purpose or task of object (acc. IEC 61346-2)	Examples of terms describing purpose or task of objects and functions	Examples for products
M	Providing mechanical energy (rotational or linear mechanical motion) for driving purposes	Actuating driving	Actuator Actuating coil Electric motor Linear motor
N	Reserved for future standardization		
P	Presenting information	Alarming communication displaying indicating informing measuring (presentation of quantities) presenting printing warning	Acoustical signal device Ammeter Bell Clock Continuous line recorder Display unit Electromechanical indicator Event counter Geiger counter LED Loudspeaker Optical signal device Printer Recording voltmeter Signal lamp Signal vibrator Synchronoscope Voltmeter Wattmeter Watt-hour meter
Q	Controlled switching or varying a flow of energy, of signals or of material	Opening (energy, signals and material flow) Closing (energy, signals and material flow) Switching (energy, signals and material flow) clutching	Circuit-breaker Contactor (for power) Disconnector Fuse switch Fuse-switch-disconnector Motor starter Power transistor Slip-ring short-circuiter Switch (for power) Thyristor (If main purpose is protection, see class F)
R	Restricting or stabilizing motion or a flow of energy, information or material	Blocking damping restricting limiting stabilizing	Diode Inductor Limiter Resistor
S	Converting a manual operation into a signal for further processing	Influencing manually controlling selecting	Control switch Discrepancy switch Keyboard Light pen Mouse Push-button switch Selector switch Set-point adjuster

Code -	Purpose or task of object (acc. IEC 61346-2)	Examples of terms describing purpose or task of objects and functions	Examples for products
T	Conversion of energy maintaining the kind of energy Conversion of an established signal maintaining the content of information Conversion of the form or shape of a material	Amplifying modulating transforming casting compressing converting cutting expanding material deforming size enlargement/ reduction, turning	AC/DC converter Amplifier Antenna Demodulator Frequency changer Measuring transducer Measuring transmitter Modulator Power transformer Rectifier Rectifier station Signal converter Signal transformer Telephone set Transducer
U	Keeping objects in a defined position	Bearing carrying holding sujpporting	Insulator
V	Processing (treating) of material or products (including preparatory and post-treatment)	Coating Cleaning Dehydrating Derusting Drying Filtering Heat treatment Packing Preconditioning Recovering Re-finishing Sealing Separating Sorting Stirring Surface treatment Wrapping	Filter
W	Guiding or transporting energy, signals, material or products from one place to another	Conducting distributing guiding leading positioning transporting	Busbar cable conductor information bus optical fibre through bushing waveguide
X	Connecting objects	Connecting coupling joining	Connector plug connector terminal terminal block terminal strip
Y	Reserved for future standardization		
Z	Reserved for future standardization		

In contrast to the rigid designation blocks of the old standard, the make-up of the reference designation to IEC 61346 is flexible. It is determined by the structure selected.

Under the terms of IEC 61346, each object considered can be structured according to three different points of view, known as aspects:

– A function-based aspect
– A product-based aspect
– A location-based aspect

Reference designations derived from these are marked with the relevant leading sign:

= Function designation
- Product designation
+ Location designation

It must be noted that the leading signs in the new standard have a different meaning from those in the old standard. The combination of designation blocks that was customary in the old standard is also no longer applicable here.

IEC 61346-3 presents a guide to a systematic procedure which can be adopted for structuring and designating. To summarize, the following steps are recommended:

– Clear identification and naming of the object to be considered.
– Decision on which aspects are to be used.
– Identification of the component objects in the relevant aspect.
– Further subdivision of those component aspects in the same aspect.
– Classification and designation of each component object defined.

The IG EVU[1]) has established a number of simple rules for the application of the new standard in the field of switchgear installations:

– The function-based structure and corresponding reference designations are used for the unequivocal identification of objects and describe purposes or tasks (functions), irrespective of their implementation.
– The product-based structure and corresponding reference designations are used to identify components, assembly units, parts of systems and complete systems, etc.
– The location-based structure and corresponding reference designations are used to identify localities such as site, building, floor, room, space, etc.
– The three different structures should preferably be treated separately and the objects carry cross-references to each other if necessary.
– It is recommended to dispense as extensively as possible with transitions between the structures as described in IEC61346-1.
– Designation of phase assignment is to be treated as an independent technical attribute and not as part of the reference designation..
– The structures and the class assignments used are to be documented.

If these rules are followed and the stipulated code letters used, the result is the unequivocal reference designations for functions, products and locations, in accordance with the selected structure.

1) Interest Group of German Power Supply Utilities

Reference designations are formed by linking the single level reference designations assigned to the individual nodes, working through the relevant path in the tree structure from top to bottom. Reference designations in the following form are created (example of a product-based structure):

-A1B1C1D1

The following notations are identical in meaning: -A1-B1-C1-D1 or -A1.B1.C1.D1

Full stops can be used as separators, and do not have any meaning of their own, but rather that of the leading sign they replace.

The function-based structure is stipulated in an early planning phase of the substation.

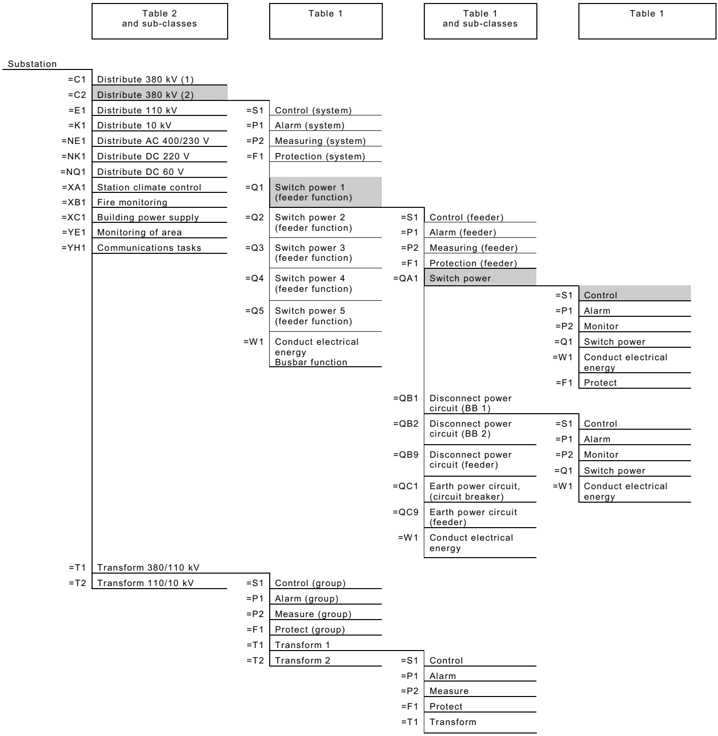
It assists in the systematic recording and description of the functions to be performed (operator's requirements). In this context it is not normally necessary to know and take account of how the functions will be implemented.

The product-based structure documents how physical objects (systems, parts of systems, units, assemblies, etc.) are composed, i.e. which parts they consist of.

In the location-based structure, places for and within the station are stipulated, so as to facilitate orientation in its topography.

The following three illustrations show examples of possible structures for a switchgear installation in the function aspect, product aspect and location aspect.

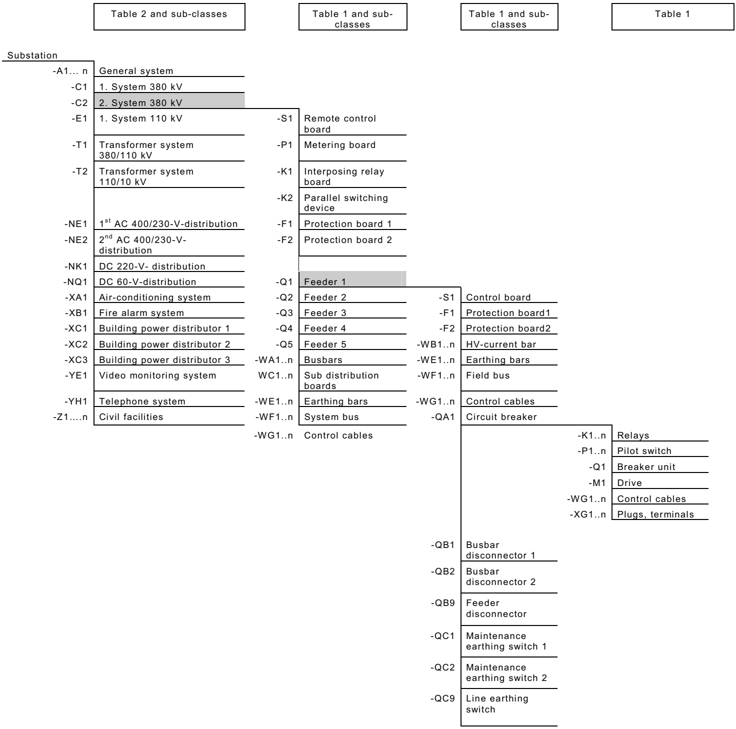
Figure 6-9 shows an example of the function-based structure of a 380/110/10 kV-switchgear system with the reference designations assigned.



Examples

Object	Referance designation	Alternative
Control of the task „switch power" of feeder function 1 of the 2nd 380 kV distribution function	=C2Q1QA1S1	=C2=Q1=QA1=S1
The task „protect" in feeder function 5 of the 2nd 380 kV distribution function	=C2Q5F1	=C2=Q5=F1

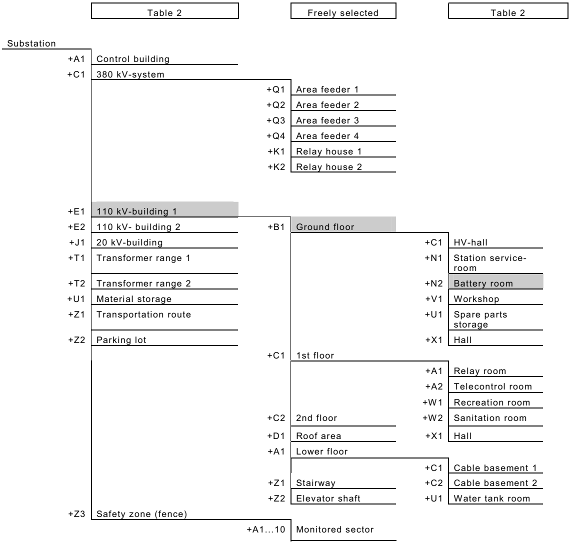
Figure 6-10
Example of a product-based structure and assigned reference designations



Examples

Object	Referance designation	Alternative
Relay in control board of feeder 1 of the second 380 kV system	-C2Q1S1K1	-C2-Q1-S1-K1
Protection board of feeder 5 of the 2nd 380 kV system	-C2Q5F1	-C2-Q5-F1

Figure 6-11
Example of a location-based structure and assigned reference designations



Examples

Object	Referance designation	Alternative
Battery room in ground floor of the 1st 110 kV building	+E1B1N2	+E1+B1+N2
The 7th monitored sector in the defined security zone (fenced area of the station)	+Z3A7	+Z3+A7

Drawing on the stipulations of the old standard, recommendations have also been issued on designations of switching devices and instrument transformers in high and medium voltage switchgear following the new rules.

Table 6-10
Recommended designations for switching devices in high and medium voltage switchgear

Device type	Reference designation
Circuit breaker, load break switch	
1. Switch	-QA1
2. Switch	-QA2
n. Switch	-QAn
Disconnector	
Disconnector for busbar 1 ... 4	-QB1 ... 4
Freely accessible	-QB5
2. Disconnector for busbar 1 ... 4	-QB10, 20, ... 40
Freely accessible	-QB6
Disconnector for transfer bus	-QB7
Freely accessible (for example disconnector for 2nd transfer bus)	-QB8
Disconnector for line	-QB9
Several disconnectors for lines	-QB91, 92, ... 99
Disconnector for sectionalizing of busbar 1	-QB11, 12, ... 19
Disconnector for sectionalizing of busbar 2	-QB21, 22, ... 29
Disconnector for sectionalizing of busbar 3	-QB31, 32, ... 39
Disconnector for sectionalizing of busbar 4	-QB41, 42, ... 49
Freely accessible	-QB51, 52, ... 59
Freely accessible	-QB61, 62, ... 69
Disconnector for sectionalizing of transfer bus 1	-QB71, 72, ... 79
Disconnector for sectionalizing of transfer bus 2	-QB81, 82, ... 89
Earthing switch	
Earthing switch	-QC1, -QC2, -QC3
Freely accessible	-QC4 ... 8
Earthing switch for line	-QC9
Several earthing switches for line	-QC91, 92, ... 99
Earthing switch for busbar 1	-QC11, 12, ... 19
Earthing switch for busbar 2	-QC21, 22, ... 29
Earthing switch for busbar 3	-QC31, 32, ... 39
Earthing switch for busbar 4	-QC41, 42, ... 49
Freely accessible	-QC51, 52, ... 59
Freely accessible	-QC61, 62, ... 69
Earthing switch for transfer bus 1	-QC71, 72, ... 79
Freely accessible (e.g. earthing switch for transfer bus 2)	-QC81, 82, ... 89

Table 6-11
Recommended designations for instrument transformers in high and medium voltage systems

Current transformer	
1. Current transformer	-B1
2. Current transformer	-B2
3. Current transformer	-B3
4. Current transformer	-B4
Current transformer in busbar 1	-B11, 12, 13, ...
Current transformer in busbar 2	-B21, 22, 23, ...
Current transformer in busbar 3	-B31, 32, 33, ...
Current transformer in busbar 4	-B41, 42, 43, ...
Current transformer in line	-B91, 92, 93, ...
Voltage transformer	
1. Voltage transformer	-B5
2. Voltage transformer	-B6
Freely accessible	-B7, 8, 9
Voltage transformer on busbar section 1	-B51, 52, 53, ..
Voltage transformer on busbar section 2	-B61, 62, 63, ..

Table 6-12
Comparison of the old and the new reference designations for switching devices

Device type	Reference designation (new)	old
Circuit breaker, load break switch		-Q0
1. Switch	-QA1	-Q01
2. Switch	-QA2	-Q02
Busbar system 1		
Disconnector for busbar	-QB1	-Q1
2nd disconnector for busbar	-QB10	-Q10
Disconnector for sectionalizing	-QB11, 12, ... 19	-Q11 ... 14
Earthing switch for busbar	-QC11, 12, ... 19	-Q15 ... 19
Busbar system 2		
Disconnector for busbar	-QB2	-Q2
2nd disconnector for busbar	-QB20	-Q20
Disconnector for sectionalizing	-QB21, 22, ... 29	-Q21 ... 24
Earthing switch for busbar	-QC21, 22, ... 29	-Q25 ... 29
Busbar system 3		
Disconnector for busbar	-QB3	-Q3
2nd disconnector for busbar	-QB30	-Q30
Disconnector for sectionalizing	-QB31, 32, ... 39	-Q31 ... 34
Earthing switch for busbar	-QC31, 32, ... 39	-Q35 ... 39

Device type	Reference designation (new)	old
Busbar system 4		
Disconnector for busbar	-QB4	-Q4
2nd disconnector for busbar	-QB40	-Q40
Disconnector for sectionalizing	-QB41, 42, ... 49	-Q41 ... 44
Earthing switch general	-QC41, 42, ... 49	-Q45 ... 49
Earthing switch, general		-Q5
1. Earthing switch	-QC1	-Q51
2. Earthing switch	-QC2	-Q52
3. Earthing switch	-QC3	---
Transfer bus 1		
Disconnector	-QB7	-Q7
2nd disconnector	-QB70	-Q70
Disconnector for sectionalizing	-QB71, 72, ... 79	-Q71 ... 74
Earthing switch for transfer bus	-QC71, 72, ... 79	-Q75 ... 79
Transfer bus 2		
Disconnector	-QB8	
2nd disconnector	-QB80	
Disconnector for sectionalizing	-QB81, 82, ... 89	
Earthing switch for transfer bus	-QE81, 82, ... 89	
Disconnector for line		
General	-QB9	-Q9
Several disconnectors	-QB91, 92, ... 99	-Q91, Q92
Earthing switch for feeder		
General	-QC9	-Q8
Several earthing switches	-QC91, 92, ... 99	-Q81, Q82
Free;		
e.g. earthing switch for transformer star point	unoccupied numbers for example -QC6	-Q6

6.3.2 Preparation of documents

As per IEC 61082, "document" is defined as "information on a data medium"; "documentation" as:

– collection of documents related to a given subject, and
– processing of documents.

The "standard" classification for documents in electrical engineering as per DIN 40719 distinguishes between a) purpose and b) type of representation. The most important parts of DIN 40719 were superseded by DIN EN 61082 in 1996. This standard is a direct translation of the international standard IEC 61082 "Preparation of documents used in electrotechnology". Document classification is also covered here – including new terms in some cases. The following definitions of the new standard can be assigned to the term "purpose" in the old standard without problems:

– Function oriented documents
– Location documents
– Connection documents
– Item lists
– Installation-specific documents
– Other documents
– Commissioning-specific documents
– Operation-specific documents
– Maintenance-specific documents
– Reliability and maintainability-specific documents

Regarding the "type of representation", the new standard distinguishes the following types:

– Attached representation
– Semi-attached representation
– Detached representation
– Repeated representation
– Grouped representation
– Dispersed representation
– Multi-line representation
– Single-line representation

A distinction is also made between a "functional oriented layout" and a "topographical oriented layout" in the types of representations for circuit diagrams.

An important change from the former practice as per DIN 40719 is the strict separation of title block data and information on the reference designation (formerly equipment identification). Common designation blocks for represented equipment may no longer be given in the title block. Only data relevant to the document itself is given here now. Higher-order parts of the reference designation must be given at the specified positions in the drawing field (e.g. top left of the circuit diagram).

The following definitions from IEC 61082 and descriptions are given for some documents – important for substation engineering.

Overview diagram
An overview diagram is a relatively simple diagram often using single-line representation, showing the main interrelations or connections among the items within a system, subsystem, installation, part, equipment or software (Fig. 6-12).
The overview diagram of a switchgear should include, as the minimum information, the reference designation of the station components and of the equipment represented and also the most important technical data. The designation and cross-references to documents of a lower level should also be included.

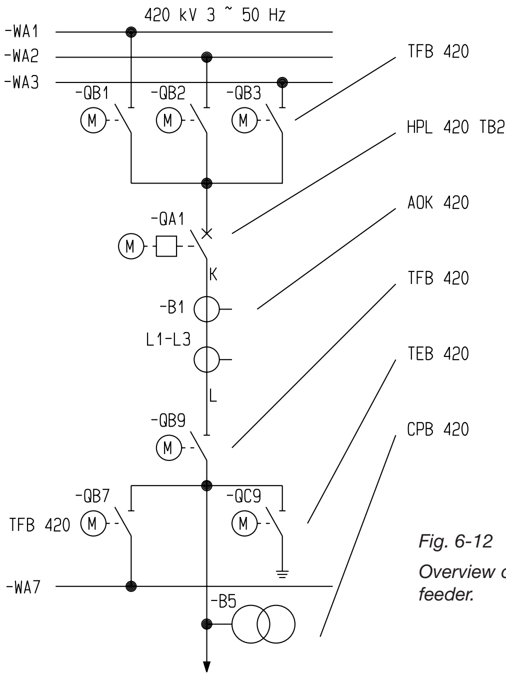


Fig. 6-12

Overview diagram of a 420 kV feeder.

Function chart
A function chart is a diagram that describes the functions and behaviour of a control or regulation system using steps and transitions.

Circuit diagram
The circuit diagram is the diagram that shows the circuits of a functional or structural unit or an installation as they are implemented. The parts and connections are represented by graphical symbols. Their configuration must show the function. The size, shape and location of the equipment does not need to be considered (Fig. 6-13).

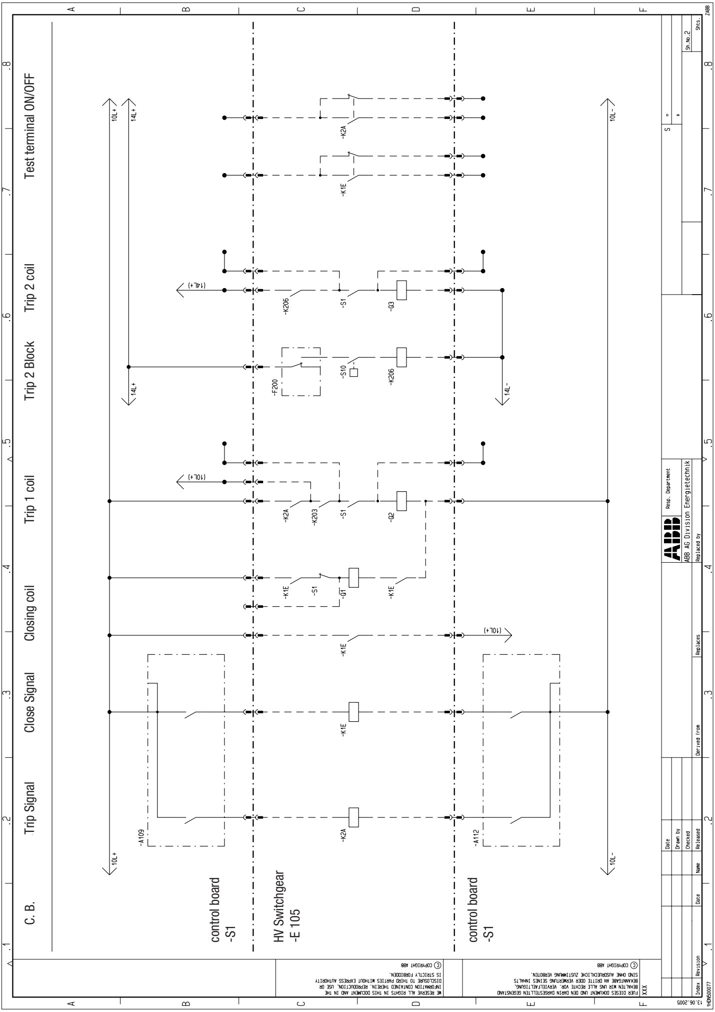


Fig. 6-13

Circuit diagram

The circuit diagram for a feeder or a functional unit is generally subdivided into function groups, such as control, position indication, interlocking, alarm, synchronization, protection, measuring etc. Above the current path, a short description of the represented subfunction using keywords is useful. The most important part of the circuit diagram is the information on following circuits or signals and notes on further representations.

Terminal function diagram
A circuit diagram for a functional unit, which shows the terminals for the interface connection and describes the internal functions. The internal functions may be shown or described in simplified form.

Arrangement drawing
A drawing showing the location and/or the physical implementation of a group of associated or assembled parts.

Terminal connection diagram
A diagram that shows the terminals of a construtional unit and the internal and/
or external connections.

6.3.3 Classification and designation of documents

The international standard IEC 61355 has the title “Classification and designation of documents for plants, systems and equipment”. The goal of this standard is described as follows in its introduction:

> *One aim of this standard is to establish a method for better communication and understanding between parties involved in document interchange. In order to get a basis for a system, it is necessary to disregard, more or less, what a document is called today. Different names are in use for the same document kind or the names may have different meanings for different parties. The purpose and object of interest are sometimes also part of document titles, which hampers general understanding. Therefore the basis for a common understanding should be a classification scheme which is based only on the content of information.*
>
> *Another aim of this standard is to set up rules for relating documents to the objects they describe. For this purpose a document designation system is provided, linking the document kind designation to the object designation used within the plant, system or equipment. Following the rules and recommendations given, the documentation reflects the structure of the “real installation”. By that also guidance is given for order and filing as well as for structured searching for information, for example in document retrieval systems.*

The principle of classification also covers the needs of computer-based documentation in general. An increasing amount of information will be stored and interchanged in a standardized data base format. The information to be delivered may be specified in such a way that each document kind required and agreed tby parties can be derived from that data base by the receiver's computer system.

This standard specifies a generally valid "Document kind Classification Code (DCC)" for the first time and explains it in a detailed table with examples – see the fields with grey background in the following table.
Documents are identified in accordance with the following scheme:

= + −	A .... N	&	A1	A2	A3	N	N	N	/	A	....	N

Object designation

Prefix sign

Identifying letters and numbers

Prefix sign

Counting numbers of sheets

The letter symbol "A1" stands for the Technical Area, e.g. "E" for electrotechnology; the letter symbol "A2" stands for the "Main Document Kind Class", e.g. "F" for function-describing documents; the letter symbol "A3" stands for the "Document Type Subclass", e.g. "S" for circuit diagram.
Object designation follows the rules of IEC 61346. The page number after the prefix sign "/" has a maximum of six data spaces.
Table 6-13 shows examples of document kind classes from switchgear installation technology.

Table 6-15
Examples for documents in switchgear installations

Letter symbol **2nd & 3rd A position as per IEC 61355**	**Document kind; examples from switchgear installation technology**
	Documentation describing documents
AA	Administrative documents: cover sheets, documentation structure, designation system
AB	Tables: lists of documents, lists of contents
	Management documents
B	Document list, schedule, delivery list, training documentation, letters, memos
	General technical documents
DA	Dimension drawings, circuit diagrams for equipment
DC	Operating and maintenance instructions
	Technical requirements and dimensioning documents
E	Environmental conditions, studies, calculations
	Function-describing documents
FA	Overview diagrams, network maps
FB	Flowcharts, block diagrams
FE	Function descriptions
FF	Function diagrams
FP	Signal descriptions, signal lists
FS	Circuit diagrams
FT	Software-specific documents
	Location documents
LD	Site plan, cable routing drawings, earthing plans, layouts, dispositions, sections
LH	Building plans
LU	Assembly drawings, arrangement drawings, equipment layout ˇ diagrams
	Connection-describing documents
MA	Terminal diagrams, connection diagrams, interconnection diagram
MB	Cable tables, cable lists
	Documents listing material
PA	Material lists (conduits, stranded wires, terminals, bolts ...)
PB	Parts lists, spare parts lists, lable lists
	Quality managment documents
QA	Test reports, test certifications, audit reports

6.3.4 Drawings

In technical drawings the information required for constructing and operating an installation or a station component is given in a font that is “readable” for engineers and technicians. The drawings, or these days preferably referred to as documents, are therefore subject to specific, generally accepted rules and implementation guidelines, which are based on national and international standards. The specifications cover such items as:

– Paper formats, paper types
– Representation, symbols, characters
– Lettering, font sizes
– General design, header, metadata
– Document types, -identification and -order
– Creation of documents, processing
– Minimum content of documents

6.3.4.1 Drawing formats

Table 6-14

A-series formats as per DIN 6771-6, and ISO 5457

Format symbol	Size		Number of fields	
	cut	uncut	short side	long side
A0	841 x 1189	880 x 1230	16	24
A1	594 x 841	625 x 880	12	16
A2	420 x 594	450 x 625	8	12
A3	297 x 420	330 x 450	6	8
A4	210 x 297	240 x 330	4	6

Table 6-15

Continuous formats as per DIN 6771-6

Format symbol	Size		Number of fields	
	cut	uncut	short side	long side
A2.0	420 x 1189	450 x 1230	8	24
A2.1	420 x 841	420 x 880	8	16
A3.0	297 x 1189	330 x 1230	6	24
A3.1	297 x 841	330 x 880	6	16
A3.2	297 x 594	330 x 625	6	12

Continuous formats should be avoided as far as possible.
For formats >A0, see DIN 476.

6.3.4.2 Standards for representation

The rules for representation in electrical engineering documents are specified in ICE and DIN standards. Table 6-16 gives an overview of the most important standards covering the preparation of electrical engineering documents.

Table 6-16
Overview of important standards for the preparation of drawings

Standard or Part	Edition	Title
ISO 128-30	05.02	Representation, views, sections
ISO 128-24	12.99	Basics, lines
ISO 7200	05.04	Data fields for Title blocks
DIN 6771-5	10.77	Standard forms for technical documentation; circuit diagram in A3 format
ISO 3098	04.76	Lettering, graphic characters
IEC 61082-1	04.06	Preparation of documents used in electro-technology – Part 1: Rules
IEC 61346-1	03.96	Structuring principles and reference designations ˜ Part 1: General requirements
IEC 61175	09.05	Designations for signals
IEC 61355	04.97	Classification and designation of documents for plants, systems and equipment

(continued)

Table 6-24 (continued)
Overview of important standards for the preparation of drawings

Standard or Part	Edition	Title
IEC 60617		Graphical symbols for diagrams; IEC database
IEC 61360-1	01.04	Standard data element types with associated classification scheme for electric components – Part 1: Definitions - principles and methods
IEC 61360-2	02.04	Standard data element types with associated classification scheme for electric components – Part 2: EXPRESS dictionary schema
IEC 61360-5	04.06	Standard data element types with associated classification scheme for electric components – Part 5: Extensions to EXPRESS dictionary schema.

On a national german level the recommendations of the IG EVU, i.e. the "Energy Distribution Group", have been developed into generally accepted rules with normative character for documentation of plants, process sequences and equipment. (www.igevu.de)

6.3.4.3 Title blocks in drawings; document management

A drawing is a document which aids in setting up or operating an installation or a system component. It must therefore include identifications and data showing its content, status and origins.

The new ISO 7200: May 2004 "Data fields in title blocks and document headers" distinguishes between:

- Identifying data fields
- Descriptive data fields
- Administrative data fields

Furthermore, a distinction is made between "mandatory" and "optional" data fields. Accordingly, the following information is specified as the mandatory minimum:

- Legal owner
- Part number (drawing number)
- Issue date
- Section / page number
- Title
- Person approving the document
- Originator
- Type of document

The design of the title blocks is not specified. The only stipulated feature is the overall width of 180 mm and, in ISO 5457, the position of title blocks on technical drawings. Examples of types of title blocks for documents in electrical engineering can be found in various parts of IEC 61082.

The stipulations of IEC 82045, "Document Management" are becoming more and more important.

The increasing use of computers, document management systems and electronic data exchange makes observance of this international standard absolutely essential. This is incumbent not only on the originators of documents, but first and foremost on the developers of EDM, PDM and CAE systems.

7 Low voltage switchgear

7.1 Low voltage switching devices

7.1.1 General

Low voltage switchgear is designed for switching and protection of electrical equipment. The selection of switching devices is based on the specific switching task, e.g. isolation, load switching, short-circuit current breaking, motor switching, protection against overcurrent and personnel hazard. Depending on the type, switching devices can be used for single or multiple switching tasks. Switching tasks can also be conducted by a combination of several switchgear units. Figure 7-1 shows the applications of various switching devices.

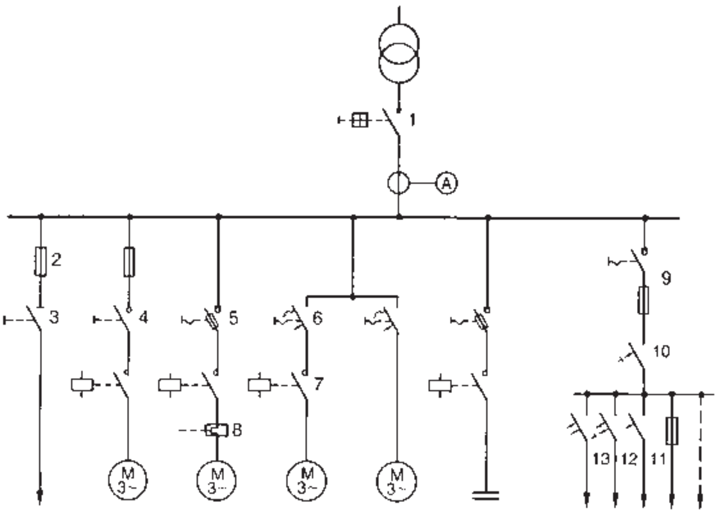


Fig. 7-1

Examples of applications for low voltage switching devices:

1 Circuit-breaker, general 2 Fuse, 3 Disconnector, 4 Load-break switch, 5 Fused switch-disconnector, 6 Motor starter (motor protection switch), 7 Contactor, 8 Overload relay, 9 Switch-disconnector with fuses, 10 Residual current-operated circuit-breaker (RCCB), 11 Miniature circuit-breaker, 12 Residual current-operated circuit-breaker with overcurrent tripping (RCBO), 13 Residual current-operated miniature circuit-breaker (RCD)

IEC 60947-1 (VDE 0660 Part 1) contains the general stipulations for all types of low voltage switching devices. Further general stipulations for electromechanical control circuit devices and switching elements can be found in IEC 60947-5-1 (VDE 0660 Part 200).

The standards set down ratings for all devices, and defined test values are assigned to these. Devices for up to 690 V, for example, have a test level of 1890 V for the rated insulation voltage. The rated impulse withstand voltage U_{imp} (stated on the switch or noted in the manufacturer's documentation) for service in power distribution is as a rule 6 kV (IEC 60947-1, Table H1). When constructing low voltage installations it must be ensured that no higher voltages than the rated insulation voltages of the devices can occur.

7.1.2 Circuit-breakers

Circuit-breakers are defined in IEC 60947-2 (VDE 0660 Part 101). Circuit-breakers must be capable of making, conducting and switching off currents under operational conditions. Furthermore, they must trip in accordance with defined current/time characteristics under overload and short-circuit conditions. Circuit-breakers are used in applications with a low switching frequency. Circuit-breakers without overcurrent releases are known as switch-disconnectors.

The basic classification criteria for low voltage circuit-breakers are the design (compact or open) and the quenching principle (non-current limiting or current limiting).

Compact circuit-breakers consist of an insulating material enclosure which surrounds the components of the breaker. Such circuit-breakers are constructed for rated currents of up to approx. 3200 A. The rated short-time current I_{cw} is up to 35 kA.

Open circuit-breakers are predominantly constructed with a metal surround and are generally larger than compact circuit-breakers. They are available for rated currents of up to 6300 A. The rated short-time current I_{cw} is up to 100 kA.

Non-current limiting circuit-breakers quench the switching arc at the natural alternating current zero. The conductors are designed with a thermal capability allowing them to conduct the full short-circuit current. All system components downstream are also subjected thermally and dynamically to the unlimited peak short-circuit current.

Current limiting circuit-breakers limit the short-circuit current before the peak of the first half-wave is reached. Limitation of the peak value significantly reduces the dynamic and thermal stresses on the connected system. Figure 7-2 shows a diagram of the development of the unlimited (prospective) short-circuit current and the short-circuit current limited by the switching device. Limitation of the short-circuit current is achieved by extremely rapid contact separation and a sudden prolongation of the breaking arc.

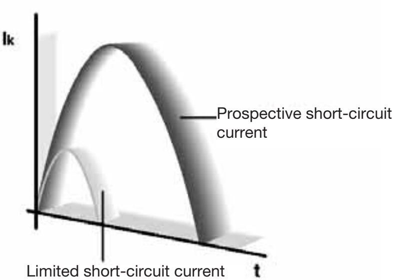


Fig. 7-2
Effect of current limitation on the development of the short-circuit current

Current limiting circuit-breakers are particularly suitable for short-circuit protection of switchgear with a relatively low switching capacity (back-up protection). Figure 7-3 shows the effects on the peak value I_p of the let-through current when a current limiting circuit-breaker is used (curve 2) in comparison with a non-current limiting circuit-breaker (curve 1), each in relation to the rms value of the rated short-circuit current.

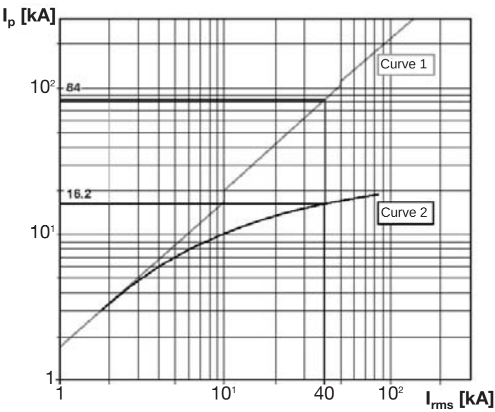


Fig. 7-3
Limitation of the short-circuit current by a current limiting circuit-breaker

At an assumed rms current I_{rms} of 40 kA, the peak level I_p with a non-current limiting circuit-breaker is 84 kA. The current limiting circuit-breaker however only permits a peak level of 16.2 kA, which significantly reduces the dynamic stresses on downstream system components (see also Back-up protection).

Selection of circuit-breakers is first based on the rated voltage U_e, the rated current I_n and the rated short-circuit breaking capacity. A distinction is made between two values for rated short-circuit breaking capacity: the rated service short-circuit current I_{cs} (test sequence O – t – CO – t – CO) and the rated ultimate short-circuit current I_{cu} (test sequence O – t – CO), where CO is a close/open operation, and t is the dead time between switching operations (3 min). The rated service short-circuit current I_{cs}

represents the higher load on the switching device. There are no stipulations in the standards as to which of the two values is to be used, but for critical applications (hospitals or congress centres) the rated service short-circuit current I_{cs} should be used as the design criterion.

The rated short-time current I_{cw}, the utilization category, the ambient temperature and the installation conditions are then to be taken into account. The rated short-time current I_{cw} is a peak value which is stipulated in accordance with table 7-1, but which does not fundamentally provide any new information.

The utilization category classifies the breaker's design-related characteristics with regard to selectivity. The distinction is made between utilization category A (circuit-breakers which are not specially designed for selectivity, e.g. current limiting circuit-breakers) and utilization category B (circuit-breakers which are specially designed for selectivity).

Table 7-1

Ratio n between short-circuit making and breaking capacity and the corresponding power factor (for AC voltage circuit-breakers) to IEC 60947-2 (VDE 0660 Part 101).

Short-circuit-breaking capacity I*) (rms value in kA)	Power factor	Minimum value for n $n = \frac{\text{Short-circuit-making capacity}}{\text{Short-circuit-breaking capacity}}$
4.5 < I**) ≤ 6	0.7	1.5
6 < I**) ≤ 10	0.5	1.7
10 < I**) ≤ 20	0.3	2.0
20 < I**) ≤ 50	0.25	2.1
50 < I**)	0.2	2.2

*) I is any value for short-circuit breaking capacity

**) For smaller breaking capacities in particular applications, see table 11 of this standard on account of the power factor.

A fundamental factor in project planning is the selection of the protection release, which generally may have up to 4 protection functions:

L Overload, with settings for trip threshold (current) and inverse time delay.

S Selective short-circuit protection, with settings for trip threshold and delay time with constant energy or definite time characteristic.

I Instantaneous short-circuit protection, with setting for trip threshold.

G Earth fault protection, with settings for trip and inverse time delay with constant energy or definite time characteristic.

Circuit-breakers can also be equipped with residual current releases, making it possible to implement operator protection. Against direct and indirect contact and protection against fire. Residual current protection devices are fundamentally distinguished by their design (add-on electronics unit with integrated instrument transformer or separate electronics unit (e.g. for door installation) and separate instrument transformer), by their response current (a.c. fault current, pulsating d.c.

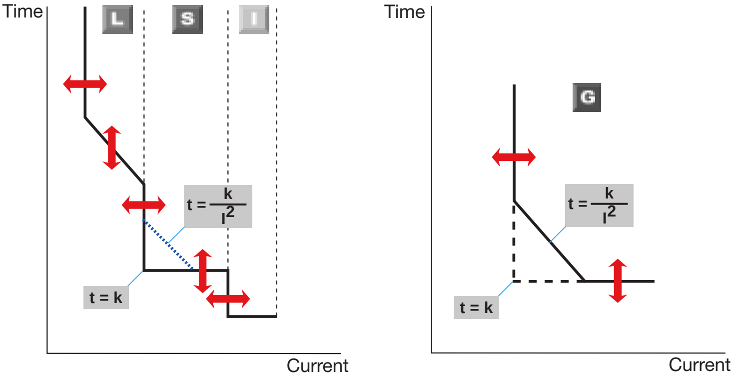


Fig. 7-4:
Time/current characteristics of protection releases

fault current, d.c. fault current) and their delay characteristics (selective or non-selective). For especially demanding applications (e.g. frequency converters), the newly developed all current sensitive release from ABB provides ideal protection.

7.1.3 Contactors

Electromagnetic contactors are defined in IEC 60947-4-1 (VDE 0660 Part 102). They are mechanical switching devices with only one position of rest, which are not operated manually and are capable of connecting, conducting and disconnecting currents in the circuit under service conditions, including operational overload. They are especially suitable for high switching frequencies. Contactors are suitable for switching in accordance with the utilization categories described below. Protection against short-circuits is to be ensured by upstream protection equipment (SCPDs). From a safety point of view, it can be necessary to provide an additional suitable switching device as a disconnection system to isolate individual loads, especially electrical machines, from the supply network.

Apart from the electromagnetic actuation most often used, there are also contactors with pneumatic or electropneumatic actuation. For contactors and control devices on a semiconductor basis, IEC 60947-4-2 (VDE 0660 Part 117) covers motor current circuits, and IEC 60947-4-3 (VDE 0660 Part 109) covers non-motor loads with a.c. voltage.

Contactors are selected by utilization categories, as shown in table 7-2. In addition, the ratings (voltage, current, ambient temperature and control voltage) are to be considered. Background conditions such as switching frequency, number of poles, type of coordination, short-circuit level, start-up conditions and contact life are also to be taken into account.

There are various aids and programs available from manufacturers and in the Internet for selection of contactors (www.abb.com/lowvoltage).

The contactor must be capable of correct operation within a range of 85% to 110% of the rated control voltage, with control current flowing.

Important accessories for contactors include for example clip-on auxiliary contact blocks and overload relays for fitting to the contactor output terminals.

The auxiliary contacts of ABB contactors are „positively driven” in accordance with IEC 60947-5-1 (VDE 0660 part 200), Annex L2.1.

NC auxiliary contacts in the contactors are „mirror contacts” in accordance with IEC 60947-4-1 (VDE 0660 Part 102), Annex F2.1, i.e. they cannot be closed at the same time as the NO main contacts. The positive driving and mirror property are essential in the implementation of safety circuits.

Table 7-2

Utilization categories for contactors to IEC 60947-4-1 (VDE 0660 Part 102)

Current type	Utilization category	Typical application
Alternating current	AC-1	Non-inductive or weak inductive load, resistance furnaces
	AC-2	Slip-ring motors: starting, disconnecting
	AC-3	Squirrel-cage motors: starting, disconnecting while running[1]
	AC-4	Squirrel-cage motors: starting, plug braking, reversing, jogging
	AC-5a	Switching gas-discharge lights
	AC-5b	Switching incandescent lights
	AC-6a	Switching transformers
	AC-6b	Switching capacitor banks
	AC-7a	Weakly inductive load in household appliances and similar applications
	AC-7b	Motor load for household devices
	AC-8a	Switching hermetically sealed refrigerant compressor motors with manual reset of the overload release[2]
	AC-8b	Switching hermetically sealed refrigerant compressor motors with automatic reset of the overload release[2]
Direct current	DC-1	Non-inductive or weakly inductive load, resistance furnaces
	DC-3	Shunt motors: starting, plug braking, reversing, jogging, resistance braking
	DC-5	Series motors: starting, plug braking, reversing, jogging, resistance braking
	DC-6	Switching incandescent lights

1) Devices for utilization category AC-3 may be used for occasional jogging or plug-breaking for a limited period, such as setting up a machine; the number of actuations in these circumstances shall not exceed five per minute and ten per ten minutes.

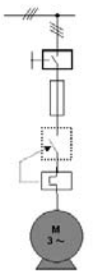
2) In the case of hermetically sealed refrigerant compressor motors, compressor and motor are sealed in the same housing without an external shaft or with the shaft sealed, and the motor operates in the refrigerant.

7.1.4 Motor starters

Motor starters based on electromechanical switching devices are also defined in IEC 60947-4-1 (VDE 0660 Part 102). Accordingly, motor starters (figure 7-5) are used to start motors, accelerate them to normal speed, ensure motor operation, disconnect the motor from the power supply and, by means of suitable protection systems, protect the motor and the corresponding circuit in the case of overload.

The starter may function as a direct-on-line starter (DOL), reversing starter (REV), star-delta starter (YD), heavy starter (HD) or soft starter. Short-circuit protection, overload protection and in many cases also an isolation device are required. Circuit-breakers are preferred for short-circuit protection.

As motor starters are as a rule used on the power distribution level, the components must be designed for a rated impulse withstand voltage U_{imp} of 6 kV.



Function	Device
Isolating	**Isolator**
Short-circuit protection	**Fuses**
Operational switching	**Contactor**
Protection from overload	**Overload relay**

Fig. 7-5
Basic structure of a motor starter

The protection requirements play a decisive role in the design of a motor starter (figure 7-6). Table 7-3 compares the performance features of the individual protection concepts.

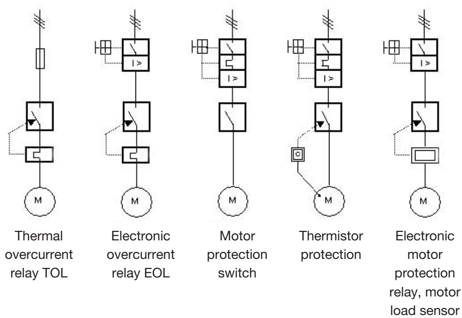


Fig. 7-6
Alternatives for motor control

Table 7-3
Concepts for motor protection

Thermal over-current relay TOL	Electronic over current relay EOL	Manual motor starter	Thermistor protection	Electronic motor protectionrelay, motor load sensor
Phase failure protection	Phase failure protection	Phase failure protection	Temperature monitoring	Phase failure protection
Manual reset	Manual reset	Manual reset	Manual reset	Manual reset
Automatic restarting	Automatic restarting	---	Automatic restarting	Automatic restarting
	Frequent motor starts		Frequent motor starts	Frequent motor starts
	Increased ambient temperature	Remote tripping	Detection of motor cooling, failure, external temperature rise	Monitoring of auxiliary voltage
	Low losses	Various accessories		Detection of load shedding
---	---	Short-circuit protection	---	Cos φ monitoring
	Highly accurate, constant tripping			Earth fault protection
	Broad current ranges			Use as controller

Overload relays detect overloading of the motor or the failure of a phase, and then act on the contactor to switch the motor off. There are both thermal and electronic overload relays, with various tripping classes (e.g. Class 10 or Class 30) for normal starting or heavy starting of the motor. For direct online starting the overload relay is set to the rated service current of the motor (I_e), and for star-delta starting to 0.58 x I_e. The ABB overload relays all have temperature compensation which automatically overcomes the interference by different ambient temperatures. The user can select either manual or automatic resetting of the overload relay after tripping.

In its simplest version, a motor starter can consist of a single device, namely a circuit-breaker with thermal/electromechanical releases. A manual motor starter switch is a circuit-breaker with a special tripping characteristic, as shown in figure 7-7.

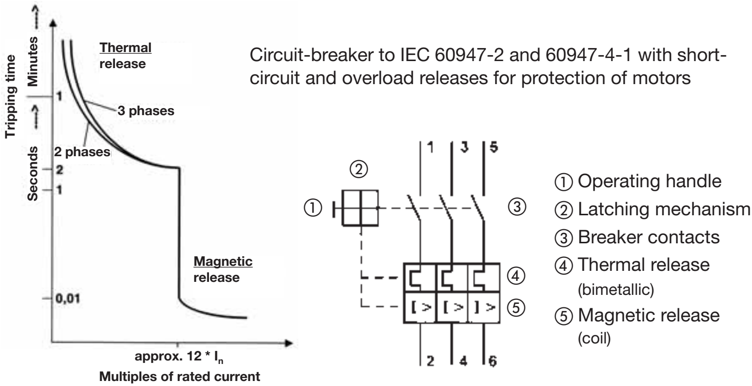


Fig. 7-7
Function of a manual motor starter

Short-circuit protection is to be provided depending on the voltage level and the rated short-circuit breaking capacity of the motor starter. Figure 7-8 shows an example of this relationship for the motor starter type MS325. In the greyed area, the switch itself has sufficient breaking capacity, and therefore no series fuses are required up to a prospective short-circuit current of 100 kA. Under different conditions (setting range and voltage), the breaking capacity I_{cs} of the device is lower. If the short-circuit calculation results in prospective currents I_{cc} which are higher than the I_{cs} values in the left-hand column of the two assigned to service voltages, additional fuses are to be provided for short-circuit protection. Their rated currents may not exceed the values in the right-hand column.

Setting ranges of the MS 325			Left column: Rated service short-circuit breaking capacity I_{cs} of the MS325 Right column: Maximum rated current of the short-circuit fuse when $I_{cc} > I_{cs}$											
			at 230 V AC		at 400 V AC		at 440 V AC		at 500 V AC		at 660 V AC		at 690 V AC	
			I_{cs}	gL, aM	I_{cs}	gL, aM	I_{cs}	gL, aM	I_{cs}	gL, aM	I_{cs}	gL, aM	I_{cs}	gL, aM
from		to	kA	A	kA	A	kA	A	kA	A	kA	A	kA	A
A		A		Fuse types: Diazed, LV HRC, Utilization categories: gL, aM (VDE), gL/gG (IEC)										
0,1	...	0,16												
1	...	1,6												
1,6	...	2,5	No series fuse necessary until I_{cc} = 100 kA										40	25
2,5	...	4							60	35 / 40	15	35 / 40	10	40
4	...	6,3					70	50	40	50	10	50	7	40
6,3	...	9					50	80	30	80	7,5	50	5	50
9	...	12,5			75	80	45	80	27	80	6,5	50	4,5	50
12,5	...	16			60	100	40	100	25	100	6	50	4	50
16	...	20			55	100	35	100	22	100	5	50	3,5	50
20	...	25			50	125	30	125	20	125	4	50	3	50

Fig. 7-8
Short-circuit protection for motor protection switch MS 325 for prospective short-circuit currents ≤ 100 kA

For the design of a motor control unit, assignment to a type class in accordance with IEC 60947-4-1 which indicates the level of service continuity to be achieved with the equipment is also necessary. Two type classes are defined. The maximum permissible limits for damage are stated for both types. Machine operators must on no account be exposed to hazards. The distinction is made between:

Type 1: Damage to the contactor and/or the overload relay is permissible if there is no hazard to the operator and no other apparatus other than the contactor and overload relay have to be replaced.

Type 2: Only light welding of the contacts, which can be easily separated again with a screwdriver or the electrical operating mechanism, is permissible. According to the classification test for type 2, all the functions of the protective devices must continue to be operational. Furthermore, the manufacturer must demonstrate that the contactor is still operational for 20 operating cycles at 2 x I_e (AC3) after separation of the contacts (only applicable when a tool is used).

Coordination of the devices suitable as parts of the motor starter for a particular size of motor requires extensive knowledge of their behaviour in service. Extracts from coordination tables based on the manufacturer's experience are presented in table 7-4.

Table 7-4

Extracts from a coordination table for direct online starters (normal) with motor protection switches (source: www.ABB.com/lowvoltage)

Motor		Motor protection switch			Contactor
Power [kW]	Rated current [A]	Type	Undelayed tripping current [A]	Current setting range [A]	Type
0.06	0.22	MS325-0.25	2.44	0.16-0.25	A9
0.18	0.72	MS325-1.00	11.5	0.63-1.00	A9
0.55	1.45	MS325-1.60	18.4	1.00-1.6	A9
1.5	3.45	MS325-4.00	50	2.50-4.00	A12
5.5	11.1	MS325-12.5	187.5	9.00-12.00	A26
18.5	37	MS450-40	520	28.0-40.00	A40
51	94	MS495-100	1235	80.0-110	A110

7.1.5 Disconnectors, load-break switches and switch disconnectors

The requirements for mechanical switching devices for switching of load currents and safe isolation of systems or subsystems from the supply network are the subject of standard IEC 60947-3 (VDE 0660 Part 107).

Disconnector

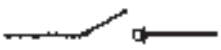
The isolating function of the disconnector in the open position is characterized by the following features:

Increased dielectric strength of the contact gap (demonstrated by a test at impulse voltage)
Low leakage current across the isolating distance
Clear indication of the OFF position of the contacts
No inadvertent closing (e.g. by vibration)
Facilities for actions to prevent impermissible reclosing

A disconnector can only open and close a circuit if either a current of negligible quantity is switched off or on, or if there is no significant voltage difference between the two contacts of each pole.

Load-break switch

A load-break switch can, under normal conditions in the circuit, if applicable with specified overload conditions, make, conduct and break currents and, under specified abnormal conditions such as a short-circuit, conduct these short-circuit currents for a specified period.



Switch-disconnector

A switch-disconnector is a load-break switch that meets the requirements specified for an isolating distance in the open position.

Switch-disconnector with fuses

Unit comprising switch-disconnector and fuses, in which one fuse is connected in series with the switch-disconnector in one or more phases.

Fuse switch-disconnector

A fuse switch-disconnector is a switch-disconnector in which a fuse link or a fuse holder with fuse link forms the movable contact.

Switching mechanisms for disconnectors, load-break switches and switch-disconnectors

Dependent manual actuation

Actuation exclusively by human effort, so speed and power for the switching movement depend on the operator.

Independent manual actuation

Actuation by a stored-energy mechanism, in which the energy applied manually is stored as tension and released during the operating motion, so speed and power for the contact movement are independent of the operator.

Stored-energy operation

Actuation by energy stored in the actuating mechanism, which is sufficient to complete the switching operation under specific conditions. The energy is stored before the actuation begins.

Stored-energy mechanisms are differentiated by the type of

- energy storage (spring, weight etc.),
- energy source (manual, electric motor etc.),
- energy release (manual, release coils etc.).

Table 7-5

Utilization categories for switchgear to IEC 60947-3 (VDE 0660 Part 107) for alternating current

Utilization category		
Frequent operation	Occasional operation	Typical applications
AC-20A*)	AC-20B*)	Closing and opening without load
AC-21A	AC-21B	Switching resistive load including minor overload
AC-22A	AC-22B	Switching mixed resistive and inductive load including minor overload
AC-23A	AC-23B	Switching motors or other highly inductive loadst

*) Application of these utilization categories is not permitted in the USA.

Utilization category AC-23 includes occasional switching of individual motors. Switching of capacitors and incandescent lamps requires agreement between the manufacturer and user. Utilization categories with B apply to devices that are only switched occasionally in accordance with their design or application. Examples are disconnectors that are only operated for disconnection during maintenance work or switching devices in which the contact blades of the fuse links form the movable contact.

The same definitions of utilization categories apply to d.c. switching devices as for a.c. devices. AC is replaced by DC in the designations of the utilization categories. Category DC-22 includes switching of shunt-wound motors. Series-wound motors are considered to be highly inductive loads.

Switch-disconnectors of type OT (figure 7-9) are notable for their highly compact design, which saves space and reduces costs for installation in switchgear cabinets. Arc quenching is performed in a quenching system with double interruption. The switch position is visible through a sight glass. As the switches are modular in structure, the location of the operating mechanism can be freely selected either beside or between the poles.

Fig. 7-9
Switch-disconnector type OT, three-phase, with mechanism unit on the left

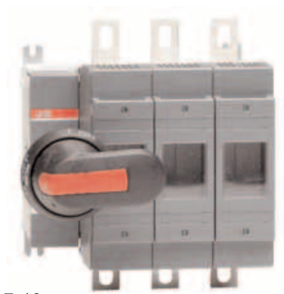


Fig. 7-10
Switch-disconnector with fuses type OS, three-phase, with mechanism unit on the left

The switch-disconnectors with fuses of type OS (figure 7-10) have fuses integrated in the conductor path inside the pole housing. The fuse is located behind a sight glass through which the type, data and condition of the fuse can be seen. Here too, interruption of currents in normal operation without faults is performed in arc quenching systems with double interruption.

7.1.6 Fuses

Low voltage fuses are defined in accordance with IEC 60269-1 (VDE 0636 Parts 10 ff.). Fuses are protective devices which open a circuit when one or more fuse elements blow and interrupt the current when it exceeds a given level for a specified duration.

The application ranges of fuses are identified by two letters. The first letter identifies the breaking range:

g – General purpose fuse links

These can continuously conduct currents up to their rated current and can interrupt currents from the smallest fusing current to the rated breaking capacity.

a – Back-up fuse links

These can continuously conduct currents up to their rated current and can interrupt only currents above a specific multiple of their rated current.

The second letter identifies the application, i.e. the time-current characteristic.

G – for general application
M – for the protection of motor circuits and switching devices
R – for protection of semiconductor components (VDE 0636 Part 40)
Tr – transformer protection (VDE 0636 Part 2011)
B – mine substation protection (VDE 0636 Part 2011)
D – fuse links with delay   North American
N – fuse links without delay   practice

See table 7-6 for rated voltages and rated currents.

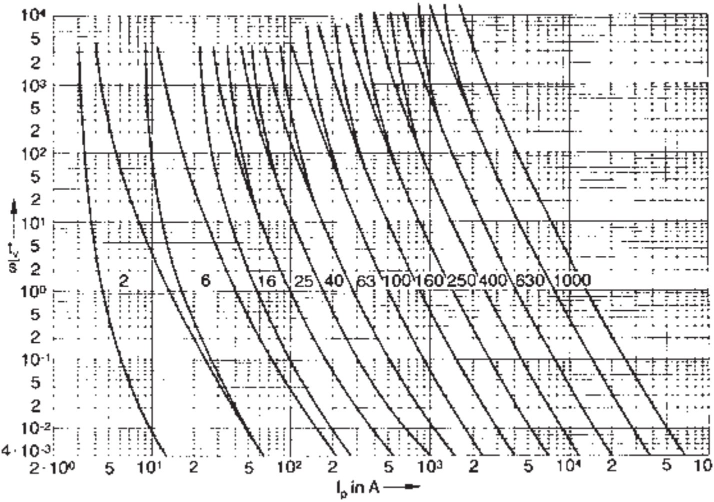
The time response of fuse links depending on the breaking current that causes the fuse to melt and interrupt is shown in time/current characteristics, figure 7-11.

The interrupting behaviour of the fuse links is characterized by the small test current (I_{nf} – no interruption during the test period) and the large test current (I_f – interruption during the test period) (table 7-7).

Table 7-6

Rated voltages and rated currents of fuse links

(DIN VDE 0636 Part 10), standardized values as per IEC 60038 are underlined	
AC voltage	
Series I	230 400 500 690 V
Series II	120 208 240 277 415 480 600 V
DC voltage	110 125 220 250 440 460 500 600 750 V
Current I_n	2 4 6 8 10 (12) 16 20 25 32 40 50 63 80 100 125 160 200 250 315 400 500 630 800 1 000 1 250 A



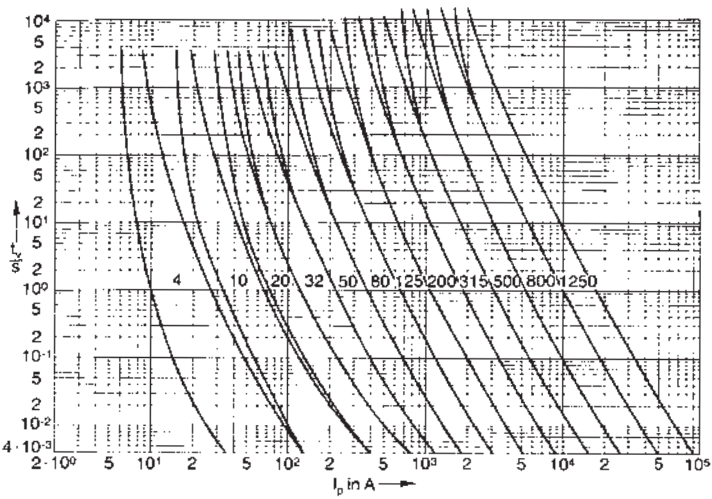


Fig. 7-11

Time/current characteristics for LV HRC fuse links of duty class gG
Top) 2 to 1000 A, Bottom) 4 to 1250 A, to VDE 0636 Part 201

Table 7-7

Conventional times and currents for gG and gM fuse links to IEC 60269-1 and IEC 60296-2-1 (VDE 0636 Part 201)

Rated current I_n for gG Characteristic I_{ch} for gM [1]) current	Conventional test duration	Test current I_{nf}	I_f
A	h		
$I_n \leq 4$	1	1.50 I_n	2.1 I_n
$4 < I_n < 16$	1	1.50 I_n	2.9 I_n
$16 \leq I_n \leq 63$	1	1.25 I_n	1.6 I_n
$63 < I_n \leq 160$	2	1.25 I_n	1.6 I_n
$160 < I_n \leq 400$	3	1.25 I_n	1.6 I_n
$400 < I_n$	4	1.25 I_n	1.6 I_n

[1]) I_{ch} is an additional designation for the time/current characteristic to IEC 60269-1 Table 3 for gM fuse links.

With short-circuit current, fuses limit the short-circuit current before the peak value is reached, see current limitation diagram, figure 7-12.

Fuse links whose rated currents are in the ratio of 1:1.6 respond selectively up to 690 V rated voltage at rated currents ≥ 16 A.

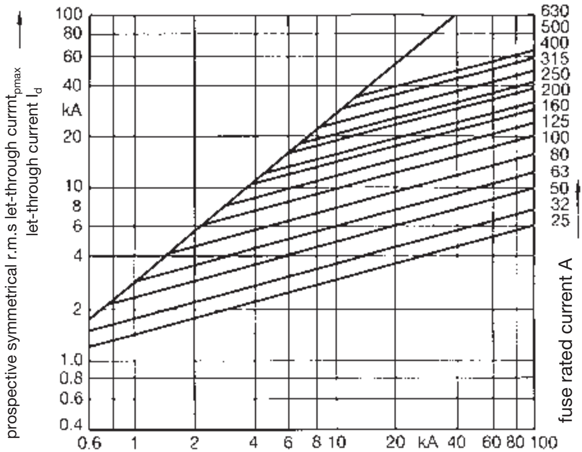


Fig7-12
Current limitation diagram

Initial symmetrical short-circuit current →

Low voltage heavy-duty (LV HRC) fuses

For an overview of the sizes, fuse bases/fuse rails and associated rated currents of the fuse links, see table 7-8.

The breaking capacity must be at least 50 kA. LV HRC fuses with a nominal breaking capacity of at least 80 kA and up to more than 100 kA are available on the market. LV HRC fuse links must have an indicator to show the status of the fuse.

Table 7-8

Rated currents for HRC fuse bases and fuse rails and also for gG fuse links (VDE 0636 Part 201), values in brackets = deviations for aM links

Size	HRC fuse bases	HRC fuse rails	HRC fuse links ~ 400 V ~ 500 V	~ 690 V	= 440 V
	A	A	A	A	
000	100	-	2 to 100	2 bis 100	-
00	160	160	6 to 160 (100)	up to 100	100
0	160	160	6 to 160	up to 100	160
1	250	250	80 to 250	up to 200 (250)	250
2	400	400	125 to 400	up to 315 (400)	400
3	630	630	315 to 630	up to 500 (630)	630
4	1000	–	500 to 1000	up to 800 (1000)	1250
4a	1600	–	500 to 1600	up to 1000 (1250)	-

The time/current ranges for gTr HRC fuses are adjusted to the time /current ranges for gG HRC fuses so that gG HRC fuses are selective for upstream gTr HRC fuses when the rated currents of the gG HRC fuses are not larger than those in Table 7-9.

LV HRC fuse links are available in versions with isolated metal grips and as low loss variants. HRC fuse links are not non-interchangeable with regard to rated current, and therefore they must only be replaced by specialist electricians. The available range includes HRC fuse switch-disconnectors (horizontal arrangement of the HRC fuse links) and HRC fuse disconnect rails (vertical arrangement of the HRC fuse links) for switching of the connected circuits and replacement of the fuse links in the off-circuit condition.

With HRC fuse links of duty class gTr, the rated power of the three-phase transformer that is to be protected takes the place of the rated current. In kVA: 75, 100, 125, 160, 200, 250, 315, 400, 500, 630, 800, 1000. See table 7-10.

Table 7-9

Rated currents of HRC fuse links for selective protection

Size	aM I_n / A	gG I_n / A		gTr S_n/kVA
	AC 1000 V	AC 500 / 690 V	AC 1000 V	AC 400 V
00C	6-100	-	6-63	
3C	200-500	-	200-315	
00	6-160	6-160	6-160	
1	50-250	80-250	50-200	50-250
2	125-315	125-400	125-315	250-400
3	200-500	315-630	200-400	400-1000

Table 7-10

Rated currents for selectivity of HRC fuses on the low voltage side of transformers (VDE 0636 Part 2011)

Rated apparent power S_n of the transformer	Rated I_n of the gTr fuse link	Maximum rated current I_n of the gG fuse link, A
50	72	50
75	108	80
100	144	100
125	180	125
160	231	160
200	289	200
250	361	250
315	455	315
400	577	400
500	722	500
630	909	630
800	1 155	800
1000	1 443	1000

7

Fuses, D and DO systems

Table 7-11 shows an overview of the rated voltages and rated currents for these fuses. The devices are available for screw fastening, for fastening by clamps, or for snap-on fastening to top hat rails to IEC 60715. The range also includes switch-disconnectors fitted with NEOZED system fuses, which permit both switching of the connected circuits and replacement of the fuse links in the off-circuit condition. The required breaking capacity is 50 kA for alternating current and 8 kA for direct current.

The colour coding of the indicator for the status of the fuse is listed in table 7-12.

D-type fuses E 16 for rated currents of up to 25 A and rated voltages of up to 500 V according to DIN 57635 (VDE 0635) are used for measurement and control equipment. In addition, VDE 0635 is significant with regard to use at 750 V and rated currents up to 100 A for mining applications and in electric railways.

Table 7-11

Rated voltages and rated currents for screw-type fuses to DIN VDE 0636-301

Size	Thread	Mounts and screw caps	Fuse links	Gauge pieces
NEOZED fuse system (400V AC, 250V DC)				
D0 1	E 14	16 A	2 to 16 A	2 to 10 A
D0 2	E 18	63 A	20 to 63 A	20 to 50 A
With special gauge sleeves also for 2 to 16 A				
D0 3	M 30 x 2	100 A	80 to 100 A	to 80 A
D-fusesystem (660V AC)				
NDZ (500V AC)*	E 16	25 A	2 to 25 A	2 to 20 A
D II (500V AC)	E 27	25 A	2 to 25 A	2 to 25 A
D III (690V AC)	E 33	63 A	32 to 63 A	35 to 63 A
D IV (500V AC)	R 1 1/4“	100 A	80 to 100 A	80 to 100 A
D V (500V AC)	R 2“	200 A	125 to 200 A	125 to 160 A

*) Breaking capacity only 4 kA AC, 1.6 kA DC.

Table 7- 12

Colour of indicator (DIN VDE 0636-301)

Rated current of fuse link A	Colour of indicator
2	pink
4	brown
6	green
10	red
16	grey
20	blue
25	yellow
35*)	black
50	white
63	copper
80	silver
100	red

*) In some countries rated currents of 32 A and 40 A are used in place of rated current 35 A.

As per VDE 0638, the fuse-combination unit, DO system, is specified as a factory-assembled combination of a switch part and a fuse part. The switching properties of these devices are classified under the utilization categories AC 21 and AC 22 in table 7-5.

7.1.7 Protective circuit-breaker

These protective switching devices are suitable for protection of persons and apparatus. They are modular in structure, available for both single and multiple phase application, and can be combined with auxiliary switches. They are primarily designed for snap fitting on top hat rails to IEC 60715. Further analog devices such as switches, pushbuttons, signal lamps, alarms, electrical sockets, stairwell light time switches, remote control switches, installation relays, time delay relays, load shedding relays, operating hour counters, measuring instruments, dimmers, power consumption meters, time clocks, timers, small transformers, doorbells or undervoltage detection relays can be linked with the protection switchgear, resulting in an extensive range for both building installations and industry.

Miniature circuit-breakers

Fundamental stipulations for miniature circuit-breakers (MCBs) are set down in IEC 60898-1 (VDE 0641 Part 11)

Stipulations on special applications and use with d.c. voltage can be found in IEC 60898-2 (VDE 0641 Part 12).

Miniature circuit-breakers are primarily manually actuated, current limiting switches with fixed magnetic and delayed thermal tripping, a rated current of no more than 125 A and a rated short-circuit breaking current which does not normally exceed 25 kA. They are available in both a.c. and d.c. versions. ABB also supplies units with rated short-circuit breaking capacities over 25 kA, for rated voltages up to 690 V AC and for different frequencies.

The energy limitation class – there are 3 classes, 1, 2, 3 – characterises the degree of short-circuit current limitation for circuit-breakers up to 32 A. Energy limitation class 3 leads to the lowest energy throughput, both in the switching device an at the fault location. Devices with energy limitation class 3 are therefore dominant on the market.

According to the standards, only MCBs with tripping characteristics B, C and D are to be used in new installations. Miniature circuit-breakers with other tripping characteristics such as K for motors, transformers, lamps, etc. or Z for semiconductor protection and line protection of long control lines have a thermal tripping characteristic which is similar to that in IEC 60947-2 (circuit-breakers). The magnetic tripping range is set corresponding to the starting currents with K at 10 to 14 I_n and with Z at 2 to 3 I_n to ensure instantaneous tripping even at low overcurrents. Figure 7-13 shows the tripping characteristics B, C, D, and K and Z.

Selective main line miniature circuit-breakers

Selective miniature circuit-breakers are also manually operated current limiting overcurrent protection devices with short-time delayed magnetic and delayed thermal tripping, which guarantee optimum availability of the downstream apparatus due to their tripping characteristics (selectivity) and their suitability for operation by laypersons.

Voltage-dependent main line miniature circuit-breakers to E DIN VDE 0643 require mains voltage or a control voltage to be applied for their function.

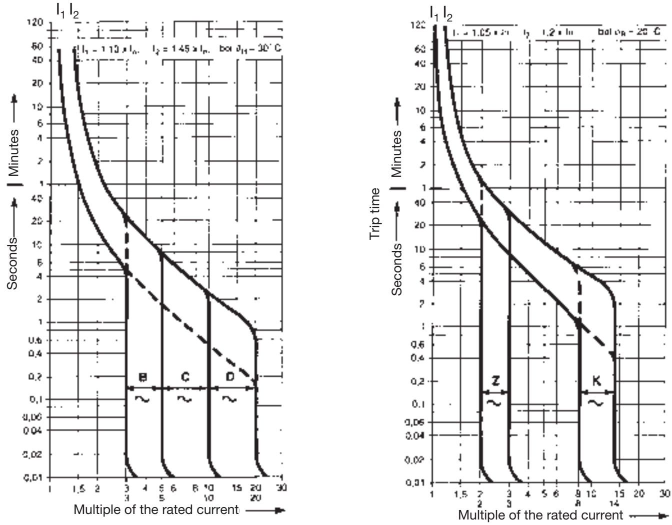


Fig. 7-13

Examples of tripping characteristics of miniature circuit-breakers:
a) tripping characteristics B, C, D,
b) tripping characteristics K and Z.

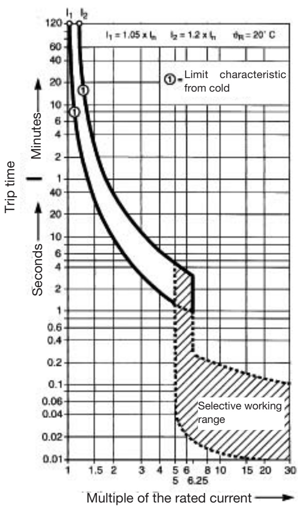


Fig. 7-14

Tripping characteristic E for selective main line MCBs

Voltage-independent main line miniature circuit-breakers SHU to E DIN VDE 0645 do not need any power supply for their protection function. Their tripping behaviour in the case of short-circuits is dependent on the extent of the short-circuit current. On overload and short-circuit they possess selectivity in broad ranges in relation to upstream HRC fuses even with the same rated current, and full selectivity in relation to downstream mcbs up to their rated short-circuit breaking capacity. The manufacturer provides detailed tables on the limits to selectivity. The devices are available with tripping characteristics E (see figure 7-14) and K (see figure 7-13).

RCDs (Residual Current-operated Devices)

RCD is a general term covering fault current protection devices and differential current protection devices. Fault current protection devices trip without any auxiliary power source when a fault current arises, whereas differential current protection devices require auxiliary voltage to perform the same function. This distinction is made in German standards, but not by IEC.

The characteristic feature of an RCD is the summation current transformer (toroidal core transformer) which measures the current in the phase conductor(s) and neutral conductor of the monitored feeder. If an earth fault current occurs in the monitored area, this current is detected even at extremely low levels, and the switch is tripped immediately.

RCDs are used for protection of persons against indirect contact (fault protection against fire hazards from electrically ignited fires and (additional) protection of persons against direct contact (see section 5.1).

There are a series of features used for classification of RCDs:

Classification by tripping method

– Devices independent of mains voltage, to IEC 60008-2-1 (VDE 0664 Part 11) and IEC 60009-2-1 (VDE 0660 Part 21)
– Devices dependent on mains voltage, not standardized in Germany and therefore not usually approved for operator protection (see also VDE 0100 Part 530).

Classification by rated residual current:

0.01A, 0.03A: Accepted as additional operator protection (see sections 5.1.1 and 5.1.2).
0.1A, 0.3A, 0.5A: Suitable for all other protection purposes.

Classification by behaviour on occurrence of d.c. components (for example during operation of frequency converters and rectifiers):

AC Tripping on AC residual current (not approved in Germany, see VDE 0664 Part 10)

A Tripping on AC residual current and pulsating DC residual current

B Tripping on AC residual current, pulsating DC residual current and smoothed DC residual current (designated all current sensitive), with standards in preparation.

Classification by time delay from presence of a residual current to tripping:

RCDs without time delay for general purposes

RCDs with time delay for selective tripping with code letter S

RCDs in short-time delayed design (Pulse-type leakage currents caused by the charging of interference suppression circuits at the load do not lead to tripping.)

RCDs can trip when only 0.5 times the rated residual current is reached. At rated residual current, tripping occurs within 0.3 s, and at five times the rated current within 0.04 s.

RCCBs are to be protected against overload and short-circuits in accordance with the manufacturer's instructions either by overcurrent protection apparatus or by the structure of the system.

Classification by construction type:

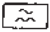
RCCB: Residual current-operated circuit-breaker without integral overcurrent protection for household and similar uses to IEC 61008-1(VDE 0664 Part 100) and IEC 61008-2-1(VDE 0664 Part 11).

RCBO: Residual current-operated circuit-breaker with integral overcurrent protection for household and similar uses to IEC 61009-1 (VDE 0664 Part 20) and IEC 61009-2-1 (VDE0664 Part 21). These combinations of MCBs and residual current protection switches disconnect all phases of the circuit from the network when the specified values for fault, overload or short-circuit current are exceeded. RCBOs with rated residual currents of 0.01 mA and 0.03 mA are thus the ideal protection devices for mains socket-outlet circuits.

SRCD: Residual current device without integral overcurrent protection, incorporated in or associated with fixed socket-outlets, to DIN VDE 0661-10. Frequently used to increase the protection level of existing, old two-core installations.

PRCD: Portable residual current devices without integral overcurrent protection for household and similar uses. Draft IEC 23E/386/CD:2004-07 applies. Suitable for raising the protection level. Interruption takes place in all phases.

Identification of residual current-operated circuit-breakers:


Type A for AC and pulsating DC fault currents


Type AC for AC fault currents


For low temperatures

Temperature range – 25 °C to + 40°C
Selective type (delayed tripping)

7.1.8 Overvoltage protection devices

The basic principles for design of a lightning protection system for low voltage installations and equipment are dealt with in section 4.1.2. Accordingly, three types of arresters, whose energy absorption capacities fundamentally differ, are used. The test requirements to which these devices are subjected are also correspondingly different.

Type 1 (lightning arrester). These protection devices are tested with an impressed lightning current I_{imp} of wave form 10/350µs. Typical peak values of the test current are between 5 kA and 25 kA. Higher values (e.g. 100 kA) are possible, but only of importance in exceptional cases, for instance as an arrester between N and earth in TT systems. When lightning strikes a building, lightning arresters must be capable of carrying a portion of the lightning current, and as a rule are only used in conjunction with lightning protection systems (lightning conductors). Type 1 arresters are generally designed as spark gap arresters, and can therefore, according to the relevant VDN directive (VDN = Association of German Network Operators), also be installed in main supply systems (i.e. upstream from the electricity meter).

Type 2 (surge arrester) is subjected in testing to lightning currents I_n and I_{max} of wave form 8/20µs, and used for protection against lightning overvoltages and switching overvoltages in overhead lines and building installations. Typical test values are between 1 kA and 50 kA. Type 2 arresters are generally designed as varistor arresters. Surge arresters for service in overhead lines must be suitable for outdoor installation. For protection between N and PE, however, only arresters which have no leakage current, i.e. spark gap arresters or gas arresters, may be used (in a 3 + 1 circuit to DIN V VDE V 0100 Part 534 and IEC 60364-5-53/A2 (draft)).

Type 3 (surge arrester) is tested with a hybrid generator and is intended for service at less exposed locations, predominantly for protection of terminal equipment.

The first step in selection of arresters is the choice of arrester type with regard to its energy absorption capacity. Experience shows that arresters of type 2 with I_n = 5 kA and I_{max} = 25 kA are sufficient for connection to overhead lines under normal conditions. Arresters with I_n = 10 kA and I_{max} = 40 kA are only to be preferred when electrical storms are relatively frequent or the lines are particularly exposed. It is advantageous that, when lightning strikes low voltage lines, the small clearances ensure that all three conductors in the three-phase system are involved in conducting the discharge energy.

Stipulation of the maximum continuous service voltage U_c for the arresters is made on the basis of the maximum voltage in the system, and also taking account of temporary increases in service voltage where these are apparent. Assuming a margin of approx. 10% for the voltage tolerance, should be used with

– U_c = 255 V for the phase-neutral and neutral-earth configurations in TT and TN systems,
– U_c = 440 V for the phase-neutral and neutral-earth configurations in IT systems, and
– U_c = 440 V for the phase-phase configurations in TT, TN and IT systems

for a system in the 230/400 V range.

The next step in selection of arresters is the stipulation of the arrester protection level U_p. As a rule, a margin of 20% below the impulse voltage insulation levels assigned to the overvoltage categories of the devices and components provides sufficient safety. The rated discharge current I_n of wave form 8/20µs is assigned to this protection level.

Furthermore, attention is to be paid in the selection of the arresters and in designing the overvoltage protection system to the measures necessary for coordination of the arresters (minimum line lengths required) and the necessity of back-up fuses (according to the manufacturer's instructions).

Table 7-13 provides an overview of the ratings of ABB's arrester series for low voltage installations in buildings, and at the same time illustrates the relationships described above. All arresters in these series are available as individual devices (single pole design) and can be mounted on top hat rails (35 mm). There are however also prefabricated combinations of several arresters (multiple pole versions) for use in particular network systems (as indicated by the type designation). All arrester types in these series are optionally available with remote signalling facilities.

In the arresters of series Limitor VP, the protection modules can be simply unplugged from the base for performance of regular control measurements of the insulation resistance and tripping behaviour in the connected system. Arresters of this series with the suffix Res in the type designation have an integral back-up transistor. They are intended for installations with special protection requirements.

For service in low voltage networks under outdoor conditions there are the ABB arrester series POLIM and LOVOS, all on a varistor basis, with test certificates for type 2, and in the case of POLIM also for type 1.

Fig. 7-15

Examples of ABB overvoltage protection devices for installations in buildings

a) Limitor VD *b) Limitor VP TT Res* *c) Limitor B TNC*

Table 7-13

Typical data for overvoltage protection devices

Arrester type	Lightning impulse current I_{imp} / kA (10/350µs)	Follow current extinction capability I_{fi} / kA	Protection level U_p / kV	ABB type designation	Arrester system
Single pole design					
1	25	50	2.5	Limitor B 1P	Spark gap
1	50	0.1	2.5	Limitor B NPE 50[1)]	Spark gap
1	100	0.1	4	Limitor B NPE 100[1)]	Spark gap
Multiple pole design for single phase application					
1	25 per pole	50	2,5	Limitor B TN 2P	Spark gap
1	25 / 50[2)]	50	2,5 / 2,5[2)]	Limitor B TT 2P	Spark gap
Multiple pole design for three-phase application					
1	25 per pole	50	2,5	Limitor B TNC	Spark gap
1	25 per pole	50	2,5	Limitor B TNS	Spark gap
1	25 / 100[2)]	50	2,5 / 4[2)]	Limitor B TT	Spark gap
Single pole design					
1 and 2	25	15	1,5	Limitor Combi 1P	Spark gap with varistor
Two pole design for single-phase application					
1 and 2	25 per pole	15	1,5	Limitor Combi TN 2P	Spark gap with varistor
	max. discharge current I_{max} / kA (8/20µs	Rated discharge current I_n / kA (8/20µs)	Protection level U_p / kV“		
Single pole design					
2	40	20	1,5	Limitor VP	Varistor
2	65	20	1,8	Limitor VP NPE[1)]	Spark gap
Multiple pole design for three-phase application					
2	40	20	1,5	Limitor VP TNC	Varistor
2	40	20	1,5	Limitor VP TNS	Varistor
2	40 / 65[2)]	20	1,5/1,8[2)]	Limitor VP TT	Varistor, spark gap
	No-load voltage U_{oc} / kV	Rated discharge current I_n / kA (8/20µs)	Protection level U_p / kV		
Two pole design for single phase application					
3	10/3[3)]	5/3[3)]	0,8/1,2[3)]	Limitor VD	Varistor

1) N - PE arrester
2) L - N / N - PE
3) L / N- PE / L - N

7.1.9 Selectivity

Selectivity, according to IEC 60947-2 (VDE 0660 Part 101), means that in the case of a fault only the overcurrent protection device closest to the fault location interrupts the current, and upstream protection devices do not trip. In this respect, there is a requirement that the time/current curves of two selectively functioning switching devices do not touch or intersect.

Distinctions are made in practice between current, time and zone selectivity (signal-controlled selectivity).

Current selectivity is achieved in switching devices on different short-circuit current levels by the different response currents.

Time selectivity is achieved by setting a delay on the upstream switching device relative to the downstream switching devices.

Zone selectivity circumvents the restrictions of current and time selectivity by transmitting blocking signals through a separate two-wire line. Standard switch-off times with zone selectivity are around 100 ms. Thanks to ABB's newly developed EFDP (Early Fault Detection and Prevention) system, this feature, established in open-type circuit-breakers, is now also available for compact circuit-breakers. With a special fault detection algorithm, total breaking times of 10 ms are now achieved by compact circuit-breakers. This also applies to other switching devices of the same size.

Selectivity can generally be determined by comparison of the breaking characteristics. A distance of at least 100 ms is to be maintained between the curves of two circuit-breakers. If the time/current curves of two switching devices are close together, selectivity can only be reliably determined by experimental trials. For this purpose, the device manufacturers provide tables for coordination of the switching devices.

If selectivity is not achieved over the entire current range, but only up to a maximum current level, this constitutes partial selectivity.

Fuse – fuse selectivity

Fuses generally respond selectively when their time-current characteristics do not touch. This requirement is usually met when grading the fuse current ratings in the ratio of 1:1.6.

Circuit-breaker – circuit-breaker selectivity

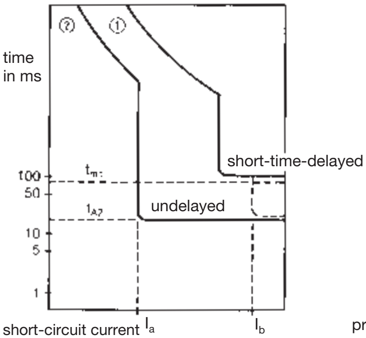
If selectivity by grading the response times of the electromagnetic releases is not possible (no current selectivity), the short-time delayed tripping function (S) is also to be used. In practice, this means a change from an LI release system to an LSI release system. (See section 7.1.2!)

Fuse – circuit-breaker selectivity

In addition to comparing the time/current characteristics, it should be ascertained, particularly in the short-time range, whether the let-through energy $I^2 \cdot t$ of circuit-breaker on disconnecting is less than the melting energy of the backup fuse.

Non-current limiting circuit-breaker / current limiting circuit-breaker selectivity

Normally the selectivity limit is higher than the response value of the undelayed short-circuit release. The short-circuit current up to which this switchgear assembly is selective should be determined experimentally (figure 7-17).



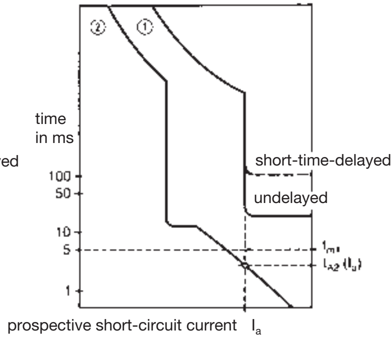


Fig. 7-16

Selectivity of 2 non-current limiting circuit-breakers connected in series:

1 Upstream circuit-breaker with short-time delayed short-circuit release (e.g. incoming feeder) L SI

2 Downstream circuit-breaker (e.g. outgoing feeder) L I

t_m *Minimum command time*

t_A *Total break time*

Selectivity with $t_{A2} < t_{m1}$

Fig. 7-17

Selectivity of non-current limiting circuit-breaker – current limiting circuit-breaker

I_a *Release current for undelayed tripping of breaker 2*

I_b *Release current for undelayed tripping of breaker 1*

Zone selectivity (signal-controlled selectivity)

With time selectivity, the grading time required between two circuit-breakers requires that a fault near the power supply is only disconnected with a large delay depending on the number of grading steps. The system of zone selectivity avoids this disadvantage (figure 7-16). Use of zone selectivity is appropriate when no further selectivity can be achieved either due to the large number of grading stages or to the use of switching devices of the same size. Zone selectivity is based on the transmission of blocking signals through twisted pair cables. Each switch that detects the short-circuit current sends a blocking signal to all upstream switching devices. Only the switch that detects a short-circuit current but does not receive a blocking signal interrupts the current. This simple technology leads to high fault immunity and tripping reliability. Recently, ABB has also introduced a directional protection system with which zone selectivity can also be implemented in meshed networks.

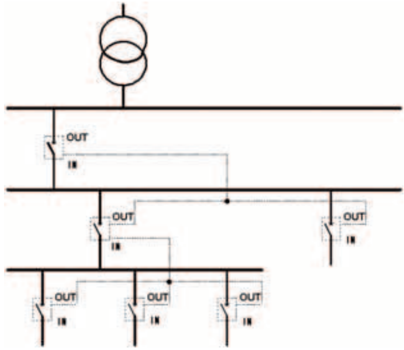


Fig. 7-18

Basic principle of zone selectivity with interlocking of the circuit-breakers

IN Blocking signal entrance of the circuit-breaker (electrical or mechanical)

OUT Blocking signal outlet of the circuit-breaker (electrical or mechanical)

Residual current-operated circuit-breaker – residual current-operated circuit-breaker selectivity

If selectivity is required for residual current-operated circuit-breakers connected in series, a selective master RCCB, identified by [S], must be used. Master RCCBs typically have a rated residual current $I_{\Delta n}$ = 300 mA at rated currents of 40 and 63 A. These breakers are time-delayed in comparison to the standard RCCBs (see section 7.1.7). They also perform fire protection functions in the electrical installation.

7.1.10 Backup protection

The arrangement of two overcurrent protection devices connected in series, one of which provides protection with or without the second protection device and prevents excessive stress on the second protection device, is referred to as backup protection.

Current limiting circuit-breakers and fuses are best suited for backup protection. The let-through power value $I^2.t$ of the upstream short-circuit protection device must be less than the $I^2.t$ value of the protected device at its rated breaking capacity.

Backup protection should always be experimentally confirmed.

Selectivity and backup protection are normally mutually exclusive. However, the selective master RCCB performs both functions: The contact system opens dynamically when a short-circuit current occurs, without releasing the latching system of the breaker mechanism, and limits the short-circuit current (current limiting selectivity). This property opens up new opportunities for applications, also in conjunction with an upstream fuse. The short-circuit release trips with a delay if the downstream circuit-breaker does not interrupt the current.

7.2 Low-voltage switchgear installations and distribution boards

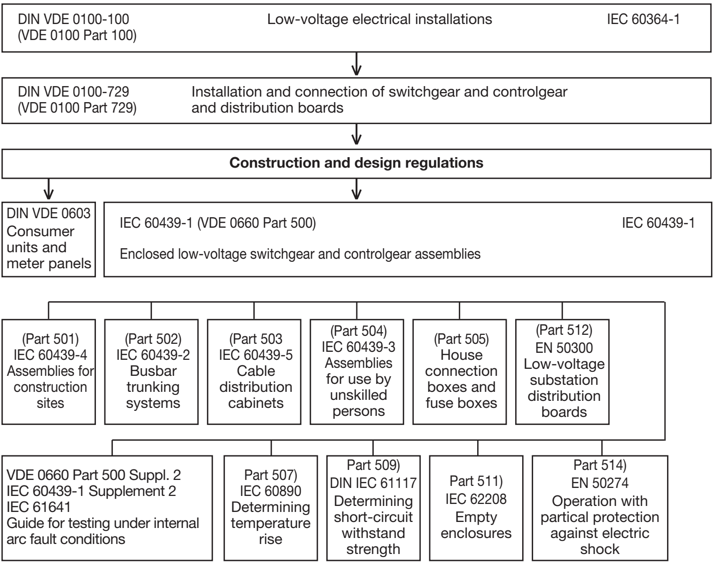
7.2.1 Basics

Low voltage switchgear installations and distribution boards are used for power generation, transmission, distribution and conversion of electrical energy and for the control of equipment which consumes electrical energy.

Depending on the application, they include equipment for switching, protecting, conversion, control, regulation, monitoring, measurement and communication. Because of the extremely varied utilization conditions and requirements for operation, the product standards define corresponding construction requirements. Table 7-14 provides an overview of the erection, construction and design regulations.

Table 7-17

Standards for low voltage switchgear installations and distribution boards



Apart from the small distribution boards (VDE 0603), all other low voltage switchgear installations and distribution boards are considered under the heading low voltage switchgear assemblies in the standard IEC 60439-1 (VDE 0660 Part 500) and the provisions in its subsections. The sections in the individual parts add to, amend or replace sections in the basic standard IEC 60439-1.

The dimensions of switchgear assemblies are based on a 25 mm grid (as per DIN 43660) for flexible internal structure and for modular design. This technology provides the prerequisite for economical planning and manufacture of systems and simplifies later conversion in the event of changes and extensions. The preferred external dimensions, on a basic 200 mm grid, are specified in the DIN 41485 standard.

7.2.2 Type tested and partially type tested switchgear and controlgear assemblies

The following terms are defined in IEC 60439-1:

– *Low voltage switchgear assembly (SA):* Combination of one or more low voltage switching devices with associated equipment for control, measurement, monitoring and the protection and process control units etc., fully assembled under the manufacturer's supervision, with all internal electrical and mechanical connections and structural parts.

– *Type-tested low voltage switchgear assembly (TTA):* Low voltage switchgear assembly not substantially different from the original type or system of the switchgear assembly that was type-tested according to the standard.

Type-tested switchgear assemblies are modular and standardized in structure for reasons of cost-effectiveness, and can therefore cover a broad range of applications. Standardized assemblies such as busbars and distribution busbars are tested in the typical combinations subject to the greatest stresses. This ensures that when the conditions of service and the planning and manufacturing specifications are observed, the various switchgear combinations fulfil the requirements for type-tested switchgear assemblies.

– *Partially type-tested low voltage switchgear assembly (PTTA):* Low voltage switchgear assembly consisting of type-tested and not type-tested modules derived from type-tested modules that have passed the relevant test.

Partially type-tested switchgear assemblies are used for individual applications and particular service conditions, e.g. adaptations of existing installations. The term „partially type-tested" could lead one to assume that the manufacturer only had to demonstrate part of the required properties by testing. According to the standard, however, all results are to be derived from a type test and individually documented accordingly. PTTAs are not permissible for switchgear assemblies to VDE 0660 Parts 501, 502, 503, 504, 505, 511 and 512.

Instead of the derivation from type-tested modules, compliance with the temperature rise limit as per VDE 0660 Part 507 and the short-circuit current capability as per VDE 0660 Part 509 may both be confirmed by calculation for simple, non-subdivided switchgear installations with simple busbar routing.

On careful consideration of these requirements, there is no difference in terms of safety between PTTAs and type-tested switchgear assemblies.

7.2.3 Classification of switchgear assemblies

The variety of applications results in many different designs of low voltage switchgear assemblies. They can be classified under different criteria. These criteria must be used to select a switchgear assembly suitable for the basic requirements of the specific application (table 7-14).

Classification of switchgear assemblies
Basic requirements

- **External design**
  - Open-type assembly
  - Dead-front assembly
  - Enclosed assembly
  - Cubicle-type assembly
  - Multiple cubicle-type assembly
  - Desk-type assembly
  - Box-type assembly
  - Multiple box-type assembly
  - Busbar trunking system
- **Type of installation**
  - Indoor installation
  - Outdoor installation
- **Type of installation**
  - Stationary
  - Movable
- **Enclosure material**
  - Metal
  - Insulating material
- **Enclosure protection**
  - Indoor installation, IP00-IP65
  - Outdoor installation, min. IP48
- **Mounting**
  - Stationary mounted devices Non-drawout assemblies (not replaceable when energized)
  - Removable part (replaceable when energized)
  - Withdrawable part (with disconnected position)
- **Terminals**
  - Function
    - Incoming feeder
    - Outgoing feeder
    - Auxiliary circuit
  - Technology
    - F – fixed connection
    - D – disconnectable connection
    - W – withdrawable connection
- **Internal subdivision**
  - Form 1 No internal subdivision
  - Form 2 Subdivision between busbars and functional units
  - Form 3 Additional subdivision between individual functional units
  - Form 4 Additional subdivision between functional units and their terminals
- **Protection** *(to VDE 0100 Part 410)*
  - **Protection against direct contact**
    - Complete by insulation / cover / enclosure
    - Partial by barriers / clearances
    - Additional by RCD
  - **Protection against indirect contact**
    - By tripping or indication *(Class I)*
    - By protective insulation *(Class II)*
    - By extra low voltage or protective separation *(Class III)*

Table 7-18

Classification of switchgear assemblies by basic requirements

7.2.4 Equipment in low voltage switchgear assemblies

The electrical functions of a switchgear assembly are predominantly fulfilled by standard commercial electrical equipment. The ratings of this equipment are based on standardized test conditions in accordance with the IEC 60947 group of standards.

The ambient conditions for the electrical equipment in a switchgear assembly generally deviate from those standardized test conditions. Manufacturers of switchgear assemblies are therefore required to stipulate and test rated values for electrical functions which correspond to the conditions of installation.

The following conditions are to be observed:

- Ambient temperature of the switchgear installation / effective losses in the panel / degree of protection / installation height in the panel
- Hysteresis and eddy current losses in supporting structures and enclosures
- Cable cross-sections of the internal and external terminals
- Bar cross-sections and heat sink functions of the internal terminals
- Reduction of the arcing space of switching devices
- Influence of busbar and cable connections and their supports on mechanical short-circuit withstand capability

In particular, enclosed switchgear assemblies have an influence on service temperatures. Table 2 of IEC 60439-1 (VDE 0660 Part 500) specifies temperature rise limits.

Table 7-16

Temperature rise limits for switchgear assemblies to IEC 60439-1

Parts of the switchgear assembly	Temperature rise limit (K)
Terminals of conductors led in from outside	70
Busbars	105
Operating parts of	
metal	15
insulating material	25
Touchable external parts of	
metal	30
insulating material	40

The temperature rise limits always apply on the basis of a mean 24 h ambient temperature of the switchgear installation of 35°C, and must not be exceeded in the type tests. A maximum ambient temperature of 40°C is permissible in the service conditions for the switchgear assembly.

No further limit temperatures have been specified, and these are to be determined by the manufacturer of the switchgear assembly, observing the data supplied by the equipment manufacturer.

Table 7-17 shows the usual limit temperatures.

Table 7-17

Limit temperatures in switchgear assemblies to IEC 60439-1

Parts of the switchgear assembly	Temperature rise limit (°C)
Average temperature of the electrical equipment (air temperature in the switchgear assembly)	55
Maximum temperature at insulated conductors	90
Terminals on electrical equipment for insulated conductors	105
Busbar connections	130
Maximum ambient temperature of the switchgear assembly with natural heat dissipation	50

7.2.5 Demonstration of the ratings of low voltage switchgear assemblies

The high level of safety of a switchgear assembly is to be ensured by the manufacturer's documentation of type and routine tests. Table 7-18 shows the tests and documentation required for a TTA or PTTA.

7

7.2.6 Retrofitting, modifying and maintaining low voltage switchgear assemblies

According to IEC 60439-1 (VDE 0660 Part 500), there is no obligation to replace or retrofit older switchgear assemblies which were manufactured before the standard in its current version came into effect.

If modifications or retrofitting are performed on a switchgear assembly, the necessity of testing depends on the nature and scope of the work performed, and is to be decided from case to case. Fundamentally, the person or organization performing the modification or retrofitting bears the manufacturer's responsibility.

Periods are always to be stipulated by the manufacturer for the performance of inspections and maintenance work. If the switchgear assembly is not constantly monitored by a professional electrician, testing is required: in Germany at least every 4 years by table 1A, "Repeat Testing of Permanently Installed Electrical Equipment", of Accident Prevention Regulation BVG A3 of January 2005. The tests are to be performed by a specialist electrician.

7.2.7 Modular low voltage switchgear system (MNS system)

Cost-effective, compact switchgear systems require design and production documentation for functional units in the form of modules that can be combined as necessary (combination modules). The basis for the design is a basic grid dimension E of 25 mm (DIN 43660) in all three dimensions (height, width, depth).

Table 7-18

Demonstration of compliance with the technical requirements for type-tested low voltage switchgear assemblies (TTA) and partially type-tested low voltage switchgear assemblies (PTTA)

No.	Requirements to be tested	Section[1]		TTA		PTTA
1	Temperature rise limit	8.2.1	Type tests	Verification of compliance with temperature rise limit by testing	Tests	Verification of compliance with temperature rise limit by testing, extrapolation from TTA or as per VDE 0660 Part 507
2	Dielectric strenght	8.2.2	Type tests	Verification of dielectric withstand by testing	Tests	Verification of dielectric withstand as in section 8.2.2 or verification by dielectric test as in section 8.3.2 or verification of insulation resistance as in section 8.3.4 (see no. 11)
3	Short-circuit withstand	8.2.3	Type tests	Verification of short-circuit withstand by testing	Tests	Verification of short-circuit strength by testing, extrapolation of similar type-tested configurations or as per VDE 0660 Part 509
4	Effectiveness of the protective conductor	8.2.4	Type tests	Verification of intact connection between exposed conductive parts of switchgear assembly and protective conductor by checking or resistance measurement	Tests	Verification of intact connection between exposed conductive parts of switchgear assembly and protective conductor by checking or resistance measurement
	Proper connection between exposed conductive parts of the switchgear assembly and protective conductor	8.2.4.1				
	Short-circuit current withstand strength of the protective conductor	8.2.4.2	Type tests	Verification of short-circuit strength of the protective conductor by testing	Tests	Verification of short-circuit strength of the protective conductor by testing or corresponding design and configuration of the protective conductor (see section 7.4.3.1.1. last paragraph[1]
5	Creepage distance and clearances	8.2.5	Type tests	Verification of creepage distance and clearances	Tests	Verification of creepage distance and clearances
6	Mechanical function	8.2.6	Type tests	Verification of mechanical function	Tests	Verification of mechanical function
7	IP degree of protection	8.2.7	Type tests	Verification of IP degree of protection	Tests	Verification of IP degree of protection
8	Wiring, electrical function	8.3.1	Routine tests	Visual inspection of switchgear assembly including wiring and if applicable electrical function test	Tests	Visual inspection of switchgear assembly including wiring and if applicable electrical function test
9	Insulation	8.3.2	Routine tests	Insulation test	Tests	Dielectric test or verification of insulating resistance as in section 8.3.4 (see no. 11)[1]
10	Protective measures	8.3.3	Routine tests	Checking protective measures and visual inspection of electrical continuity of the electrical protective conductor connection	Tests	Checking protective measures
11	Insulation resistance	8.3.4	Routine tests	–	Tests	Verification of insulation resistance if not tested as in section 8.2.2 or 8.3.2 (see nos. 2 & 9)[1]

1) IEC 60439-1 (VDE 0660 Part 500)

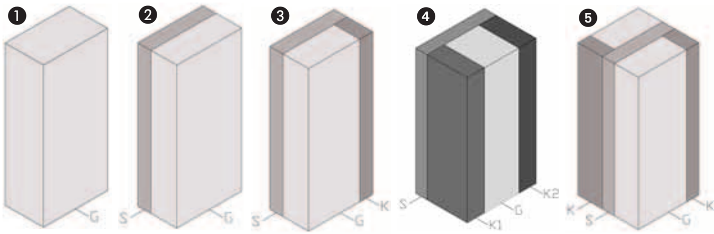


Fig. 7-19

Possible arrangements of the functional compartments in the MNS system
1 to 3 Single side control, 4 Separate cable compartments for power/control
5 Double side control (duplex)
G = Equipment compartment, S = busbar compartment, K = Cable termination compartment, K1 = Control cable, K2 = Power cable

7

The standardized subdivision of a panel into various functional compartments, i.e. equipment compartment, busbar compartment and cable termination compartment, offers advantages not just for design but also in operation, maintenance, modification and also safety.

The basic design of a panel with the configuration of the busbars and the distribution busbars for supplying power to fixed or withdrawable parts is shown in figure 7-20. A particular advantage of the MNS system is the location of the busbars at the rear of the panel. It provides space for two busbar systems if required, enables an advantageous back-to-back configuration with only one busbar system and allows cables to be fed in optionally from above or below.

The panel distribution busbar panel is located behind a function wall in order to prevent accidental contact. The panel function wall of the MNS system, as the most important internal subdivision, provides electric shock protection (IP20) and acts as an arc barrier between the equipment compartment and busbar compartment. This is achieved by design features only without automatically actuated protective shutters.

When the fixed parts and the withdrawable parts are inserted, labyrinthine insulation configurations are formed around the plug-in contacts, safely preventing flashovers between the conductors.

Fixed and withdrawable parts both have plug-in contacts as busbar-side terminals. In fixed parts the equipment is arranged two-dimensionally on the functional units, while a three-dimensional design is used in withdrawable parts for maximum use of the cabinet depth. With predominantly small modules (<7.5 kW), the demands on panel volume are therefore around 40 % less with the withdrawable part design. The withdrawable part sizes are matched to one another to enable small and large modules to be economically combined in one panel (figure 7-21). Subsequent changes to the components can be made without accessing the panel function wall. Reliable mechanical and electrical interlocking of the switchgear prevents operating errors when moving the withdrawable parts.

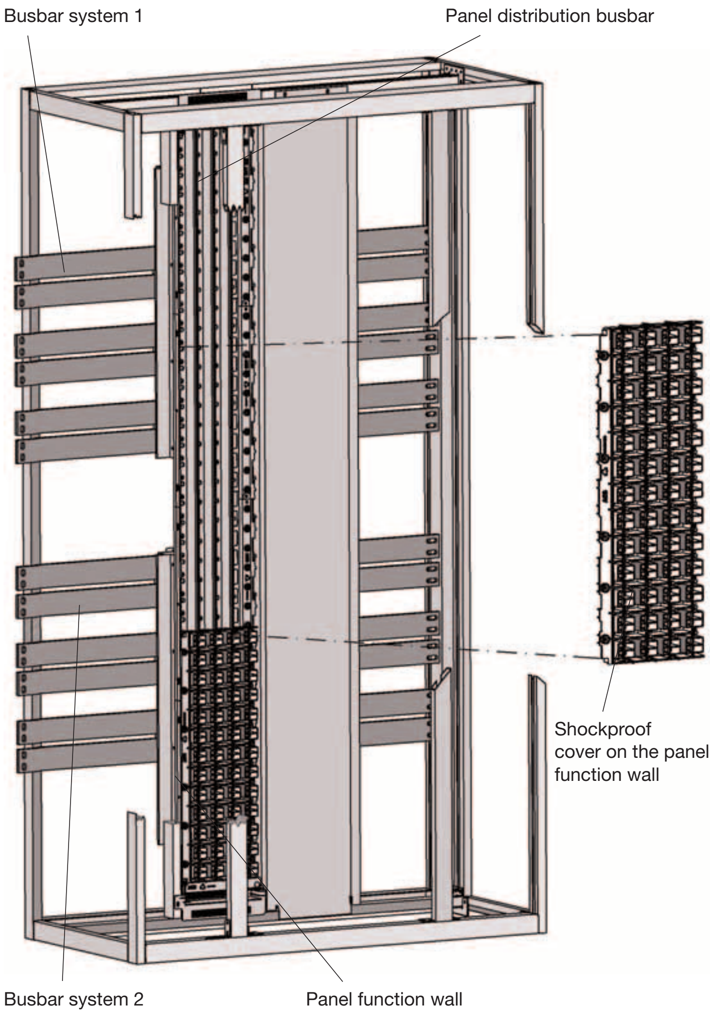


Fig. 7-20

MNS switchgear system busbars and distribution busbars

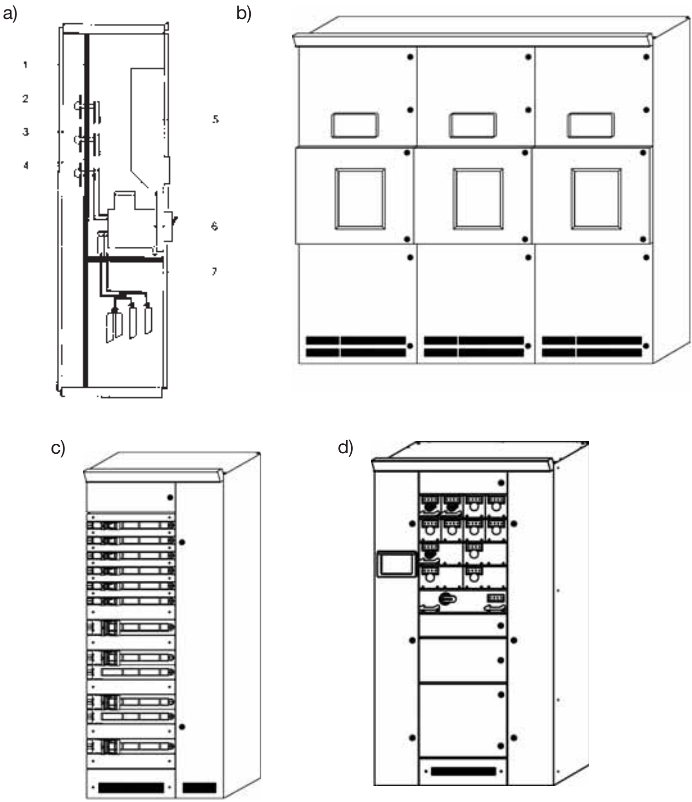


Fig. 7-21

MNS system panel types
a) and b) Sectional view and front view of MNS panels with circuit-breakers
1 Arcing partition, 2 Busbar compartment, 3 Primary busbars, 4 Distribution busbars, 5 Instrument compartment, 6 Circuit-breaker, and 7 Cable termination compartment
c) MNS panel with power output modules in strip form
d) MNS panel with withdrawable units

The circuit diagrams of typical motor starters, which can be obtained as fixed or withdrawable parts, are shown in figure 7-22. Table 7-19 shows a selection of the associated module sizes.

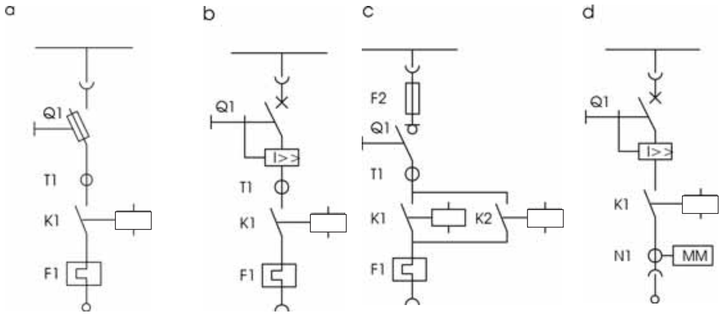


Fig. 7-22

Examples of standard modules in the MNS system for motor starters
a) with fuse switch-disconnector and thermal relay (fixed part design)
b) with circuit-breaker and thermal relay (withdrawable-part design)
c) with load-break switch, fuse, thermal relay and reversing (withdrawable-part design)
d) with circuit-breaker and motor protection with communication facility (withdrawable part design)

Table 7-19

Standard type range of motor starters

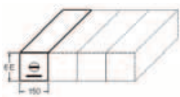
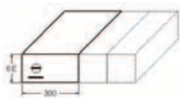
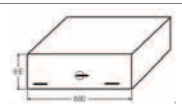
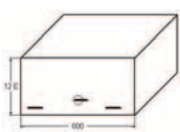
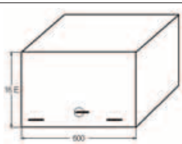
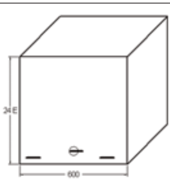
Rated motor power for 400 / 500 / 690 V Coordination 2 (50 kA)								
Withdrawable part size		Starter type	Motor starter with fuse (kW)			Motor starter without fuse (kW)		
			400 V	500 V	690 V	400 V	500 V	690 V
6E/4		DOL	≤ 15	≤ 18.5	≤ 22	≤ 11	≤ 2.2	≤ 1.1
		REV	≤ 5.5	≤ 7.5	≤ 5.5	≤ 11	≤ 2.2	≤ 1.1
		HD	≤ 15	≤ 18.5	≤ 18.5			
6E/2		DOL	≤ 22	≤ 30		≤ 30	≤ 37	
		REV	≤ 22	≤ 30	≤ 22	≤ 30	≤ 37	
		HD	≤ 22	≤ 30		≤ 22	≤ 30	
6E		DOL	≤ 37	≤ 37	≤ 37	≤ 75	≤ 55	≤ 15
		REV						
		HD			≤ 30	≤ 75	≤ 55	≤ 15
6E		DOL					≤ 110	≤ 160
		REV	≤ 37	≤ 37	≤ 37	≤ 37		
		HD					≤ 90	≤ 110
12E		DOL	≤ 55	≤ 75	≤ 75			
		REV				≤ 75	≤ 75	≤ 75
		HD	≤ 45	≤ 55	≤ 55			
16E		DOL	≤ 132	≤ 160	≤ 160	≤ 200	≤ 250	≤ 250
		REV	≤ 75	≤ 75	≤ 75			
		HD	≤ 90	≤ 110	≤ 110	≤ 132	≤ 160	≤ 200
24E		DOL	≤ 250	≤ 250	≤ 250	≤ 250		
		REV						
		HD	≤ 200	≤ 200	≤ 200	≤ 200	≤ 200	

Table 7-20

Type-tested switchgear assemblies
MNS system ratings

Electric parameters

Rated voltages	Rated insulation voltage U_i	1000 V 3~, 1500 V
	Rated service voltage U_a	690 V 3~, 750 V–
	Rated impulse withstand voltage U_{imp}	8 / 12 kV
	Overvoltage category	II / III / IV
	Pollution severity	3
	Rated frequency	up to 60 Hz
Rated currents	**Busbars:**	
	Rated current I_e	up to 6300 A
	Rated peak withstand current I_{pk}	up to 250 kA
	Rated short-time withstand current I_{cw}	up to 100 kA
	Distribution busbars:	
	Rated current Ie	up to 2000 A
	Rated peak withstand current I_{pk}	up to 176 kA
	Rated short-time withstand current I_{cw}	up to 80 kA

Mechanical parameters

Dimensions	Cubicles and supporting structure	DIN 41488
	Preferred module sizes, height	**2200** mm
	Preferred module sizes, width	400, **600,** 800, **1000**, 1200 mm
	Preferred module sizes, depth	400, **600,** 800, **1000**, 1200 mm
	Basic grid dimension	E = 25 mm as per DIN 43660
Surface protection	Frame	Al-Zn coating
	Internal subdivisions	Al-Zn coating
	Enclosure	Al-Zn coating and paint coat RAL 7035
Degrees of protection	to IEC 60529 (VDE 0470 Part 1)	IP 00 to IP 54
Plastic parts	CFC and halogen-free, flame-retardant, self-extinguishing	
Internal subdivisions	Form 1 – Form 4 to IEC 60439-1, table 6A	
Specifications	IEC 60439-1 (VDE 0660 Part 500), arc fault resistance to IEC 61641 and VDE 0660 Part 500 Supplement 2	

7.2.8 Systems for power factor correction

The reactive power modules for the MNS system are designed to conform to the installation dimensions of the system, i.e. they are designed for a 600 mm wide and 400mm deep equipment compartment. Four or five modules and one controller unit fit into one switchgear panel. The direct association of the PF correction modules with the electrical equipment (motor feeder modules) enables a very compact design. On the supply side, the plug-in contacts allow the fixed modules to be replaced quickly by electrical technicians when necessary.

Table 7-21

Technical data of modules for power factor correction with dry-type capacitors

System voltage	Chocking	Module output
400 V ~	0%	4 x 10 kvar, 4 x 12.5 kvar, 3 x 20 kvar, 3 x 25 kvar
	5.67%, 7%	2 x 10 kvar, 2 x 12.5 kvar, 2 x 20 kvar, 2 x 25 kvar, 1 x 40 kvar, 1 x 50 kvar
	12.5%	2 x 10 kvar, 2 x 20 kvar, 1 x 40 kvar
	5.67%/12.5%	1 x 20 kvar, 1 x 40 kvar
525 V ~	0%	4 x 10 kvar, 3 x 20 kvar
	5.67%, 7%	2 x 10 kvar, 2 x 20 kvar, 1 x 40 kvar
	12,5%	2 x 10 kvar, 2 x 20 kvar, 1 x 40 kvar
	5.67%/12.5%	1 x 20 kvar, 1 x 40 kvar
690 V ~	0%	4 x 10 kvar, 4 x 12.5 kvar, 3 x 20 kvar, 3 x 25 kvar
	5.67%, 7%	2 x 10 kvar, 2 x 12.5 kvar, 2 x 20 kvar, 2 x 25 kvar, 1 x 40 kvar, 1 x 50 kvar
	12,5%	2 x 10 kvar, 2 x 20 kvar, 1 x 40 kvar
	5.67%/12.5%	1 x 20 kvar, 1 x 40 kvar

7.2.9 Automation systems for low voltage switchgear

Automated operation of low voltage systems for power distribution, supply of power for motors and connection to higher-order automation systems requires control components based on microprocessors even for low voltage switchgear installations. ABB supplies the INSUM system as an optional protection, control and monitoring system in MNS installations. It can be supplied in MNS withdrawable part design (preferred), and also in MNS fixed assembly design.

INSUM performs the following functions:

Protection functions:

– Overload protection/automatic restarting
– Low-load indicator
– Off-load protection
– Blocking protection

– Phase failure monitoring
– Reclosing lockout
– Safety interlocking
– Thermal overload protection by thermistor
– Loss of supply monitoring / sequential starting of motors after voltage recovery
– Earth-fault detection
– Cyclic bus monitoring / fault protection

Control functions:
– Control of the motor starter/circuit-breaker via the HMI, the local control panel, with the integrated INSUM OS monitor workstation or the higher-order process control system test function

Measured and metered value recording:
– Phase currents
– Voltages
– Power outputs
– Earth-fault current
– Switching cycle counter
– Operating hours

Signalling functions:
– Status messages and signals
– Warning and fault messages in plain text in the local language

The various protection and control functions in the INSUM system are performed by one motor control unit (MCU) per motor starter and one energy control unit (ITS) per fuse block. The motor ratings are stored as parameters (depending on the type of starter, motor data and protection concept) in the MCU.

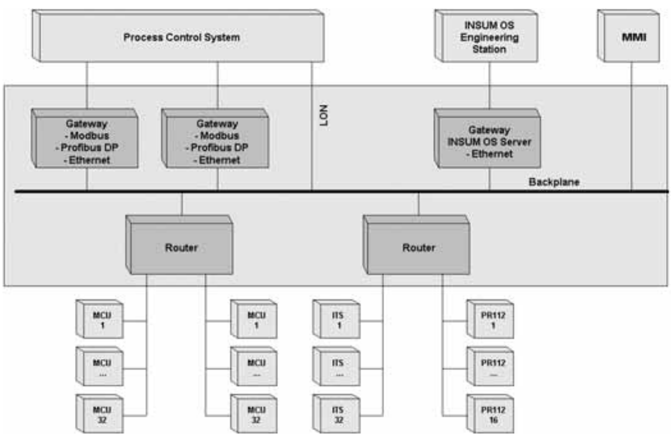


Fig. 7-23 Overview of the INSUM system

The user obtains access to the motor starters, for instance to issue switching commands, read measured values, detect alarms or faults or change motor parameters, via the human-machine interface (HMI) installed centrally in the switchgear system, or via the INSUM OS PC control station.

INSUM facilitates connection of the motor control centre to higher-order process automation systems. The system can be connected directly, for instance to ABB Advant OCS, by field bus links. Protocol converters (gateways) for Profibus DP, Modbus RTU or Ethernet TCP/IP are available for communication with process automation systems from other manufacturers.

7.2.10 MNS *i*S motor control centre

Motor control centres (MCCs) in manufacturing industry and in power stations are as a rule controlled by the process automation system. Field bus systems are now used to connect the MCC to the process automation system. This exchange of information is dependent on the type of process controlled, and is as a rule time-critical.

In addition, information required for maintenance and analyses which is not critical with respect to time is transmitted either acyclically through field bus systems or through separate bus systems. Bus communication is also required to assist in parameterization and commissioning.

MNS iS is a motor control centre which has been developed and optimized to meet the various requirements of automation system connection in terms of type (bus system), availability (redundancy) and functionality.

The hardware and software functions are scalable to meet the requirements. Functions which were previously performed by individual devices, e.g. motor protection, field bus connection, and current and voltage sensors, are integrated in the MCC.

Furthermore, MNS iS motor control centres provide all the control, protection and monitoring functions for the motor and motor starter in the form of special hardware and software modules conforming to the relevant specification. MNS iS therefore provides a broader range of functions than INSUM.

Hardware

The M*Start* motor starter modules contain the electrical power components appropriate for the type of starter and the motor power, while the M*Control* control modules contain the electronic components for control, monitoring and protection of the motor. (System functions are loaded as software.)

Software

The system functions (control, measurement and protection) are available as software function modules which are loaded into the M*Control* module. Only the functions needed have to be loaded. Additional functions are available as options. A system function can be installed at any time without any changes being made to the hardware and wiring.

The system's flexibility permits modification by means of a simple "Plug and Produce" concept. Replacement of modules and changes to parameter settings can be easily effected with the integrated system functions and tools.

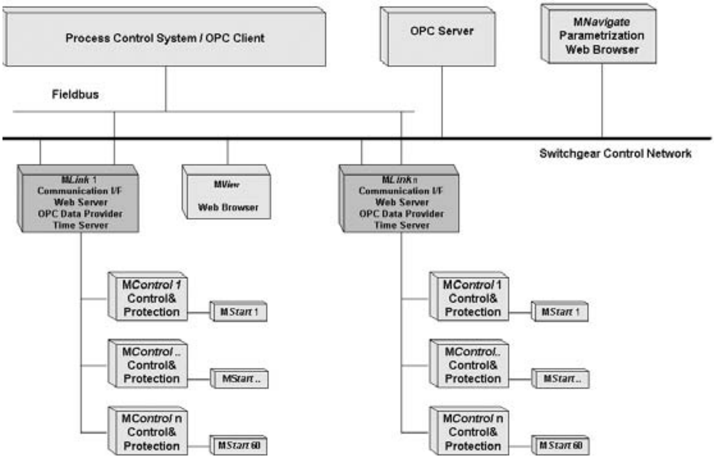


Fig. 7-24 Overview of the MNS iS system

MNS *i*S system properties:

Power and control circuits completely separated

Physically separated cable termination compartments for the power and control circuits in the switchgear provide for safe access to the various components in the system and avoid electromagnetic interference.

Standardized motor starter module M*Start*

Completely assembled and tested modules for the entire power range (0 – 250 kW) and various starter types simplify project development.

Versatile control module M*Control*

Control modules can be adapted by using hardware and software options to meet an extensive range of requirements with regard to protection functions and the use of I/O contacts.

Integrated control circuits

All the links between the M*Start* motor starter modules and the M*Control* control modules are already integrated on the starter level. No wiring work or assignment of inputs or outputs is required. The adaptation work is limited to the assignment of freely usable I/O signal contacts which can be linked to logic operations.

Three measured variables

Temperature, current and voltage measurements supply the input variables for various protection functions for the motor and the switchgear itself. Intelligent sensors in the motor starter modules are used to perform the measurements.

Demand-orientated data flow

Standard communications systems such as PROFIBUS DP, Modbus and OPC Interface ensure than the right information is distributed to the right person (operator, service technicians and management).

Time synchronization

On synchronization with a central or local time server, signals and events recorded in the control module are precisely time-stamped.

Access to the system with standard web browsers M*View* and M*Navigate*

Via the integrated web server, the user can access the system, for instance to perform switching operations, read data or change parameters, with any web browser based equipment. The user interface is accessible both from devices permanently installed in the switchgear (M*View*) and from PCs or laptops (M*Navigate*).

Monitoring of the module locations

Self-monitoring functions ensure that the modules are correctly assigned. On the one hand, the compatibility of the motor starter module type with the corresponding control module is monitored. On the other hand, installation of the modules at the correct locations is also monitored. This functionality enhances safety during installation and operation, and assists when work is performed on the system.

Optimized maintenance

Maintenance functions are already integrated in the system. Maintenance data (e.g. temperatures, module cycles and number of switching operations) are recorded and assist in optimizing maintenance schedules.

Switchgear system

MNS iS is based on the tried and tested MNS switchgear system.

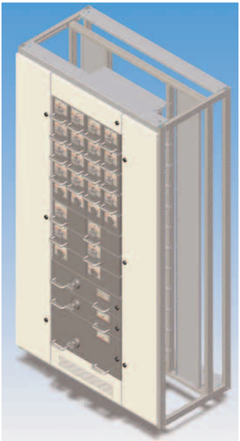


Fig. 7-25

MNS iS motor control centre

7.3 Planning aids

Some suggestions for the planning of low voltage switchgear installations are given below.

7.3.1 Keeping within the temperature rise limit

The temperature rise limits that must be maintained for switchgear assemblies are listed in table 2 of IEC 60439-1 (VDE 0660 Part 500). An ambient temperature of max. 40 °C, or 35 °C as the 24 hour average, is specified as a base. The temperature rise limits for the individual components are also presented in section 7.2.4, table 7-16.

At higher ambient temperatures (up to 50 °C for export), the same limit temperatures must be maintained. This is preferably to be achieved by using a lower component density for the switchgear or by reducing the degree of protection where possible. Forced ventilation or air conditioning may also be necessary.

Figure 7-26 shows the connection between the degree of protection and the heat load of a switchgear panel and the influence of the ambient temperature. When the power dissipation generated in a panel reaches the maximum permissible value according to the corresponding curve, the air temperature in the top section of the panel settles at a daily average of 55 °C.

A calculation method for determination of the temperature rise in partially type-tested low voltage switchgear assemblies is proposed in IEC 60890 (VDE 0660 Part 507). This method is suitable for demonstration of compliance with the temperature rise limits in simple switchgear configurations with evenly distributed power dissipation and few internal subdivisions.

The factors and coefficients set out in that report were derived from measurements on a large number of switchgear assemblies and verified by comparative tests.

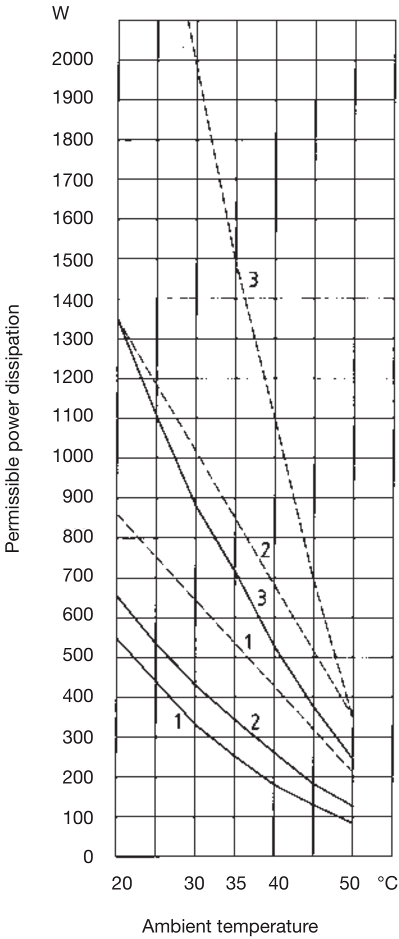


Fig. 7-26

Guideline values for the maximum permissible effective power dissipation in an MNS switchgear cubicle

Dimensions of the switchgear cubicle (middle cubicle)

Height 2200 mm
Width 1000 mm
Dept 600 mm

Instrument compartment
Width 600 mm

Clearance from wall
8 cm

Legend

______ Degree of protection IP52 to IP54

---------- Degree of protection IP32 to IP42

1 = Withdrawable part design

2 = Fixed part design

3 = Switchgear cubicle with open-type circuit-breakers

7

7.3.2 Verification of the short-circuit current capability of busbar systems

The short-circuit strength of circuits with a rated short-time withstand current of greater than 10 kA or a let-through current of 17 kA for current limiting feeders, is always to be verified by testing. For partially type-tested switchgear assemblies, the short-circuit capability can be demonstrated by extrapolation of the results for similar type-tested assemblies.

An extrapolation procedure for simple busbar arrangements is described in the technical report IEC 60117 (VDE 0660 Part 509). This method is based on IEC 60685-1 (VDE 0103), „Calculation of the effects of short-circuit currents".

7.3.3 Calculation programs for planning and design of low voltage switchgear installations

Many companies supply computer-aided engineering (CAE) programs for the PC for planners. These highly developed aids make rapid, standard-compliant and nevertheless economical planning of more and more complex systems in low voltage applications possible.

D.O.C.Win 2.1 (Design Optimization on Computer) from ABB is mentioned here as an example. The current version of this program (2.1), available now for almost 20 years and continuously developed during that period, provides the following functionalities:

– Load flow and short-circuit calculation in radial and meshed systems

– Automatic dimensioning on transformers, circuit-breakers, fuses, miniature circuit-breakers, residual current protection devices, contactors, etc.

– Automatic cable dimensioning

– Selectivity and backup checks

– Documentation of release characteristics and let-through power curves

– Management and calculation of various operating conditions in one project

– Visual display of equipment specified by the user

– Aids for dimensioning of busbars

– Calculation of temperature rises in switchgear cubicles

– Databases for coordination and motor protection

– Selection from 5 languages (en, fr, es, it, de) for the program and reports

– Report editor

– Reports in PDF format

– Integration of D.O.C.Win 2.1 in „ABB Software Desktop", the new uniform ABB interface for technical software

– Automatic, free Internet update service for registered users covering all programs in the ABB Software Desktop

7.3.4 Internal arc testing

Correct dimensioning of low voltage switchgear assemblies to IEC 60439-1 ensures adequate protection of cables and loads from the injurious effects of overloads and short-circuits.

Faults in a switchgear assembly are rare. When they do occur, however, they frequently develop into internal arc faults with disastrous consequences for operator safety and system availability.

Internal arc faults generally occur as consequential faults. The causes are

– equipment faults,
– maloperation,
– maintenance errors,
– foreign bodies or vermin,
– contamination, and
– planning errors.

It is recommended that the behaviour of switchgear assemblies in the event of a fault be taken into account during planning as set out below, at least for the following arc power W_{arc} and above:

- Operator protection against the effects of an internal arc fault is necessary at $W_{arc} > 250$ kWs.

This arc energy is reached for example on the 400 V side of a 630 kVA transformer after a fault duration of 60 ms. Serious injuries with long-term effects do not normally occur below this limit.

- Equipment protection against the effects of an internal arc fault is necessary at $W_{arc} > 100$ kWs.

This arc energy is also reached after approx. 60 ms on the 400 V side, but at a transformer of only a 250 kVA transformer. Up to this limit, further operation of the switchgear assembly should be possible after a limited amount of cleaning.

Testing the response of switchgear to internal arcing – specified for medium voltage assemblies for many years now by a test directive (see section 8) – is also regulated for low voltage systems. The test directive is available as Supplement 2 to IEC 60439-1 (VDE 0660 Part 500) or as IEC 61641. The test duration is between 100 ms and 500 ms. The preferred arcing duration in the test is 300 ms. The response of the switchgear is assessed by the following criteria:

– Properly secured doors or barriers shall not open.
– Parts that could cause a hazard shall not come loose.
– Arcing must not burn any holes in freely accessible, external parts of the enclosure.
– The vertically installed indicators (black cotton cloth = cretonne) must not ignite.
– The protective conductor function for the exposed conductive parts of the enclosure must be retained.

An extension of the testing criteria with regard to equipment protection under arc fault conditions was published in the March 2001 draft of Supplement 2 to IEC 60439-1. The following test criteria were added:

– Arcing remains limited to a defined area. Functional compartments to which this limitation applies can be defined on the basis of the internal subdivisions.

– Emergency operation is possible after rectification of the fault without thorough cleaning.

The occurrence of internal arc faults can be greatly reduced by appropriate design. A successful safety philosophy always follows this strategy:

1. Avoid faults (active safety)

2. Limit faults (passive safety)

Arc-proof internal subdivisions limit arc faults to their point of origin and the tested enclosure retains them.

Arc sensors are available which detect arc faults and protect the system from major damage by extremely rapid short-circuiting and/or interruption. These solutions however have the disadvantage that power supply to the entire process may be missing for a relatively long period.

8. Switchgear and switchgear installations for high voltage up to and including 52 kV (medium voltage)

8.1 Switchgear apparatus (< 52 kV)

This voltage range is generally referred to as ”medium voltage“, even though the term has not been standardized anywhere.

The principal terms relating to switchgear are defined in section 10.1.

8.1.1 Disconnectors

The classic design of the disconnector is the knife-contact disconnector (Fig. 8-1). It has become less common with the increasing use of withdrawable circuit-breakers and switch-disconnectors. This functional principle is now again becoming more frequent in gas-insulated switchboard technology.

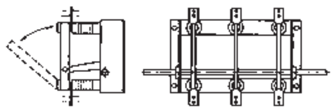


Fig. 8-1
Medium-voltage knife-contact disconnectors

The blades of knife-contact disconnectors installed in an upright or hanging position must be prevented from moving by their own weight.

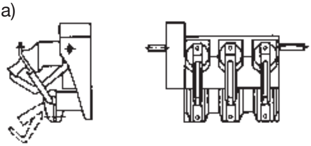
Disconnectors can be actuated manually and, in remotely operated installations, by motor or compressed-air drives.

8.1.2 Switch-disconnectors

Switch-disconnectors are increasingly being used in distribution networks for switching cables and overhead lines. Switch-disconnectors in connection with HRC fuses are used for protection of smaller transformers.

Switch-disconnectors are switches that in their open position meet the conditions specified for isolating distances. General purpose switches can make and break all types of operating currents in fault-free operation and in the event of earth faults. They can also make and conduct short-circuit currents.

a)



b)

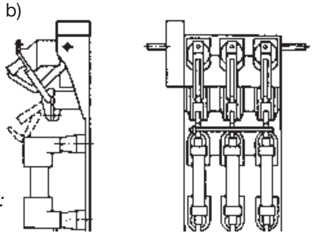


Fig. 8-2
NAL type knife-contact switch-disconnector:
a) without and
b) with fuse assembly

a) b)

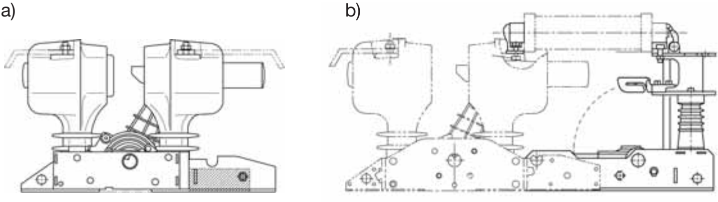


Fig. 8-3
C4 rod-type switch-disconnector:
a) without fuse assembly b) with fuse assembly

Knife-contact switch-disconnectors as per figure 8-2 and rod-type switch-disconnectors as shown in figure 8-3 are actuated in two ways, depending on their type:

a) ”Snap-action mechanism”, also referred to as toggle-spring mechanism. With this type of operating mechanism, a spring is tensioned and released shortly before the operating angle is completed and its release force actuates the main contact systems. This is used for both closing and opening.

b) ”Stored-energy mechanism”. This mechanism has one spring for closing and a second spring for opening. During the closing operation, the opening spring is simultaneously tensioned and latched. The stored energy for the opening operation is released by magnetic trips or the striker pin of the HRC fuse.

The rod-type switch-disconnector is particularly suitable for the design of compact switchgears, because the knife-contact switch-disconnector requires a greater depth for the switching zone because of the projecting contact blade in its open state. The rod-type switch-disconnectors also enable very small phase spacings without phase barriers.

8.1.3 Earthing switches

Earthing switches are installed in switchgears primarily near cable sealing ends, i.e. before the main switching device. However, earthing switches are often specified also for busbar earthing, for example in metering panels. If the main switching device is a switch-disconnector, the earthing switch and the switch-disconnector will often be on a common base frame (Fig. 8-4).

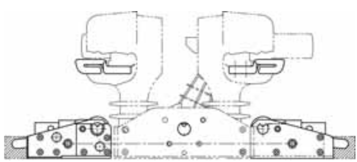


Fig. 8-4
Arrangement of earthing switches on a switch-disconnector base frame

Every earthing switch must be capable of conducting its rated short-time current without damage. ”Make-proof” earthing switches are also capable of making the associated peak current at rated voltage. For safety reasons, make-proof earthing switches are recommended with air-insulated switchgear because of possible faulty actuations (DIN VDE 0101, Section 4.4). In gas-insulated switchgear, the earthing of a feeder is often prepared by the earthing switch and completed by closing the circuit-breaker. In this case, a separate make-proof earthing switch is not required.

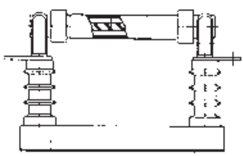
8.1.4 Recognizable switch position

Because disconnectors, switch-disconnectors and earthing switches are very important to safety in the isolation of cables, lines and station components, there are special requirements for their position indication. It is true that the switch contacts themselves no longer need to be directly visible, but it is required that the switch position be recognizable, i.e. that actuation of indicators or auxiliary switches must be picked up directly at the switch contacts and not from a link in the force transmission mechanism upstream from the operating spring (IEC 62271-102 (VDE 0671 Part 102)).

8.1.5 HRC fuse links (DIN VDE 0670 Part 4)

The load current flows in fuse links through narrow melt-out conductor bands, which are arranged spirally in a sealed dry quartz sand filling in the interior of an extremely thermally resistant ceramic pipe. The conductor bands are designed with a narrower cross-section at many points to ensure that in the event of an overcurrent or short-circuit current, a defined melting will occur at many points simultaneously. The resulting arc voltage ensures current limiting interruption in case of high short-circuit currents.

Fig. 8-5
Fuse base with fuse link



The cap-shaped end contacts of the HRC fuse link are picked up by the terminal contacts of the fuse base. HRC fuse links can be fitted with indicators or striker pins, which respond when the band-shaped conductors melt through. The striker pin is required for mechanical tripping of the switching device when used in the switch/fuse combination (IEC 62 271-105 (VDE 0671 Part 105)).

Characteristic current values for HRC fuse links:

Rated current

The majority of fuse links in operation have a rated current < 100 A. For special applications with smaller service voltages (e.g. 12 kV), fuse links up to 315 A are available. The associated melt-through times of the fusible conductors can be found in the melting characteristics published by the manufacturers (Fig. 8-6).

Rated maximum breaking current

This value must be provided by the manufacturer of the fuse link. It is influenced by the design for a specified rated current. When selecting fuse links for transformer protection in distribution systems, the maximum breaking current is not a critical quantity.

Rated minimum breaking current

Classification of fuse links into three categories

- <u>Back-up fuses</u>
  Smallest breaking current (manufacturer's information) in general at 2.5 to 3.5 times rated current. Suitable for application in switch/fuse combinations. Very common!
- <u>General purpose fuses</u>
  The smallest breaking current is that which results in melt-through after 1 hour or more of exposure time (generally twice the rated current).
- <u>Full-range fuses</u>
  Every current that results in a melt-through can be interrupted.

Cut-off current characteristic

The maximum value of the current let-through by the fuse depends on its rated current and the prospective short-circuit current of the system at the point of installation. Fig. 8-7 shows a characteristic field.

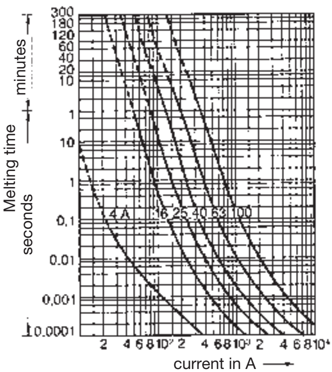


Fig. 8-6

Melting time in relation to overcurrent / short-circuit current

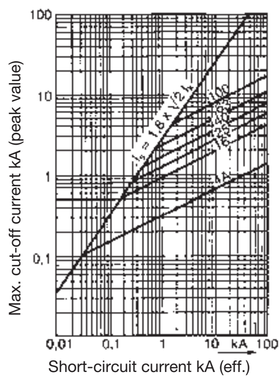


Fig. 8-7

Cut-off current in relation to short-circuit current

Selecting fuse links for specific conditions

When protecting transformers and capacitors with fuses, the inrush currents must be taken into account. When protecting transformers, selectivity is required by making the melting times of low-voltage fuses and HRC fuses match to ensure that the low-voltage fuses respond first.

In capacitor banks the rated current of the HRC fuse links should be at least 1.6 times the rated current of the capacitors. Experience has demonstrated that this covers also the influences of possible system harmonics and increased voltage.

When selecting fuse links for protection of high-voltage motors, the starting current and the starting time of the motors must be taken into account. The frequency of start-ups must also not be neglected, if this is frequent enough to prevent the fuses from cooling down between starts.

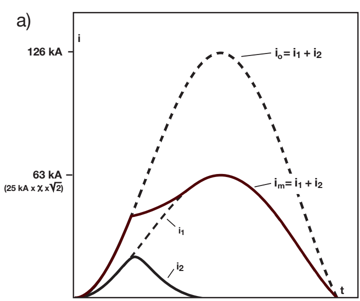
8.1.6 I_s-Limiter® – the world's fastest switching device

The increasing requirements for energy throughout the world demand higher rated or supplementary transformers and generators and tighter integration of the supply systems. This can also result in the permissible short-circuit currents of the equipment being exceeded and the equipment being dynamically or thermally destroyed.

It is often not technically possible or not economical for the user to replace switchgear and cable connections with new equipment with increased short-circuit current capability. The implementation of I_s-limiters when expanding existing installations and constructing new installations reduces the possible short-circuit current and costs.

A circuit-breaker does not provide protection against impermissibly high peak short-circuit currents, because it trips too slowly. Only the I_s-limiter is capable of detecting and limiting a short-circuit current in the initial rise, i.e. in less than one millisecond. The maximum instantaneous current value that occurs remains well below the peak value of the short-circuit current of the system.

The I_s-limiter, like a fuse, is therefore a current-limiting switching device, which detects and limits the short-circuit current in the initial rise (figure 8-8). The short-circuit current through the I_s-limiter is limited so quickly that it does not contribute in any way to the peak value of the short-circuit current at the fault location.



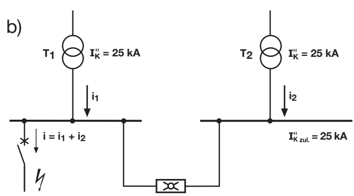


Fig. 8-8

Short-circuit breaking with I_s-limiter
a) Current path
i_o Total current without I_s-limiter
i_m Total current with I_s-limiter
b) Single line diagram

In principle, the I_s-limiter consists of an extremely fast switching device that can conduct a high rated current but has only a low switching capacity, and a parallel configured fuse with high breaking capacity (figure 8-9). To achieve the desired short switching delay, a small charge is used as energy storage to interrupt the main conductor. When the explosive charge has detonated, the current commutates to the parallel fuse, where it is limited within 0.5 ms and then is finally interrupted at the next voltage zero.

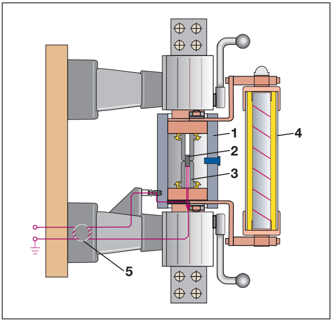


Fig. 8-9

Holder and insert of an I_s-limiter

1 Insulating tube
2 Charge
3 Bursting bridge (main conductor)
4 Fuse
5 Pulse transformer

Depending on the voltage, the rated currents of I_s-limiter inserts range up to 4,000 A (and even up to 4,500 A at 0.75 kV) and they can be connected in parallel for higher current levels.

I_s-limiters are most commonly used (figure 8-10)
– in couplings,
– in connections between the public network and internal power supply systems
– in parallel with reactors,
(avoidance of copper losses and voltage drops at reactors)
– in transformer or generator feeders, and
– in outgoing feeder panels.

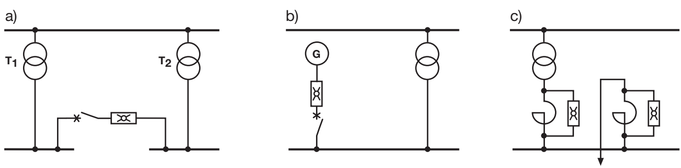


Fig. 8-10

Example applications of I_s-limiters

a) couplings, b) feeders, c) parallel circuits to reactors in incoming and outgoing feeders

8.1.7 Circuit-breakers

There are still a number of ”small-oil-volume” circuit-breakers in use for rated voltages up to 52 kV in systems, but for new installations only vacuum or SF_6 circuit-breakers are used.

Circuit-breakers can be stationary mounted or integrated into the panel in withdrawable unit design with appropriate interlocking mechanisms.

Circuit-breakers must be capable of making and breaking all short-circuit and service currents occurring at the operational site. See 10.4.3 for details. The testing conditions for the corresponding verifications can be found in DIN VDE 0671 Part 100.

Vacuum circuit-breakers

Vacuum circuit-breakers of the VD4 type are available from the ABB production range for short-circuit breaking currents up to 63 kA with rated currents from 400 to 4,000 A. The VD4 range covers the voltage ranges of 12 kV, 17.5 kV, 24 kV and 36/40.5 kV.

Fig. 8-11 shows a vacuum circuit-breaker of the VD4 type in column design.

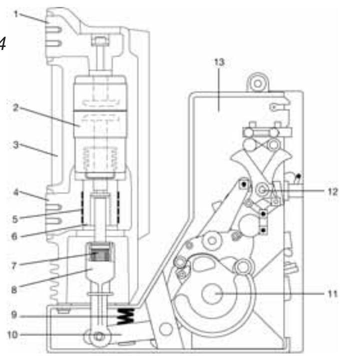


Fig. 8-11

Section of a vacuum circuit-breaker type VD4 for 12 kV, 2,000 A, 40 kA
1 Upper terminal
2 Vacuum interrupter
3 Cast resin enclosure
4 Lower terminal
5 Multi-contact
6 Piston
7 Contact pressure spring
8 Insulated actuating rod
9 Opening spring
10 Guide lever
11 Mechanism shaft
12 Release mechanism
13 Mechanism enclosure with stored-energy spring mechanism

The components of the main current path (upper breaker terminal, vacuum interrupter, lower terminal, etc.) are embedded in cast resin and thus completely enclosed by insulating material. The concept of these embedded pole parts, in which the vacuum interrupter forms a positive and non-positive unit with the entire pole, precludes disruptive external influences on the switching element proper. The VD4 vacuum circuit-breaker is therefore particularly suitable for construction of compact panels.

Figure 8-12 shows the VD4 circuit-breaker with isolating contact arms on the withdrawable module frame for service in air-insulated panels of type UniGear ZS1.

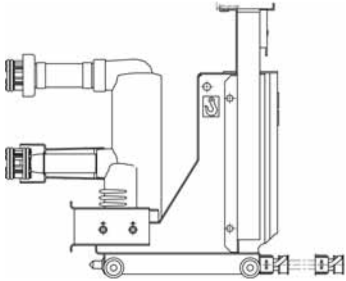


Fig. 8-12

Vacuum circuit-breaker type VD4 for 12 kV as a withdrawable unit

Fig. 8-13 shows the most important components of a vacuum interrupter from the ABB range in sectional view. All joints of the conducting path and of the external enclosure are manufactured by brazing in vacuum furnaces with the aid of special hard solder. This results in an extremely reliable and long-lasting seal.

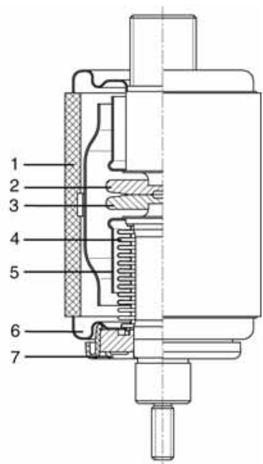


Fig. 8-13

Partial section of a vacuum interrupter, simplified schematic illustration

1 Insulator
2 Fixed contact
3 Moving contact
4 Metal bellows
5 Screen
6 Interrupter lid
7 Anti-rotation element

The contacts are a copper/chromium composite material, a copper base containing evenly distributed fine-grained chromium particles, which has a good extinguishing and arc-resistant response when switching short-circuit currents, and is also distinguished by low-chopping current values when breaking small inductive currents.

Switching overvoltages

Switching overvoltages when switching inductive loads with vacuum circuit-breakers have long been a subject of discussion. The introduction of copper/chromium as the contact material has significantly reduced the occurrence of hazardous overvoltage levels. To cover the residual risk, surge arresters based on metal oxide (MO) are recommended for certain applications. Examples of such applications are:

– small motors (with starting current below about 600 A),
– small generators,
– reactor coils for power factor correction,
– dry-type transformers in industrial applications.

Only in special cases (e.g. furnace transformers) are supplementary RC circuits required, preferably in the form of ZORC combinations (zinc oxide+R+C).

Actuating systems

The travel of the moving contact between the open and closed positions in the vacuum circuit-breaker is between 8 and 14 mm depending on the rated voltage. At the end of the closing stroke, the energy for tensioning the contact pressure springs is required. The relatively low total energy requirement for vacuum circuit-breakers is generally provided by mechanical spring stored energy operating mechanisms, as with the VD4 type. Tripping is initiated by magnetic releases or manually. The mechanical operating mechanism of the VD4 circuit-breaker is always suitable for autoreclosing (0 – t – CO).

Figure 8-14 shows a new operating mechanism system for the vacuum circuit-breaker of type VM1.

1 Upper terminal
2 Vacuum interrupter
3 Cast resin enclosure
4 Lower terminal
5 Flexible connector
6 Contact pressure spring
7 Insulated actuating rod
8 Lever shaft
9 Sensor for switch position ON
10 Sensor for switch position OFF
11 ON coil
12 Permanent magnets
13 Magnet armature
14 OFF coil
15 Emergency manual switch-off
16 Mechanism enclosure

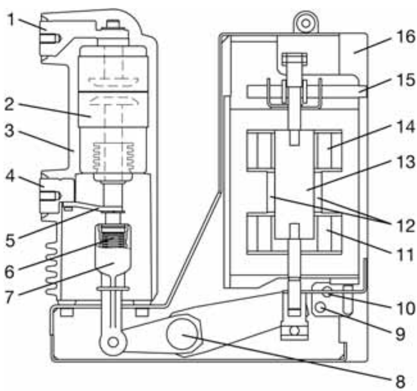


Fig. 8-14
Vacuum circuit-breaker type VM1 with magnetic actuator (compatible with type VD4)

The movable contacts here are actuated by a permanent magnet mechanism with two stable limit positions. The contact movements are initiated by current pulses to one coil for each contact (approx. 100 Watt / 45 ms), generated by discharge of a capacitor, i.e. with less energy than with the magnetic releases of the stored-energy spring mechanism.

The release currents are exclusively controlled by electronic components (thyristors and transistors). A fixed-programmed logic circuit coordinates the processes and interlock conditions. The contact position is detected by sensors. The interface to the automation system is through binary inputs and outputs.

Because of the extremely small number of individual parts, this actuating system offers significant advantages in reliability, durability (up to 100,000 switching cycles) and manufacturing costs.

The pole section (figure 8-14) with the vacuum interrupter moulded in epoxy resin has optimum dielectric properties, permanent protection against external influences of all types and because of the small number of parts, very little likelihood of faults occurring. This eliminates the requirement for maintenance of this switching device under standard operating conditions.

SF_6-circuit-breakers

After its successful implementation in the range of transmission voltages (cf. section 10), SF_6 has also become established in the medium-voltage range. The puffer type arc-quenching principle, which was introduced first, provides an effective arc-quenching gas flow by a mechanically driven piston. However, this requires high energy driving systems. Hence self-blast arc-quenching systems of different types were developed, where the relative movement between the gas and the arc is provided by the arc itself.

The ABB SF_6 circuit-breakers of type HD4 make use of a combination of these two-different arc-quenching principles (see figure 8-15). They cover the voltage range up to 24 kV, with short-circuit breaking currents up to 50 kA and service currents up to 4,000 A. The arc-quenching system applies the gas compressed in the lower chamber to interrupt small currents with overvoltage factors < 2.5 p.u. even in the case of small inductive currents. High short-circuit currents are interrupted by the self-blast effect applying the pressure built up in the moving chamber by the arc energy.

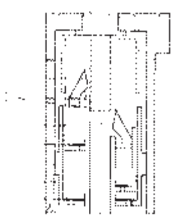


Fig. 8-15:

SF_6 circuit-breaker: Functional principle of the "Autopuffer" quenching system

1 Upper terminal
2 Main contact
3 Nozzle
4 Arcing contact
5 Nozzle pressure chamber
6 Valves
7 Lower chamber
8 Insulating enclosure
left: closed
right: open

8.1.8 Vacuum contactors

Vacuum contactors, in connection with HRC fuses, are particularly suitable for operational switching of motors with very high switching frequency, e.g. medium voltage motors for pumps, fans, compensators and capacitors. HRC fuses provide protection for cables and circuit components in case of a short circuit. Vacuum contactors have a life expectancy (electrical) of $1 \bullet 10^6$ operating cycles, and can handle a switching frequency up to 1,200 on/off operations per hour. The vacuum contactors of type VSC (figure 8-16) have rated voltages of 3.6 to 12 kV and a rated current of 400 A, and are suitable for switching of motors with ratings of 1,500 (3.6 kV) to 5,000 kW (12 kV), and capacitors from 1,500 to 4,800 kVAr. This does not however take account of whether suitable fuses are available to take advantage of the listed performance ranges.

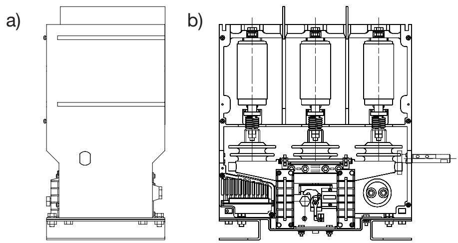


Fig. 8-16

Vacuum contactor, type VSC, with magnetic actuator
a) Front view
b) Sectional view

8

8.2 Switchgear installations (≤ 52 kV)

8.2.1 Specifications for switchgear installations

This voltage range – generally referred to as medium voltage – covers switchgears and controlgears in use and on the market that can be classified as per one of the two following standards:

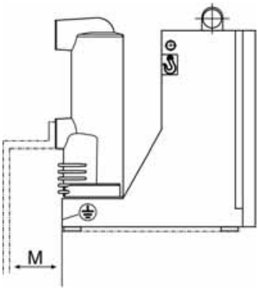
DIN VDE 0101 or
IEC 62271-200 (VDE 0671 Part 200)

8.2.2 Switchgear and controlgear DIN VDE 0101

Switchgears and controlgears to DIN VDE 0101 are designed to comply with fixed minimum clearances of live components from one another, from earth potential and from protecting barriers. They can basically be manufactured at the site where they will be operated. Current-carrying capacity for service and short-circuit currents must be verified by calculation (see also section 4). Type testing is not required.

When setting up these installations in electrical equipment rooms with restricted accessibility, protection against accidental contact with live components, e.g. screens or rails, is sufficient. The switchgear can also be designed with sheet metal walls and doors (minimum height 180 cm) (cf. sections 4.5; 4.6 and 5.2). Reinforced wallboard is also frequently encountered as a wall material. The switchgears can also be completely enclosed for full protection for operation outside locked premises.

The use of insulating materials and intelligent design will allow smaller clearances, particularly in the terminal zone of circuit-breakers and switch-disconnectors, than the specified minimum clearances as per DIN VDE 0101 (cf. Table 4-12). A device of this kind must be tested with connected conductors in the zone in which the permissible minimum clearances are not met. This zone is referred to as the ”tested terminal zone” (see DIN VDE 0101). It must be included in the user’s manual for the switching devices with the main dimensions (figure 8-17).



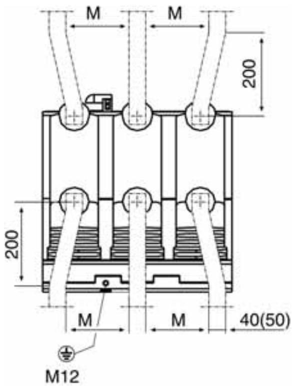


Fig. 8-17

Tested terminal zone to DIN VDE 0101
M = Minimum clearance to DIN VDE 0101.
Here, the tested terminal zone = 200 mm.

Today, switchgears and controlgears to DIN VDE 0101 are mainly encountered in individual installation design on site or are manufactured by smaller companies without in-house test laboratories.

DIN VDE 0101 also includes basic specifications for the general design of a substation, including the structural requirements. They are also applicable for the installation of type-tested switchgear as per IEC 62271-200 (VDE 0671 Part 200).

8.2.3 Metal-enclosed switchgear and controlgear to IEC 62271-200 (VDE 0671 Part 200)

Metal-enclosed switchgear and controlgear are generally assembled from type-tested panels these days. As per IEC 62271-200 (VDE 0671 Part 200) metal-enclosed switchgear installations must be designed so that their insulation capacity, degree of protection, current carrying capacity, switching capacity and mechanical function conform to the requirements set by the testing provisions. This is verified by a type test on a prototype panel. In addition, a routine test is made on every completed panel or every transport unit.

Note: Together with IEC 62271-200 (VDE 0671 Part 200), the higher-order standard IEC 60694 (VDE 0670 Part 1000) is always to be observed. Type-tested switchgear installations with insulated enclosures are subject to IEC 60466. However, there is no longer a corresponding European or German standard.

Rated voltage

The rated values for the insulation level of a switchgear installation must be selected on the basis of the requirements of the system at the installation site from the selection tables in IEC 60 694 (VDE 0670 Part 1000).

Table 10-1 (Section 10) shows the selection values for the range of rated voltages up to 52 kV. The voltage values ”over the isolating distance” only apply for switching devices with which the safety requirements for the open contacts of disconnectors must be met.

Table 10-1 lists two value pairs that can be selected for the rated lightning impulse voltage level for almost all rated voltages. The options correspond to the former subdivision in list 1 and list 2.

When making the selection, the degree of danger from lightning and switching overvoltages, the type of neutral treatment and, if applicable, the type of overvoltage protection should be considered. The higher value pairs in each case are the ones to be selected for installations and equipment exposed to atmospheric overvoltages, e.g. by direct connection to overhead lines. The lower value pairs can be used for installations that are not exposed to atmospheric overvoltages or are protected from these overvoltages by arresters.

Insulating media

IEC 62271-200 covers both switchgear in which atmospheric air acts as the gaseous insulation within the enclosures and also switchgear in which an insulating medium in the form of a fluid other than the atmospheric air (e.g. SF_6) is used (air-insulated: AIS/gas-insulated: GIS).

Degree of protection for metal-enclosed switchgear and controlgear

The metallic and earthed enclosure protects personnel against approach to live components and against contact with moving parts. It also protects the installation against the penetration of foreign bodies. One of three different degrees of protection may be selected for switchgear to IEC 62271-200. The difference is whether the enclosure is suitable for repelling fingers or similar objects (IP 2X to IEC 60694, Minimum requirements for metal-enclosed switchgear), rigid wires more than 2.5 mm in diameter (IP 3X) or rigid wires more than 1 mm in diameter (IP 4X).

Compartments, accessibility and service continuity

Within the general term ”metal-enclosed”, distinctions were formerly made between three categories – ”metal-clad”, ”compartmented” and ”cubicle” switchgear – depending on the design of the internal compartmentalization. This structural definition of compartmentalization has now been replaced in IEC 62271-200 by classification according to the accessibility of the compartment with high voltage components. Three of four classes are determined by how access is controlled, and whether it is necessary to open the compartment in normal operation or only for maintenance. Opening of all compartments which are only accessible by means of tools is not part of normal operation. The fourth class describes non-accessible compartments, such as those found in gas-insulated switchgear.

With a view to the accessibility of the compartments, the following distinctions are made:

– ”Interlock-controlled accessible compartment”
  Integral interlocks enable access to open the compartment for normal operation and/or maintenance.

– ”Procedure-based accessible compartment”
  Access to open the compartment for normal operation and/or maintenance is regulated by a suitable procedure combined with locking.

– ”Tool-based accessible compartment”
  The compartment can be opened with tools, but not for normal operation and/or maintenance.

– ”Non-accessible compartment”

Categorization is then determined by the loss of service continuity, focusing on the main switching device. The LSC categories result from the scope of switchgear components to be taken out of service when a compartment is opened:

– LSC 1:
  This category covers the lowest level of service continuity. It applies to an accessible compartment in a panel which would require at least one further panel to be taken out of service when it is opened. If a busbar compartment is opened, all the panels in the relevant section must be de-energized.

– LSC 2A:
  Category 2A stands for a panel which has to be taken completely out of service when a compartment is opened. The panel has partition walls separating it from the adjacent panels and at has least two compartments and an isolating distance.

– LSC 2B:
  Category 2B provides the least restriction to service continuity and means that all other panels in the installation and all cable termination compartments (including that in the panel concerned) remain in operation when a compartment is opened. It requires partition walls to the adjacent panels and at least three compartments and two isolating distances per panel.

When a compartment has been opened, partitions and shutters to the adjacent compartment or panel provide a degree of protection against live high voltage components. The ”partition class” indicates whether the partition is metallic throughout or contains parts of insulating material.

– Class PM:
  ”Partition of metal”; metallic shutters and partitions between live parts and an open compartment.

– Class PI:
  ”Partition of insulating material”; discontinuity in the metallic partition/shutter between live parts and an open compartment, which is covered by insulating material.

Both partition classes provide the same protection against accidental contact for the worker, but a metallic partition also screens off the electric field.

The decision on which of these installation categories is to be used in any specific case is up to the user, with most attention paid to safety of personnel during maintenance and cable work inside the metal-encelosed switchgear and controlgear. Restricting the effects of faults is important only when the resistance of the compartment walls to arcing has been verified and when the compartmentalization forms a true potential separation (class PM).

Internal arcing

All specialists are in basic agreement that manufacturers and users must make every effort to prevent under all circumstances faults in switchgear installations in which internal arcing occurs. However, it is also acknowledged that such faults cannot be completely prevented in all cases. For this reason, it is expected that current switchgear designs have been tested for response to internal arcing.

Internal short-circuit arcs during operation can occur by overvoltage, faulty insulation or improper control. The test consists of inducing the arc with an ignition wire connected over all three phases. The arc has temperatures of around 4.000 K in the area of its footing points and around 10.000 K or more in the area of the arc column. Immediately after the arc has been ignited, the gas in the immediate vicinity of the arc heats up instantly, causing a very steep rise in pressure in the compartment concerned. This pressure increase would continue to the load limit of the enclosure if pressure relief vents were not built into it. The sealing covers or membranes of these vents respond in ca. 5 to 15 ms and open the path to allow the heated gases to vent (figure 8-18). This characteristic process is not determined only by the response time of the pressure relief valves but it also results from the mechanical inertia of the heated gas mass.

The maximum pressure reached is dependent on the volume of the compartment where the fault occurs and on the magnitude of the short-circuit current. The greatest quantity of heated gases is given off into the area around the switchgear during the expansion phase. The pressure stress on the panel exceeds its high point as early as about 15 ms, that of the building has reached its maximum stress after around 40 ms. A powerful ejection of still heated gases of low density and glowing particles occurs in the subsequent emission phase and in the thermal phase.

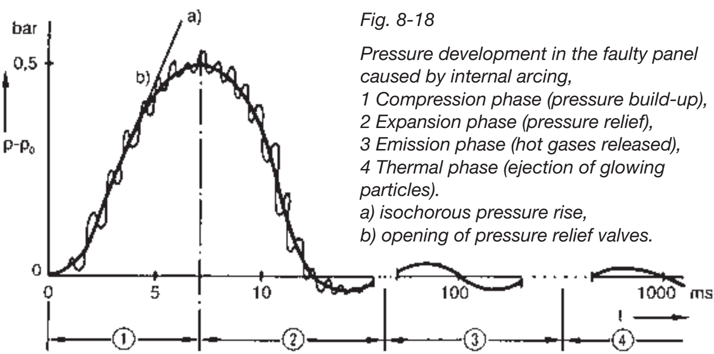


Fig. 8-18

Pressure development in the faulty panel caused by internal arcing,
1 Compression phase (pressure build-up),
2 Expansion phase (pressure relief),
3 Emission phase (hot gases released),
4 Thermal phase (ejection of glowing particles).
a) isochorous pressure rise,
b) opening of pressure relief valves.

8

Guidelines for testing metal-enclosed switchgear for its response to internal arcing can be found in Appendix A of IEC 62271-200 (VDE 0671 Part 200).

The specified test conditions require the internal arcing to be ignited with a thin ignition wire in each compartment of the panel to be tested. The point of ignition and the direction of energy flow are specified in such a way that the arc burns as long as possible at the most distant location from the feeder. The short-circuit test plant supplying the test object, which consists of at least two panels, must have sufficient power to allow a short-circuit current as high as the rated short-time withstand current to flow in three phases over the internal arcing during the agreed duration of the test (recommended times 1.0, 0.5 or 0.1 s). This will cover the normal protection grading times at full short-circuit current. With this short-circuit duration, the test result is restricted to the question of whether the tested compartment withstands the stress caused by the internal overpressure.

During the test, fabric indicators (black, cretonne or cotton-wool batiste) are stretched vertically at a defined spacing on metal frames in front of the accessible walls of the panels and horizontally at 2 m height above the zone where personnel would be when operating the installation. With metal-enclosed switchgear, a distinction is made between two degrees of accessibility which are possible at the point of installation:

Accessibility type A: For authorized personnel only

Accessibility type B: Unlimited access for the general public

The test conditions are also defined in accordance with these accessibility types (figure 8-19). Different sides of a switchgear installation can have different degrees of accessibility. The identification code for these uses the letters F (front), L (lateral) or R (rear).

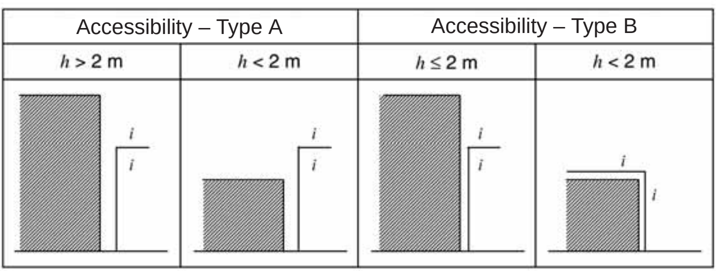


Fig. 8-19

Arrangement of the indicators for an arc fault test
h = height of switchgear; i = arrangement of indicators

On completion of the short-circuit test, the behaviour of the tested panels is recorded on the basis of five criteria:

- Criterion 1:
  Doors and covers remain closed. Deformations are acceptable if no part reaches the indicators or walls.
- Criterion 2:
  No fragmentation of the enclosure occurs within the duration of the test. Projections of small parts, up to an individual mass of 60 g, are acceptable.
- Criterion 3:
  Arcing does not cause holes in the accessible outer sides of the enclosure up to a height of 2 m
- Criterion 4:
  Horizontal and vertical indicators must not be ignited by hot gases. Permitted exceptions: ignition by burning paint coatings, stickers or glowing particles.
- Criterion 5:
  Earth connections remain effective, as demonstrated by visual inspection.

Additional information can be obtained in the form of high-speed camera pictures or videos taken during the test, and these are therefore highly recommended.

If the arc fault test is passed, for instance in the context of a type test, this is documented by the designation IAC ("Internal Arc Classified") on the type plate. The confirmation of testing is supplemented by additional data such as the accessibility type, indications of the accessible sides, the test current and duration.

There are further points to be considered over and above criterion 5 of the assessment, as in the event of ejection of hot gases, the switchgear and controlgear itself is not primarily relevant for the effects. Reflection from the ceilings and walls in the emission phase and the thermal phase (figure 8-18) can divert the hot gases coming from the pressure relief vents into zones accessible for personnel and cause hazardous conditions there. The highest degree of damage also occurs during this period inside the switchgear and controlgear. The ejection of very hot gas reaches its most hazardous amount under the condition when caused by the direction of supply (from below) the electromagnetic forces compel the arc to persist in the immediate vicinity of the pressure relief vent. A panel type may be considered fully tested only after this case has been considered.

Countermeasures for protection of the operating personnel against these effects can be as simple as installing screens or discharge plates. At high short-circuit currents, hot gas conduits with blow-out facilities using absorbers discharging into the switchgear installation room are the perfect solution. However, even better results without additional installations can be achieved if it is possible to limit the arc duration to approximately 100 ms by appropriate trip times. Because the grading times of the system protection do not generally allow such a short-term tripping of the feeder circuit-breaker, additional sensors are required, such as the I_{th}-limiter. When one of the pressure relief valves opens and there is simultaneous persistent short-circuit current, it initiates an undelayed trip command to the feeder circuit-breaker. This quenches the internal arc in less then 100 ms.

The pressure load on walls, ceilings, doors and windows of the switchgear installation room is the result of the gas ejection during the expansion phase (figure 8-18). The withstand capability can generally not be verified by testing. All major manufacturers provide calculation programs for determining the pressure development in the switchgear installation compartment to find out whether pressure relief vents are required for the installation room.

8.2.4 Metal-enclosed air-insulated switchgear and controlgear to IEC 62271-200 (VDE 0671 Part 200)

Switchgear of this type currently has the largest market share worldwide

Metal-enclosed switchgear with three compartments

Figure 8-20 shows an example of such a metal-enclosed panel of type UniGear ZS1 to LSC category 2B and partition class PM.

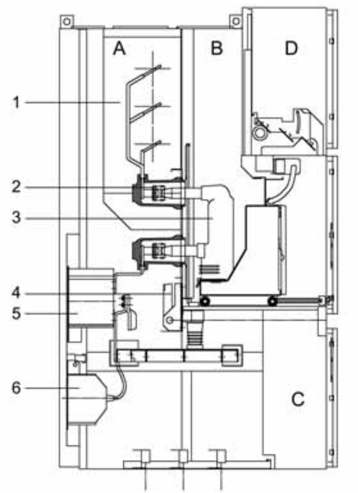


Fig. 8-20

A Busbar compartment
B Main switching device compartment
C Cable termination compartment
D Low voltage compartment

1 Busbar
2 Isolating contacts
3 Circuit-breaker
4 Earthing switch
5 Current transformer
6 Voltage transformer

The circuit-breaker of this type of switchgear can be moved between the operating position and test position when the door is closed. Because vacuum circuit-breakers under normal operating conditions are almost maintenance-free, the door to the circuit-breaker compartment can remain permanently closed. However, if it should be necessary to remove the breaker from the panel, this can be done without problems on a service truck that can be adjusted for height to the exact position.

Access to the cable sealing ends can be made much easier by removing the circuit-breaker and also removing the partition between compartments B and C.

Compartment C has room for the sealing ends of several parallel cables. Metallic oxide arresters for overvoltage protection of inductive loads can also be installed here.

When the circuit-breaker is in the test position and the panel doors are closed, the cables can be earthed via the permanently installed earthing switch (4, with short-circuit making capacity). In order to check that the cables are off-circuit, voltage indicator plugs can be inserted into test sockets at the front of the panels. The test sockets are connected to the terminals of capacitive dividers, which are integrated in the current transformers.

Instead of the vacuum circuit-breaker, an SF_6 circuit-breaker of the HD4 type with identical main dimensions can be installed in this switchgear type.

The UniGear ZS1 panel shown in figure 8-20 is designed for rated voltages up to 24 kV, rated currents up to 4,000 A and rated short-time currents (3s) up to 50 kA. For 12 and 17.5 kV, the panel dimensions range between widths of 650/800/1000 mm and depths of 1300/1350 mm, and for 24 kV between 800/1000 mm and 1500 mm respectively. The uniform height is 2200 mm.

In addition to the standard switchgear panels with withdrawable circuit-breakers, there are variations for sectionalizers, metering panels and panels with permanently installed switch-disconnectors for substation power supply transformers. A further type provides for the use of vacuum contactors. Figure 8-21 shows a sectional view of such a contactor panel of type ZVC. One advantage of this panel is the small width of only 325 mm. Short-circuit protection is performed here by an HRC fuse integrated in the contactor module. Double busbar installations are constructed from single busbar panels in accordance with the two circuit-breaker method in back-to-back or front-to-front configurations (figure 8-22 with panel type UniGear ZS1). One highly interesting variant for constricted spaces is the opportunity to accommodate two circuit-breakers

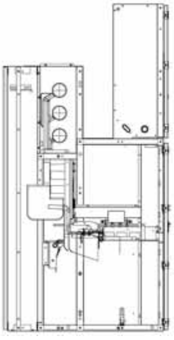


Fig. 8-21

Panel type ZVC with vacuum contactor on withdrawable part

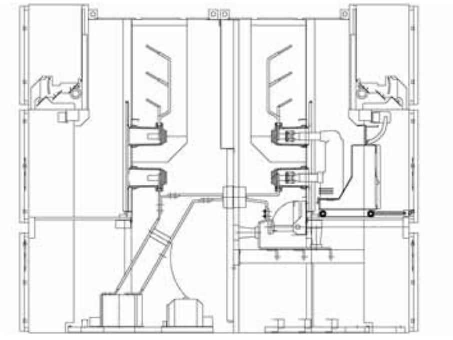


Fig. 8-22

Double busbar switchgear installation with UniGear type ZS1 panels in back-to-back configuration on two levels in a UniGear Double Level Panel with a width of only 750 mm for 12 kV and up to 31.5 kA (900 mm for 50 kA) (figure 8-23).

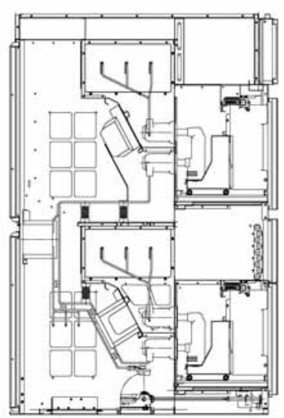


Fig. 8-23

Two level panel configuration of type UniGear Double Level

Metal-enclosed switchgear with one or two compartments

Figure 8-24 shows metal-enclosed switchgear of type ZS8 with one compartment in accordance with LSC category 1 and partition class PI. They are available as panels with permanently installed switch-disconnectors for switching cables and overhead lines and with HRC fuses for protection of distribution transformers. The switch-disconnectors can be remote-controlled by a motor-operated mechanism. In the circuit-breaker panels, the VD4 and VM1 vacuum circuit-breakers are withdrawable units that can be moved when the panel door is closed.

a) b) c)

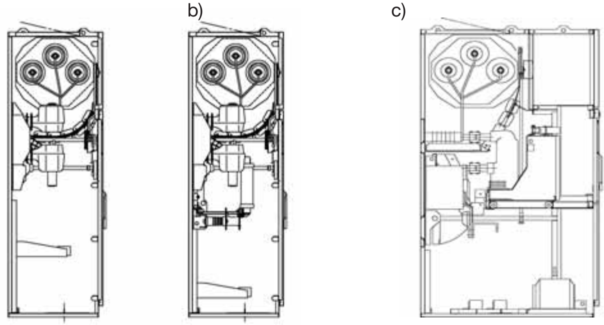


Fig. 8-24

Panels of type ZS8:
a) Switch-disconnector panel
b) Switch-disconnector panel with HRC fuses
c) Circuit-breaker panel

All the panel variants in the ZS8 series can be mounted side by side in spite of their different dimensions. The switch-disconnector panel can however also be supplied in the same depth as the circuit-breaker panel. The most important dimensions of these panels are widths of 600 or 650 mm for the switch-disconnector panel and 650 or 800 mm for the circuit-breaker panel. Depending on the ratings, the panel depths are 600/800/1000 or 1200 mm. The panel height is standardized at 1900 mm. The rated data cover a voltage range up to 24 kV, busbar currents and tee-off currents with circuit-breakers up to 1,250 A, tee-off currents with switch-disconnectors up to 630 A, and short-time currents (3s) up to 25 kA.

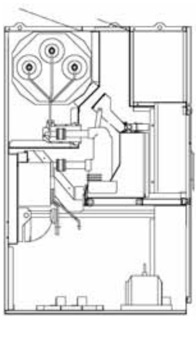
ZS8 panels are equipped with earthing switches (with short-circuit making capacity) for feeder earthing. The earthing switches can only be closed when the switch-disconnector is open or the circuit-breaker withdrawable unit is in the disconnected position. There is an insulating plate integrated in every panel, which slides into the open break of the switch-disconnector or in front of the busbar-side isolating contacts of the circuit-breaker panel. This assures protection against accidental approach to live components during work in the panel, e.g. at the cable sealing ends. There are also ZS8 panels with ”tee-off partitions” to LSC category 2A and partition class PM (figure 8-25). These panels have earthed metallic partitions, which separate the busbar system from the areas of switching devices and cable terminals. The protection against accidental contact with the isolating contacts installed in epoxy resin spouts in these panels is provided by earthed metallic shutters that swing in front of the epoxy resin spouts. The panel doors can only be opened after closing the protection shutter in all ZS8 type switchgear.

8

Checking that the cables are off-circuit can be performed with conventional voltage indicators or by using voltage indicator plugs at externally accessible test sockets. Measurements using sockets require installation of capacitive divider devices in the epoxy resin insulators of the switch-disconnector or in the current transformer of the circuit-breaker panels.

Panel variations of the ZS8 series in addition to the switchgear with switch-disconnectors or circuit-breakers include sectionalizers, busbar risers and metering panels.

Fig. 8-25
Switchgear type ZS8 with tee-off partition



Here, too, there is a special design for the use of vacuum contactors. Figure 8-26 shows a sectional view of such a panel.

Double busbar switchgear can also be implemented in this system with ZS8 panels in a special back-to-back configuration (figure 8-27).

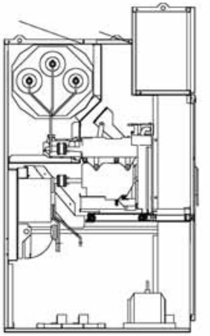


Fig. 8-26
ZS8 switchgear with contactor and HRC fuses on a withdrawable assembly

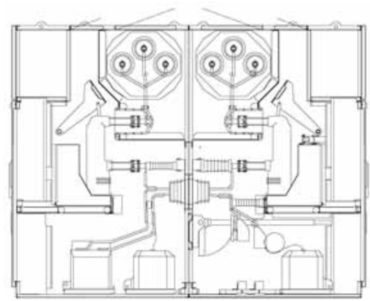


Fig. 8-27
Double busbar installation with ZS8 switchgear in back-to-back configuration

8.2.5 Metal-enclosed gas-insulated switchgear and controlgear
switchgear to IEC 62271-200 (VDE 0671 Part 200)

The same standard as for the air-insulated switchgear and controlgear described in section 8.2.4 also applies to the gas-insulated switchgear of the medium-voltage range. The term "gas-insulated" refers to the fact that atmospheric air is not used as the gaseous insulating material inside the panels, i.e. the enclosure of the installation must be gas-tight against the environment.

The gas currently used in most gas-insulated designs is a synthetic electronegative gas, SF6, with almost three times the dielectric resistance of air. (See also section 16.3.) The insulating gas can also be nitrogen, helium or air dried for the purpose and at a higher pressure level.

The decisive advantage of gas-insulated switchgear compared to an air-insulated installation is its independence from environmental influences such as moisture, salt fog and pollution. This results in less maintenance, increased operational safety and high availability. The smaller dimensions due to compact design and increased dielectric resistance of the gaseous insulating material are also advantages. Gas-insulated switchgear technology in the medium-voltage range has become increasingly significant over the last 30 years.

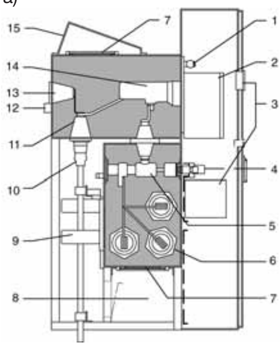
The numerous designs available on the market can be generally classified into three different application groups:
– switchgear with circuit-breakers
– switchgear with switch-disconnectors and circuit-breakers
– ring-main units
One technical solution for each of these application groups is described below as an example.

Gas-insulated switchgear with circuit-breakers

Figure 8-28 shows a panel of type ZX1 (for 12 to 36 (40.5) kV) with the versatile options offered by the advanced technology of these new switchgear designs.

The principles used for the application are:
– High-precision enclosure
– The gas-tight enclosure of the live components is manufactured from stainless steel using laser technology for high-precision cutting and welding. This not only ensures that the enclosure is gas-tight but also allows the panels to be mounted side by side at site without problems.

a)



b)

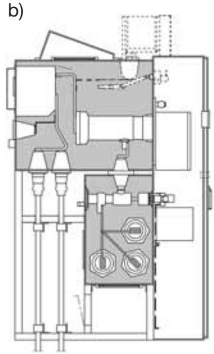
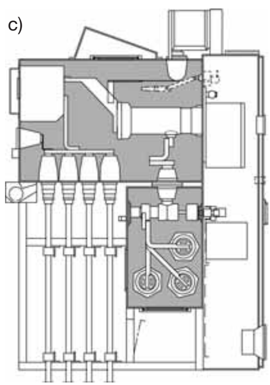


Fig. 8-28
Metal-enclosed gas-insulated switchgear of type ZX1 with single busbar system
a) Outgoing feeder panel, 630 A
b) Outgoing feeder panel, 1,250 A with 2 parallel cables and optional instrument transformers
c) Incoming feeder panel, 2,500 A with 4 parallel cables and current and voltage transformers
1 Density sensor
2 Circuit-breaker operating mechanism
3 Multifunctional protection and control unit REF542 plus
4 3-position switch operating mechanism
5 3-position switch
6 Busbar
7 Pressure relief disk
8 Pressure relief duct
9 Toroidal-core current transformer
10 Cable plug
11 Cable socket
12 Measuring sockets for capacitive voltage indicator system
13 Test socket
14 Circuit-breaker
15 Plasma deflector
■ *SF_6*

c)



Vacuum switching technology

– The application of vacuum switching technology as the quenching principle of the circuit-breaker meets a primary requirement for gas-insulated switchgear: the interrupter unit must be maintenance-free. So far, this requirement is really only met by vacuum interrupters, because of their low contact burn-off and their high electrical durability. Gas-insulated switchgear for this voltage range with SF_6 circuit-breakers is however also available.

Plug connector technology

– The application of plug-in technology is essential for ensuring short assembly times when setting up installations. Several parallel cables can be connected to the commercially available internal conical sockets in the baseplate of the core module. The plug-in technology in the area of the busbar bushings is new but based on the same technology as the cable connectors. These bushings designed as plug connectors are the most important requirement for easy installation of the completed panels. There are additional plug connectors in the supply lines for auxiliary power and in the fibre-optic connections to the higher-order control system, if present.

Sensors for measured quantities and states

– The combined current/voltage sensor has three functions. For current measurement, it has a Rogowski coil, which gives a voltage signal that has a linear dependency on the current and therefore can be used in a very broad current range (e.g. to 1250 A in one type). This not only simplifies planning but also increases the flexibility when modifying installations that are already operating.
– A high-resistance (200 MΩ) voltage divider is used as a voltage sensor. Two bell-shaped screening electrodes ensure equal distribution of the electric field along the resistance. The voltage signal captured at the subresistance of the divider is fed to the bay control unit.
– The earth side of the two screening electrodes is simultaneously used as a capacitive pick-off for voltage indication with standard commercial plugs. It is connected to test sockets on the front of the panel to allow checking that the cables are off-circuit independently of the functional availability of the bay control unit.
– The positions of the two switching devices and the ‘ready for switching’ indication of the circuit-breaker mechanism are detected by inductive proximity sensors. A temperature-compensated pressure sensor signals three pressure/density levels: filling pressure at 20°C, lower operational pressure limit and pressure with internal arcing. All sensor information goes directly to the bay control unit and is displayed and processed there.

Digital bay control and protection unit

– The multifunctional bay control and protection unit REF542 plus is the base of the intelligence and communications interface of the new switchgear (see also section 14).

It has the following functions:

– Local and remote actuation
– Display of switch positions, measured values and protection parameters
– Interlocking, internal and external

– Protection (all protective functions except for differential cable protection)
– Storage of events
– Information transmission to a higher-order control system
– Monitoring its own functions and the release and measurement circuits
– Disturbance recorder – recording time 5 s with sampling rate 1.2 kHZ

Faults in the sequence of actuation of circuit-breaker and disconnector/earthing switch function of the transfer switch are prevented by interlocking in the control unit. The earthing process can be automatically run as a programmed sequence while retaining the ”five rules of safety”. Any required protective functions can be installed as software before delivery. Software changes can be made on site at any time with a laptop computer. Parameter changes can be made by pressing buttons on the device itself.

Personnel safety design

In a switchgear system such as that of the ZX1 family, the occurrence of faults with internal arcing is unlikely from the start. However, ZX1 panels offer complete personnel protection in the event of internal arcing. In the case of a fault in the area of the insulating gas, the housing is relieved from excessive stress by the response of the pressure relief diaphragm, either directly into the switchgear room via the plasma absorber or into a pressure release duct which runs horizontally across all the panels and at the end of the installation releases the gas into the open air through an outside wall or into the switchgear installation room via an absorber. The response of the pressure sensor at 0.6 bar overpressure can be used to trip the feeder circuit-breaker immediately without requiring additional components, thereby reducing the arcing time to less than 100 ms. In the event of a fault in the cable plug area, the pressure is also relieved into the pressure relief duct.

Here too, double busbar switchgear installations can be designed with the panels of type ZX1, in accordance with the two-circuit-breaker method in back-to-back or front-to-front arrangement. Panel variants such as sectionalizers, busbar risers and metering panels are also available.

The most important ratings are as follows: Rated voltage up to 36 (40.5) kV, rated current up to 2,500 A and rated short-time current (3 s) up to 31.5 kA. The panel width is 600 or 800 mm, depending on the current, the depth varies from 1300 to 1800 mm depending on the cables connected, and the height is 2100 mm. The insulating gas is SF6 at a rated filling pressure of 130 kPa.

The switchgear of type ZX2 (figure 8-29) is suitable for ”conventional” double busbar systems that have two busbar systems for each panel. This switchgear has the same advanced features as described for switchgear of type ZX1.

The technical data implemented to date include the rated voltage of up to 36 (40.5) kV, rated current up to 2,500 A and rated short-time current (3 s) up to 40 kA. Here too, the panel width is 600 or 800 mm, depending on the current, the depth is 1760 mm and the height is 2300 mm. The insulating gas is SF_6 at a rated filling pressure of 130 kPa.

Single busbar switchgear in the ZX2 design can also be used without the rear busbar system to make full use of the advanced technical data.

a) b)

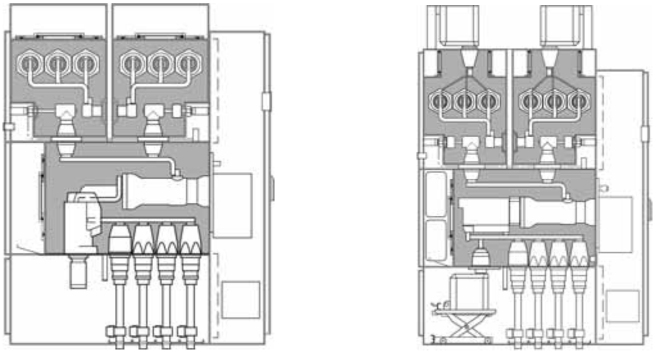


Fig. 8-29

Metal-enclosed gas-insulated switchgear with double busbar, type ZX2

a) Incoming feeder panel, 2,000 A, with 4 parallel cables and current and voltage sensors
b) Incoming feeder panel, 2,000 A, for 4 parallel cables, with conventional control equipment: current and voltage transformers with process variables of 1 A and 100 V

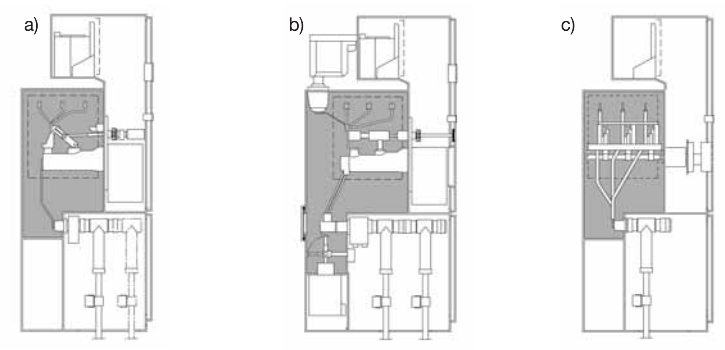
In both the ZX2 and ZX1 series, an additional double panel with two outgoing feeders is now available, requiring a width of only 400 mm per feeder for applications up to 24 kV and 630 A at 25 kA. These double panels leave the manufacturer's works as completely tested units and are connected directly to the adjacent panels at site without any additional gas work, using the tried and tested plug-in technology.

Gas-insulated switchgear with switch-disconnectors and circuit-breakers

Gas-insulated switchgear technology is becoming a subject of increasing interest for distribution systems and smaller industrial consumers. Because the high performance data of the installations described in the previous section are not required, special switchgear series have been developed for this application. A major characteristic of this application is the use of switch-disconnectors for feeders with cables and overhead lines and in combination with fuses for protection of small transformers.

Figure 8-26 shows cross-sections of variants from the ZX0 switchgear series in block design. SF_6 is used as the insulating gas and quenching medium for the switch-disconnectors for all rated voltages.

The switch-disconnectors integrated into the panels as three position switches include the function of the earthing switch for the feeder. The contact blades are actuated by the same mechanism with one actuating shaft for each function. The combination device as a switch-disconnector meets the same requirements as a switch-disconnector tested and manufactured as a single unit as per IEC 60265-1 (VDE 0670 Part 301). The requirements of IEC 62271-200 (VDE 0671 Part 102) apply for the earthing function (with short-circuit current-making capacity).



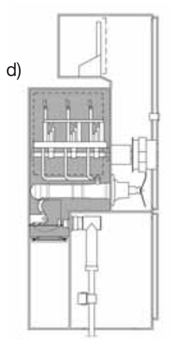


Fig. 8-30
Metal-enclosed gas-insulated switchgear system type ZX0 in block design
a) Circuit-breaker panel for outgoing feeder currents of 630/800 A
b) Circuit-breaker panel for incoming feeder current 1,250 A with integrated current and voltage transformers
c) Switch-disconnector panel
d) Switch-disconnector panel with fuses

In order to check that the cables are off-circuit before earthing, voltage indicator plugs can be inserted into test sockets at the front of the panels. These sockets are connected to the taps of field grading electrodes inside the cable-plug bushings.

The circuit-breaker panels of this type of switchgear have vacuum interrupters with a cast resin enclosure as arc-quenching systems. This also forms the pivot of the 3-position switch for disconnecting and earthing.

The connected cables are therefore earthed via the circuit-breakers. The REF542 plus digital protection and control unit also controls the actuation, interlocking, display and protection functions in the circuit-breaker panel of the ZX0 switchgear system.

The ZX0 switchgear series as a compact all-rounder is available in the block design variants with up to 6 panels grouped together to form a single gas compartment either with manual mechanisms or electrical actuation, and as a variant with individual panel partitioning and manual operation of all switching devices with the option of remote control (figure 8-31).

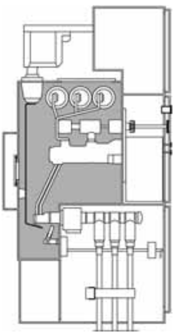


Fig. 8-31
Circuit-breaker panel of type ZX0 for 1,250 A in individual panel partitioning design with voltage metering at the feeder

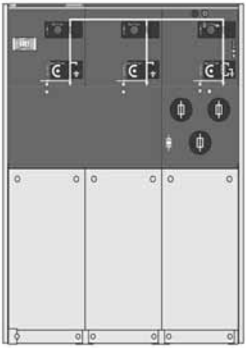
The technical data of the compact switchgear of type ZX0 are as follows: Rated voltage up to 24 kV, rated current for busbar and feeder with circuit-breaker 1,250 A and for feeder with 3-position switch-disconnector 630 A, and rated short-time current (3 s) 25 kA. The insulating gas is SF_6 with a rated filling pressure of 130 kPa. The panel widths are 400 mm and 600 mm for feeder currents > 800 A and for individual panels; the height is 2100 mm (2250 mm when increased space is required for secondary systems) and the panel depths are 850 mm and 1000 mm for feeder currents > 800 A and for individual panels.

Gas-insulated ring-main units (RMUs) for secondary energy distribution

There are two basic designs in use for the application of ring-main units:
– Systems with a common gas volume inside a common enclosure with a preset number (e.g. 3 or 4) of feeders
– Panels mounted side by side with the opportunity for subsequent extension

Figure 8-32 shows such systems of type SafeRing with common enclosures for all three feeders and the possibility of extension in type SafePlus.

a)



b)

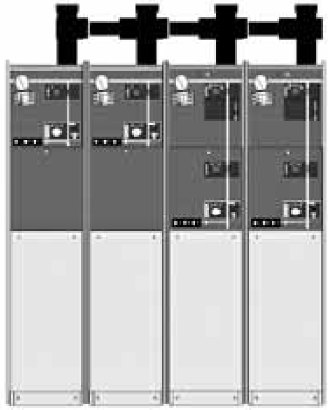


Fig. 8-32
Elevations of ring-main units
a) Ring-main unit of type SafeRing
b) Ring-main unit of type SafePlus

SF_6-switch-disconnectors are also used here to switch the connected cables and overhead lines. For protection of transformers, either a vacuum circuit-breaker with electronic protection (configuration CCV, figure 8-32a) or a switch-disconnector in combination with HRC fuses (configuration CCF, same dimensions as CCV) can be supplied.

Every panel has an earthing switch with specified making capacity to earth the connected cables. In order to check that the cables are off-circuit before earthing, voltage indicator plugs can be inserted into test sockets at the front of the panels. These sockets are connected to capacitive pick-offs on the cable plug bushings.

The switch-disconnectors and circuit-breakers of the switchgear can be remotely actuated with motor-operated mechanisms.

The technical limit data and dimensions of the SafeRing ring-main unit are as follows: Rated voltage up to 24 kV, rated current for the C panel 630 A, for the F panel in accordance with the fuse current, and for the V panel 200 A. Rated short-time current (3 s) up to 21 kA for the C and V panels; F panel with limitation by HRC fuse. The insulating gas is SF_6 with a rated filling pressure of 130 kPa. The dimensions are dependent on the number of panels per unit: widths are 696 mm (2 panels), 1021 mm (3 panels) and 1346 mm (4 panels). The heights in the same order are 622, 947 and 1272 mm, and the depths 663, 983 and 1313 mm.

8.2.6 Control systems for medium voltage switchgear

Conventional secondary technology

A wide range of devices for protection, control and monitoring tasks is available for conventional secondary technology in medium voltage switchgear installations. The planning engineer selects the required units and combines them into one installation. The output variables from the encoders are predominantly standardized to 1 A for current and 100 V for voltage.

The information on measured values, switchgear status and fault messages is transmitted through parallel wiring from the various medium voltage panels to a main control desk or a telecontrol system. Records, data storage, graphical measured value processing, help information when faults occur and self-monitoring functions are not possible with this technology.

Microprocessor control systems

The implementation of digital system designed for the requirements of medium voltage networks allows a number of much more powerful solutions at moderate expense. A system of this type is divided into the bay level, the switchgear level and the control room level (see also section 14.4).

At the bay level autonomously operating, modular and multifunctional devices that can be adapted for the required protection, control and regulating tasks by appropriate software are used. These monitoring devices are installed directly in the low voltage compartments of the medium voltage panels. Here, all measured values, switch positions and messages from the panels are acquired, processed and sent over a serial (unified) interface. The device, which operates independently of the next hierarchical level, combines the protective functions, the switching position display, the measured value display and the local operation of the switchgear, which is protected against maloperation, in one single housing. Its modular design makes it adaptable for the panel-specific protection tasks and selectively or in combination it controls functions such as motor protection, overcurrent definite-time protection, overvoltage and undervoltage protection, earth fault detection, distance protection, differential protection and disturbance recording. It has comprehensive self-monitoring functions and also allows events to be sorted by time with real-time stamping.

The multifunctional protection and control unit REF542 plus is a device of this type. It can optionally be implemented autonomously for one panel only or integrated into a higher-order automation system.

8.3 Terminal connections for medium voltage switchgear

8.3.1 Fully insulated transformer link with cables

Plastic-insulated cables and fully insulated (plug-in) cable terminals provide a number of operational improvements in substation design when consistently used at the interfaces between cables and station components. The key component for a new type of cable link, as shown in figure 8-33, between the power transformer and the switchgear installation is a multiple transformer terminal to figure 8-34 for four parallel power cables. The multiple terminal is designed for a voltage of up to 36 kV and enables currents of up to 3,150 A. The module can be retrofitted to all power transformers. In addition to the operational advantages, this technology offers savings because the transformer no longer requires a cable rack. For more information on plug connectors for power cables, see section 13.2.8.

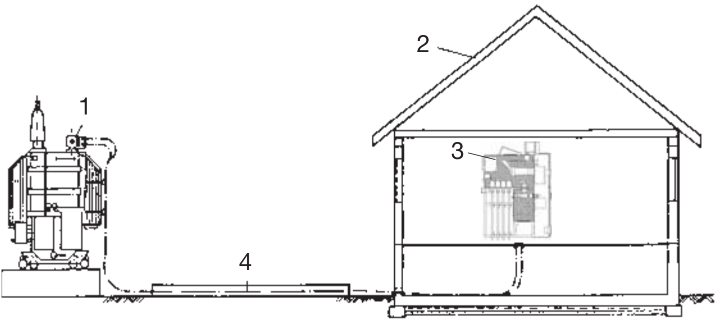
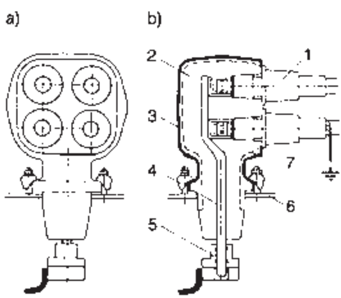


Fig. 8-33
Substation design with fully insulated cable link to the transformer
1 Multiple transformer terminal, 2 Substation building, 3 Switchgear, 4 Cable link in a protective conduit

Fig. 8-34
Multiple transformer terminal
a) Elevation
b) Sectional view
1 Cable plug
2 Cast resin body with sockets
3 Metal casing
4 Conductor bar
5 Contact system
6 Transformer housing
7 Control shield



8

8.3.2 Solid-insulated bar connection

An option for making bar connections with low space requirements is to use prefabricated epoxy resin-insulated capacitor-controlled single-phase conductors. They are available for service voltages of up to 72.5 kV and for operating currents of up to 5,000 A.

Design of the bar system

The preferred conductor material is an aluminium alloy with high mechanical strength and low weight. A high voltage coating is first applied to the entire surface of the circular or tubular conductor, and the appropriate insulation for the voltage level, consisting of paper and a special cast resin impregnation, is applied to that (figure 8-35), with capacitive control provided by conducting layers at the ends. The covering layer at earth potential is fully embedded in the insulation. For outdoor use the bars are also enclosed in a protective tube of aluminium or a flexible metal hose. The space between the bar itself and the protective cover is then filled with cast resin.

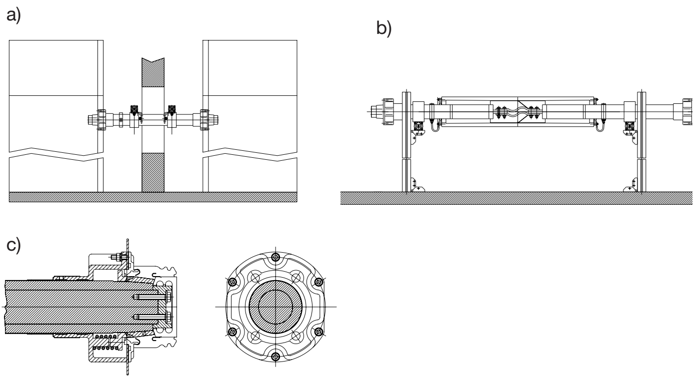


Fig. 8-35
Arrangement of a solid-insulated conductor bar for indoor use
a) Connecting bar between two switchgear sections with a wall opening
b) Connecting bar between two switchgear sections with cast resin-insulated, capacitively controlled joint
c) Inner cone plug for connection to gas-insulated switchgear

The bars are manufactured in sections of up to 12 m in length. Single or multiple bends are available as required made to fit the assembly and connection dimensions. The bars are connected rigidly or flexibly to the devices or panels with screw or plug-type terminals. Individual lengths are joined with special insulating cylinders. The recommended phase clearances, e.g. 200–300 mm at 2,500 A, correspond to the phase spacings of the switchgear. Standard support structures and clamps withstand the short-circuit forces. The earth connections comply with the relevant specifications.

9 High current switchgear

High current switchgear is understood to form the link, required in power stations of all types, between the generator and the unit transformer, through which the electrical energy generated is fed into the transmission or distribution network (see section 11, High voltage switchgear).

9.1 Generator circuit-breakers

Generator circuit-breakers are switchgear in the high-current connection between the generator and unit (generator) transformer. They must be capable of handling the very high operating currents (up to 50 kA) on the one hand, and the extremely high short-circuit currents occurring power station operation on the other hand. These requirements for generator breakers are much more stringent than those for breakers in network service and are specified in detail in the (unique in the world) "IEEE" C37.013-1997 standard (ANSI). The following list summarizes the most important areas of application and the advantages.

Functions	Advantages
Synchronization of the generator on the generator voltage level	Only 1 switching operation required instead of 5-7 switching operations for synchronization on the HV level, thus avoiding maloperation
Securing station service supply on generator shut-down	Uninterruptible supply to station service system from network via unit transformer
Disconnection of a fault in the unit transformer or station service transformer	Restriction of the effects of faults in the transformer, as the opening time is much shorter than generator shut-down by high-speed de-excitation
Disconnection of a fault in the generator	Secure disconnection of the short-circuit current in spite of missing current zeroes. Station service remains on the network without interruption, increasing reliability of power plant operation.

In specific cases there can be economic, operational and technical reasons for using such breakers.

Fig. 9-1 shows examples of unit connections with generator circuit-breakers. The various types show how these breakers ensure maximum possible availability of station services in the event of a fault for large units with several unit and station transformers.

Conventional and gas turbine power plants, hydro-electric plants and nuclear power plants with high unit capacity and special requirements for safety and availability are preferred areas of application for generator circuit-breakers.

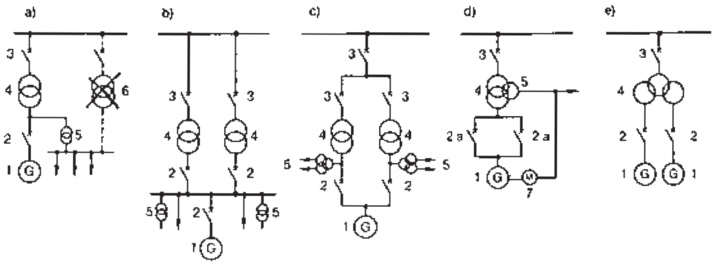


Fig. 9-1

Unit connections of power plants a) Basic circuit diagram, b) and c) Large generators with part-load transformers, d) Pumped storage power station, e) Hydro power plant;

1 Generator, 2 Generator breaker, 2a 5-pole generator breaker for switchover between motor and generator operation, 3 High-voltage circuit-breaker 4 Main transformer, 5 Station service transformer, 6 Starting transformer, 7 Starting motor

The use of generator circuit-breakers must be considered in the early stages of designing a power plant. The following requirements are important when designing the structure:

a) Space required for breaker

   Breaker dimensions, phase spacing (note minimum clearances), accessibility for operation and subsequent maintenance.

b) Space required for additional auxiliary equipment such as an external cooling system.

   (The auxiliary equipment should be located in the immediate vicinity of the generator circuit-breaker.)

c) Structural requirements

   Stable foundation (account is to be taken of reaction forces during switching operations), lifting gear for installation and maintenance, distance to be traveled to the point of installation.

Modern generator circuit-breakers are not generally offered as single unit but as a functional unit which contains the disconnectors, shorting links, earthing switches and start-up disconnectors inside single-phase enclosures.

In addition, the current and voltage transformers, surge arresters and protection capacitors required for generator and unit protection and synchronization are accommodated inside the enclosures (see figure 9-2).

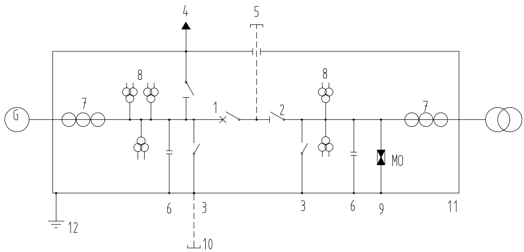


Fig. 9-2

Single-line diagram of a generator circuit-breaker system

1 Circuit-breaker, 2 Disconnector, 3 Earthing switch, 4 Start-up disconnector, 5 Short-circuiting link (manual), 6 Surge arrester, 7 Current transformer, 8 Voltage transformer, 9 Protection capacitor , 10 Short-circuiting link (motorized), 11 Breaker enclosure (single phase) 12 Earth

9

9.1.1 Selection criteria for generator circuit-breakers

Apart from the rated voltage, the most important criteria are the rated current and the rated breaking current of the power station. ABB supplies several types of generator circuit-breaker, which can be used depending on the generator capacity. These are on the one hand the SF_6 breakers of types HECS and HEC 7/8 (single-pole enclosed) and types HGI and HECI (unenclosed), and on the other hand the vacuum circuit-breaker of type VD4 G.

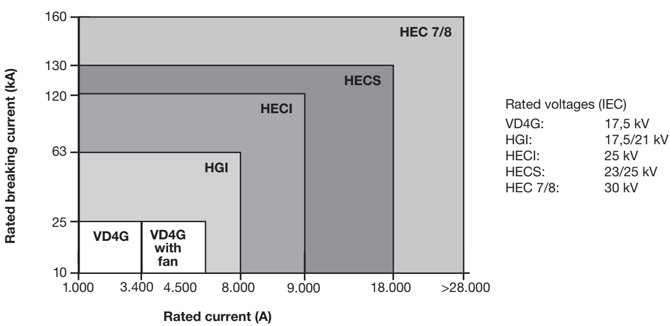


Fig. 9-3 Selection table for generator circuit-breakers

9.1.2. Generator circuit-breaker series HECS and HEC 7 / 8 (SF_6 gas breakers)

These breaker systems are designed for generator capacities of 100-2000 MVA and – depending on the type – can be used for generator voltages of up to 30 kV. They are single-pole metal-enclosed and suitable for both indoor and outdoor installation.

The power-interrupter chambers of these breakers are filled with SF_6 gas as the quenching and insulation material. The arc is interrupted by the proven ABB self-blasting principle: The arc that is generated when the contacts open heats the SF_6 gas, increases the pressure and generates a stronger gas flow, which blasts the arc and extinguishes it.

In addition, the arc is set in rotation and thus reduces contact burn-off.

The contacts, which carry current continuously, are placed separately from the interrupting contacts, guaranteeing optimum current transfer at all times.

The voltage-carrying components are air-insulated against earth.

The 3-pole design on a common base frame makes installation very simple. Special foundations are not required.

The power chambers are actuated by the proven ABB type HMB spring mechanism. The energy storage capacity is rated for 2 ON-OFF switching cycles. Disconnector, earthing switch and start-up disconnector have electric motor-operated mechanisms. They are controlled in accordance with the current requirements in power plant design by an integrated control cabinet with conventional relay technology.

The modular design makes it possible to expand these enclosed generator circuit-breakers into very compact functional systems with disconnectors, earth switches, transformers etc. (see figures 9-2, 9-4). Production and testing of the complete system in the manufacturer’s works greatly reduces the time and expense of assembly and testing at the construction site.

The single-line breaker enclosure is welded to the bus duct enclosure.

The live parts are bolted to the high-current bus duct conductor by way of flexible copper extension straps.

The service intervals, in accordance with the demands of modern power plant design, have been extended to 15 years service life or 10,000 operating cycles* for series HEC 7/8 and 20 years service life or 20,000 operating cycles* for series HECS.

* mechanical operating cycles

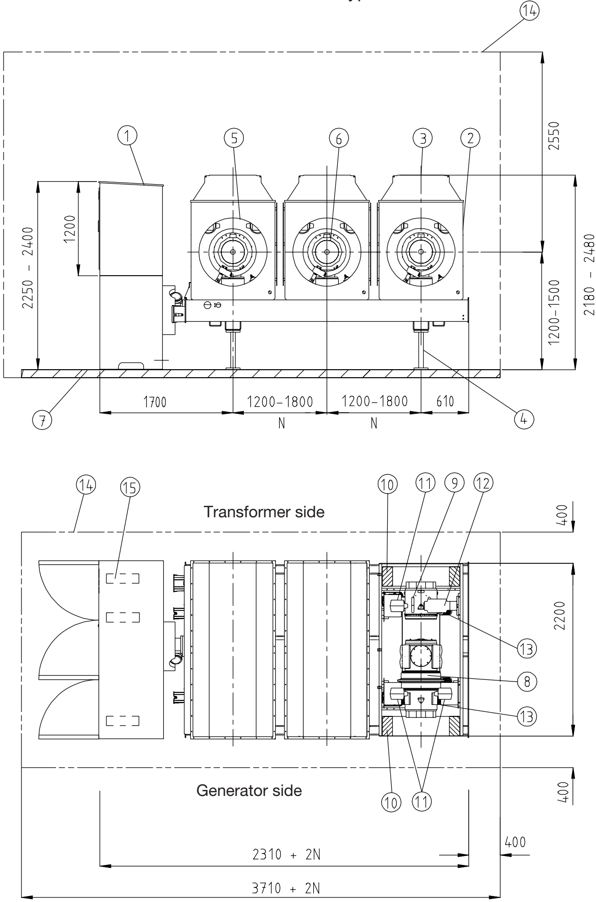
Table 9-1

Technical data of generator circuit-breakers type
HECS / HEC 7/8 (single-pole enclosed circuit-breakers)

Type designation	kV	HECS	HECS	HECS	HECS	HECS	HECS	HECS	HEC	HEC 7	HEC 8
		- 80 S	- 80 M	- 100 M	- 100 L	- 100 XL	- 130 L	- 30 XL	7 S		
Max. operating voltage	kV	23	23	25,3	25,3	25,3	25,3	25,3	30	30	30
Rated short-time power frequency withstand voltage											
50/60 Hz 1 min, against earth	kV	60	60	60	60	60	60	60	80	80	80
over isolating distance[1]	kV	70	70	70	70	70	70	70	88	88	88
Rated lighting impulse withstand voltage											
1,2/50 µs against earth	kV	125	125	125	125	125	125	125	150	150	150
over isolating distance [1]	kV	145	145	145	145	145	145	145	165	165	165
Rated current,											
natural cooling, 50 Hz	A	8.500	10.500	10.500	13.000	18.000 [1]	13.000	18.000 [1]	23.000	24.000 [2]	28.000
natural cooling, 60 Hz	A	8.000	10.000	10.000	12.000	17.000 [1]	12.500	17.000 [1]	22.000	22.000	26.000
Rated breaking current	kA_{eff}	80	80	100	100	120	130	130	140	160 [3]	160 [3]
Making current	kA_{sw}	220	220	280	280	280	360	360	390	440 [3]	440 [3]

[1] Only valid for models with disconnector
[2] Rated current information corresponding to ambient temperature: max. 40 °C
[3] Temperature of the high-current bus ducts at the breaker terminals: conductor max. 90 °C; encapsulation max. 65 °C

Generator circuit-breaker Type HECS



Weight max. 6.500 kg

Fig. 9-4

Generators circuit-breaker system of type HECS / Dimensional chart 1 Control cubicle, 2 Breaker enclosure, 3 Assembly lid, 4 Breaker feet, 5 Generator bus duct connection - enclosure, 6 Generator bus duct connection - conductor, 7 Foundation / Steel platform, 8 Circuit-breaker, 9 Disconnector, 10 Current transformer, 11 Voltage transformer, 12 Surge arrester, 13 Capacitor, 14 Space for installation and servicing, 15 Opening for control cables, N Variable phase spacing

9.1.3. Generator circuit-breaker series HGI / HECI (SF_6-gas breakers)

These generator circuit-breakers are designed for generator capacities of 100-400 MVA and are usable – depending on their type – for rated generator voltages up to 25 kV.

They are unenclosed and only suitable for indoor installation.

The areas of application for these breakers are power stations with open-type generator bus ducts (without phase insulation).

They are especially suitable as replacements for older air-blast circuit-breakers in comparatively old power stations in the course of retrofitting.

Table 9-2

Technical data of generator circuit-breakers type HGI / HECI (unenclosed breakers)

Type designation		HGI 2	HGI 3	HECI 3/R	HECI 5/R
Max. operating voltage	kV	17,5	21	25,3	25,3
Rated short-time power frequency withstand voltage					
50 Hz, 1 min against earth	kV	50	60	60	60
across open isolating distance	kv	55	70	70	70
Rated lightning impulse withstand voltage					
1.2/50 μs against earth	kV	110	125	125	125
across open isolating distance	kV	121	145	145	145
Rated current					
Naturally cooled, 50 / 60 Hz	A	6.300	8.000	9.000	9.000
Rated breaking current	kA_{eff}	50	63	100	120
Making current	kA_{sw}	138	190	300	360

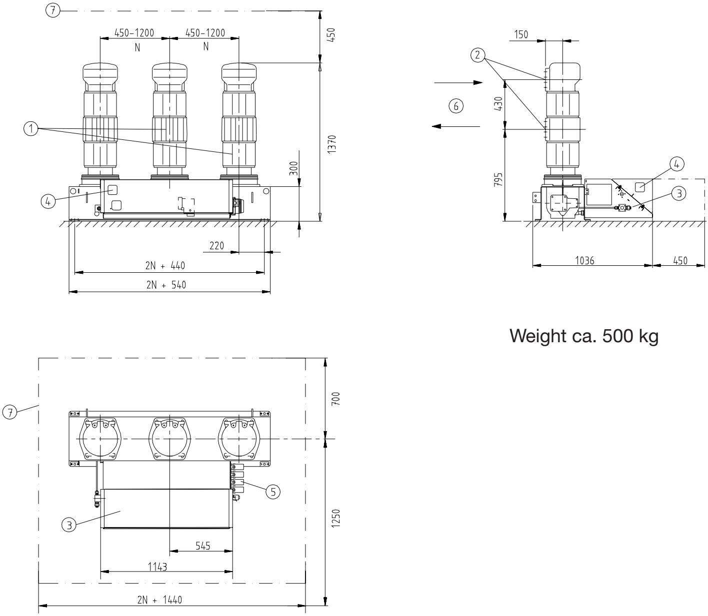


Fig. 9-5
Generator circuit-breaker type HGI / Dimensional chart

1 Circuit-breaker poles, 2 Terminal surfaces for generator bus duct, 3 Operating mechanism, 4 Position indicator, 5 Cable connection to control cubicle, 6 Current direction, 7 Min. space for servicing

9.1.4 Generator circuit-breaker series VD 4 G (vacuum circuit-breakers)

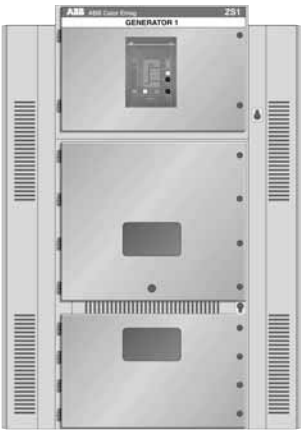
Vacuum circuit-breakers from standard ranges can also be used as generator circuit-breakers with smaller generators (up to 100 MW). These breakers allow very compact solutions. They are used as a fixed-mounted single unit or as a draw-out device within a functional system with metallic compartment walls, earthing switch and disconnector function (segregation) (figure 9-5). Current and voltage transformers and surge arresters can also be integrated.

The technical data listed in the following table are based on testing in accordance with ANSI standard IEEE C 37.013-1997.

Table 9-3

Technical data of generator circuit-breaker type VD4 G

Type designation		VD4G	
Rated voltage to IEC		kV	17,5
Rated voltage to ANSI/IEEE		kV	15,8
Rated short-time power frequency withstand voltage		kV	50
Rated lightning impulse withstand voltage		kV	(95) 110
Rated current (at max. 40°C)	without fan	A	3400
	with fan	A	5000
Rated breaking current	system source (symm.)	kA	40
	generator source	kA	25/18,5
Rated making current		kA	110



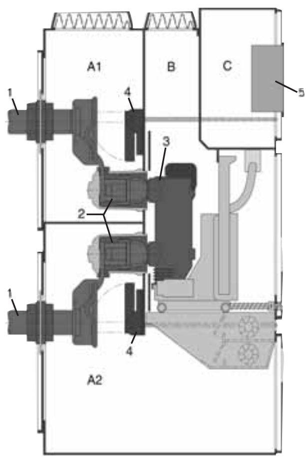


Fig. 9-6 Generators circuit-breaker VD4G

A1 Upper terminal compartment (e.g. transformer)
A2 Lower terminal compartment (e.g. generator)
B Circuit-breaker compartment
C Low voltage compartment

1 Terminal lead
2 Isolating contact
3 Circuit-breaker
4 Earthing switch
5 Bay control and protection unit REF 542

9.2 High-current bus ducts (generator bus ducts)

9.2.1 General requirements

The high-current bus ducts with all their branches are a component of the electrical installation in the power plant.

The high-current bus duct and switchgear generally serve the following functions (Fig. 9-7).

– Connection between generator and main transformer(s) including generator neutral.

– Branch connections to station services and excitation transformers as well as voltage transformer cubicles.

– Design and connection of measuring, signalling and protection devices for current, voltage and other operating data.

– Installation and connection of high-current switching devices such as generator circuit-breakers with high-current disconnectors and earth disconnectors.

– Additional facilities, e.g. for protection and working earthing, pressure-retaining systems or forced cooling.

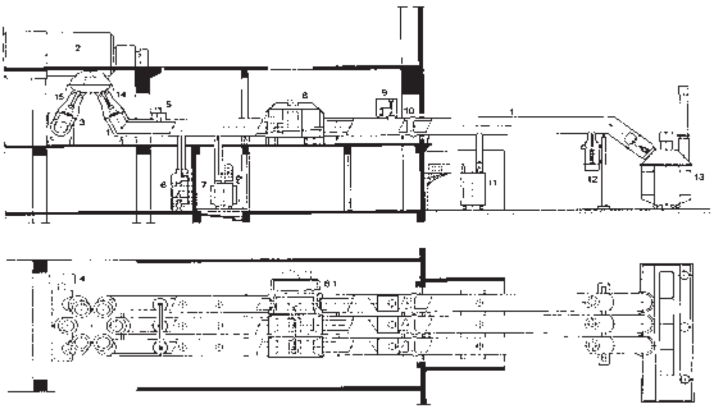


Fig. 9-7 High-current switchgear installation

1 High-current bus duct, 2 Generator, 3 Generator neutral point, 4 Neutral earthing cubicle, 5 Short-circuiting facility (temporary), 6 Voltage transformer cubicle, 7 Excitation transformer, 8 Generator circuit-breaker, HEC type with 8.1 control cubicle, 9 Voltage and capacitor cubicle, 10 Expansion joint, 11 Station auxiliary transformer, Main transformer, 14 Current transformer / feeder side, 15 Current transformer/neutral side

Note: The voltage transformers (6 and 9), the capacitors (9), the earth switch, the short-circuiting facility (5) and the surge arrester (12) can also be installed in the generator terminals.
The configuration of the current transformers (14) must be specified: a) at the generator feed, b) in the busbar run or c) in the generator circuit-breaker, to enable the short-circuiting facility to be located at the proper position.
Consultation with the supplier of the generator circuit-breaker is required.

Technical requirements

The design of the largest generators with nominal power up to 1700 MVA yields operating currents of up to 50 kA. For the high-current bus duct, this means that the generated heat in conductors and enclosure and the significant magnetic field effects in the installation and its environment must be controlled.

With the stated unit capacities and the high network outputs, short-circuit currents of up to approximately 750 kA peak value may occur in the high-current bus ducts and high-current switchgear. In the branches, peak short-circuit currents of more than 1000 kA may occur. And of course the safety and availability of a high-current bus duct must correspond with the high standard of the other power-plant components.

The high-current bus ducts must therefore comply with specified requirements:
– Adherence to preset temperature limits,
– Adequate short-circuit current carrying capability, (thermal and mechanical strength with short-circuits),
– Adequate magnetic shielding,
– Safe insulation, i.e. protection against overvoltages, moisture and pollution.

9.2.2 Types, features, system selection

Types

In smaller power plants (hydropower, CHP stations) with a load current of up to approximately 2.5 kA (5 kA), the bus ducts can still have the "classic" busbar design. The simplest designs are flat and U-shaped busbars of Al or Cu (sometimes also tubular conductors, in Al only). Exposed busbars are used with small generator ratings only because they require locked electrical equipment rooms. In contrast, laying the busbars in a common rectangular aluminium duct provides protection against contact and pollution. Aluminium partitions between the phases provide additional protection. This prevents direct short-circuits between the phases. In the event of short-circuit currents flowing, the compartment walls reduce the short-circuit forces (shielding) on insulators and busbars.

Single-phase systems can be supplied in single-insulator or triple-insulator designs.

Typical single-phase variations:
– up to 5.5 kA in single-insulator design (type HS 5500)
– up to 50 kA in triple-insulator design (type HA)

Features

The single-phase enclosure is the most commonly supplied and the most technically advanced model. The conductors and the concentrically arranged enclosure around the conductor consist of aluminium tubes and are insulated from each other by an air gap and resin insulators (Fig. 9-8)

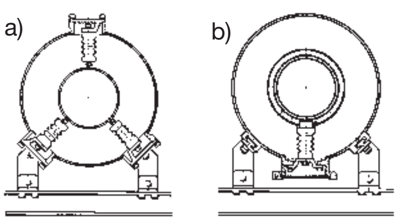


Fig. 9-8

a) Single-phase design with three insulators Type A

b) Single-phase design with one insulator Type B

An important technical feature is the single-phase enclosure short-circuited over the three phases at both ends. This enables the enclosures to form a transformer secondary circuit to the conductors. The current flowing in the enclosure – opposite to the conductor current – reaches approximately 95% of the conductor current depending on the system configuration and the impedance of the short-circuit connection between the enclosures (Fig. 9-10)

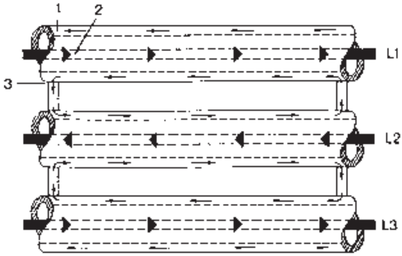


Fig. 9-9

Principle of the high-current bus duct with electrically continuous enclosure,

1 Enclosure current,
2 Conductor current,
3 Enclosure connection

The magnetic field outside the enclosure is almost completely eliminated, thereby eliminating the ambient losses.

This type has the following important features:
– Proof against contact, making locked electrical equipment rooms unnecessary,
– Protection against pollution and moisture, maintenance limited to visual checks,
– No magnetic field outside the enclosure (no induction losses in adjacent conductive material such as screens, railings, concrete reinforcement, pipes etc.),
– Reduced likelihood of ground faults and short-circuits,
– Single-phase high-current switching devices can be incorporated in the bus duct.

The type range A includes 5 voltage levels – 01 to 05 – for rated current intensities of 3 to 31 kA in self-cooling design (Table 9-5) and currents of up to about 50 kA with forced cooling.

The types range B includes 2 voltage levels, rated currents intensities up to 5.5 kA (Table 9-4)

Table 9-4 Single-phase high-current bus ducts type B

General table for system selection based on current and voltage (natural cooling)

Rated current kA	Conductor dia. mm Type B 01 and 02	Enclosure dia. mm Type B 01 and 02	Conductor/Enclosure Rated short-time p.-f. withstand voltage 50 (60) Hz 1 min in kV Type B 01	02	Rated lightning impulse withstand voltage 1.2/50 μs in kV Type B 01	02
				(36)		(95)
5.5	150	480	28	38	75	95

Notes: For explanations, see Table 9-5
For main dimensions, see Table 9-6

Table 9-5 Single-phase high-current bus ducts type A

General table for system selection based on current and voltage (natural cooling)

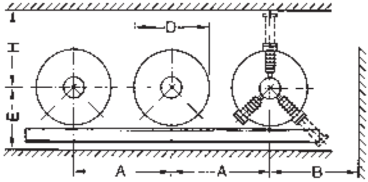
Rated current	Conductor Ø mm	Enclosure Ø mm					Conductor/enclosure Rated short-time p.-f. withstand voltage 50 (60) Hz 1 min in kV					Rated lightning impulse withstand voltage 1.2/50 ms, in kV				
	Voltage levels						Voltage levels					Voltage levels				
kA	01 to 05	01	02	03	04	05	01	02	03	04	05	01	02	03	04	05
3	100	460	460	550	640	730										
5	190	550	550	640	730	820										
8	280	640	640	730	820	910										
10	370	730	730	820	910	1 000		(36)	(60)	(80)	(80)		(95)	(110)	(150)	(150)
12	460	820	820	910	1 000	1 090	28	38	50	70	70	75	95	125	145	170
15	550	—	910	1 000	1 090	1 180										
17	640	—	1 000	1 090	1 180	1 270										
20	730	—	1 090	1 180	1 270	1 360										
22	820	—	—	1 270	1 360	1 450										
24	910	—	—	1 360	1 450	1 540										
26	1 000	—	—	1 450	1 540	1 630										
30	1 000	—	—	—	—	1 720										

Note: test voltages as IEC 600 71-1, Table 2;
( ) values in parentheses according to ANSI C 37.23.
A cooling system is required for currents over 31 kA.
Table 9-6 is appliable for structural planning.

Table 9-6

Main dimensions of the high-current bus duct

Dimensions must be clarified with supplier



Current kA 05E	Type A 01 to 05			Type A		01	02	03	04	05
	D mm	A mm	B mm	E mm	H mm	H mm	H mm	H mm	H mm	H mm
0- 3	460	750	700	500	600	600	—	—	—	—
3- 5	550	850	750	550	650	650	650	—	—	—
3- 8	640	950	800	600	650	650	700	750	—	—
3-10	730	1 000	900	650	700	700	750	800	850	—
3-10	820	1 100	950	700	750	750	800	850	900	950
5-12	910	1 200	1 000	750	800	800	850	900	950	1 000
8-15	1 000	1 300	1 050	800	850	850	900	950	1 000	1 050
10-17	1 090	1 400	1 100	850	900	900	950	1 000	1 050	1 100
12-17	1 180	1 500	1 150	900	950	950	1 000	1 050	1 050	1 100
15-20	1 270	1 600	1 200	950	1 000	1 000	1 050	1 100	1 100	1 150
17-22	1 360	1 700	1 250	1 000	1 050	1 050	1 050	1 100	1 150	1 200
20-24	1 450	1 800	1 300	1 050	1 100	1 100	1 100	1 150	1 200	1 250
22-26	1 540	2 000	1 400	1 100	1 100	1 100	1 150	1 200	1 250	1 300
24-26	1 630	2 100	1 450	1 150	1 150	1 150	1 200	1 250	1 300	1 350
26-30	1 720	2 300	1 500	1 200	1 200	1 200	1 250	1 300	1 350	1 400
	Type									
to 5.5	480	600	700	500	650	650	—	—	—	—

9.2.3 Design dimensions

Criteria for rating a high-current bus duct:

– service voltage
– load current
– operating temperatures
– insulation level
– short-circuit current carrying capability
– supplementary requirements for installed components and equipment
– climatic conditions

The dielectric strength (rated short-time p.-f. withstand and rated lightning impulse withstand voltage) is assured by standardized type-sized air clearances between conductor and enclosure, and by standard insulators as per VDE, DIN and IEC and the assigned voltage levels with the test voltages as per IEC 600 71-1 (VDE 0111 Part 1).

The test voltages for BS and ANSI are covered by the clearances provided (Table 9-4, 9-5).

The standardized type range and the connections at components of the power plant such as generator and transformer are rated for minimum clearances as per VDE and IEC. Verification by test is not required.

Computers are used for optimum and economical design of sizes and wall thicknesses for conductor and enclosure on the basis of a comprehensive heat network. The standard rating is based on maximum limit temperatures with an ambient temperature of 40°C:

Enclosure 65 °C – 80 °C; conductor 90 °C – 105 °C.

These values comply with all corresponding VDE, IEC and ANSI standards.

The short-circuit current carrying capability of the bus duct includes adequate provision for peak short-circuit and short-time current. Only one short-circuit current – either from the generator or from the system side – can occur on the main conductor, but in the branches, the sum of the two short-circuit currents must be taken into account. The single-phase enclosure design reduces the likelihood of a short-circuit by many times.

The main duct design for the rated current inevitably has a short-circuit current carrying capability by that far exceeds the rated value dynamically and thermally.

However, the branch ducts are dimensioned primarily for peak and short-time current withstand in compliance with the short-circuit calculations and the requirements of the relevant standards (Section 3 and 4). This automatically ensures compliance with the permissible temperatures at load current.

9.2.4 Structural design of typical High-current bus ducts

Conductors and enclosure are of Al 99.5% sheet (DIN 40501), which is rolled and submerged-arc welded. To improve thermal dissipation, the conductors are painted on the outside and the enclosures inside and outside.

The length of prefabricated assemblies depends on the feasibility of transport and the access and installation conditions on the construction site.

Each support of the conductor consists of one or three post insulators – in exceptional cases of four –, which are mounted from outside. Sliding surfaces or fixed pins on all insulators of each support and a spring arrangement on one insulator per support allow relative axial movements between the conductor and the enclosure.

The enclosure supports are independent of the support of the conductor and are designed as sliding or fixed-point, fastened directly to the support structure. The tube profile allows distances of enclosure supports of 10-20 m depending on the system.

All connections to the generator, to transformers and switchgear not only ensure secure electrical connection but also allow adjustment, accommodation of thermal movements and access to the junction points. The enclosure structure is particularly important at the generator terminals because of the small spaces between them. In small and medium-sized installations, three-phase terminal and neutral compartments with hatches and viewing windows allow inspection and access to the connections. At higher rated currents, only the single-phase enclosed bus duct construction provides sufficient magnetic field compensation, prevents eddy currents and therefore ensures controlled temperature conditions.

The conductors are connected to the generator, transformers and switchgear terminals with flexible press-welded copper straps fastened with bolts. Spring washers guarantee the required contact pressure and prevent unacceptable temperature rise. The contact surfaces are silver-coated if required by the conductor limit temperature (IEC and ANSI).

Current transformers for measurement and protection of the toroidal core type are either installed at the generator terminal bushings or integrated into the bus duct at a suitable point. Detachable connections are then to be integrated into the main conductor for installation and removal. Voltage transformers can be incorporated into the bus duct or installed in separate instrument cubicles connected by branch ducts. The same applies for protection capacitors for limiting capacitively transmitted voltages.

Surge arresters protect bus duct and generator, even in the event of flashover in the transformer, but are then usually overstressed. The use of housings with pressure relief will ensure the safety of personnel and the installation.

9.2.5 Earthing system

The design of earthing systems for high-current bus ducts is based on DIN VDE 0101, which also comply with the other national and international standards (such as IEC, ANSI, BS). The maximum anticipated double ground-fault current can be calculated as follows:

$$I''_{\mathrm{K\,EE}} = \frac{\sqrt{3}}{2} \cdot I''_{\mathrm{K\,3}}$$

The minimum cross section A_E for the main earthing conductor as per VDE 0103 is calculated as follows:

$$A_{\mathrm{E\,min.}} = \frac{I''_{\mathrm{K\,EE}} \cdot 10^3 \cdot \sqrt{m + n}}{S_{\mathrm{thn}} \cdot \sqrt{\frac{1}{T_{\mathrm{K}}}}}$$

The typical earthing system of high-current bus duct uses the enclosure of the three phases as the earthing conductor. The separate conductors are restricted to connecting the enclosure to the earth terminals on the generator, the transformers and the connection to the power plant earthing system. All components outside the busbar run such as cubicles etc. are connected to the enclosure and so are earthed "by spurs". See Section 5.3 for additional information on earthing.

Note:

When installing generator circuit-breakers, the earth switch and the short-circuiting facility can be integrated into the generator circuit-breaker.
For detailed information, see generator circuit-breakers in Section 9.1!

9.2.6 Air pressure/Cooling system

Operational reliability can be further improved by supplying the high-current bus duct with filtered dry air. The resulting overpressure of 500 Pa (max. 2000 Pa) allows air in the bus duct to pass from inside to outside only, preventing contamination. The dry air also prevents the formation of condensation. The incoming air is drawn through a reducing valve and a gas meter from the power plant compressed-air system with or without a dryer and water separator.

Forced ventilation of the high-current bus duct at 31 to max. 50 kA is of the closed loop type with an air-water heat exchanger for cooling. The cooling unit is normally installed under the bus duct as close to the middle as possible. The air is blown into the outer phases by fans and diverted to the middle phase at the end by control dampers and deionizing screens via a connecting duct, in which it flows back to the cooling unit at twice the speed. The closed circuit air-cooling system is 100% redundant, allowing the system to be switched to the standby fan and cooler immediately when necessary. If the cooling system fails, the availability of the high-current bus duct is still 50–70%, depending on the design. Fig. 9-11 shows the air flow diagram of a high-current bus duct.

The limited space in the generator terminal area and the requirement to be able to work with smaller dimensions may require cooling with a single-pass airflow below 31 kA.

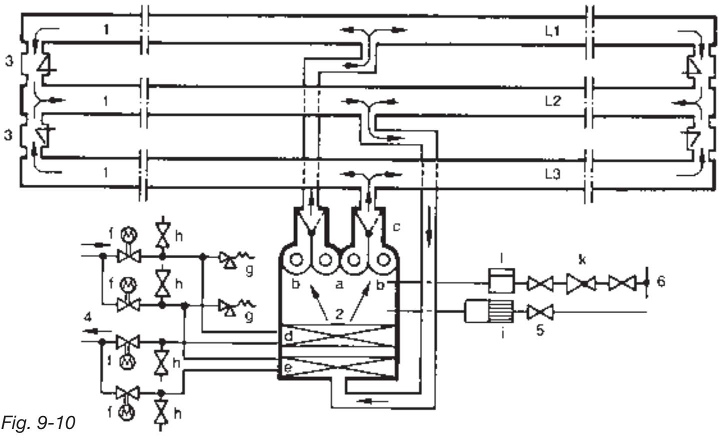


Fig. 9-10

Cooling-air flow diagram for a high-current bus duct, 1 High-current bus duct, 2 Cooling unit with fans a; Standby fans b; Dampers on standby fan c; Cooler d and standby cooler e; 3 Damper valves for flow distribution, deionization screens, 4 Cooling water circulation with motor-operated valves f for cooler and standby cooler (flow and return) with safety valves g; Vent and discharge valves h; 5 Make-up air with filter-dryer element i; 6 Alternative to 5: Make-up air from the compressed air system via reducing valve k and air meter l.

10 High-voltage apparatus

10.1 Definitions and electrical parameters for switchgear

Disconnectors are mechanical switching devices which provide an isolating distance in the open position. They are capable to open or close a circuit if either a negligible current is switched or if there is no significant change in voltage between the terminals of the poles. Currents can be carried for specified times under normal operating conditions and under abnormal conditions (e.g. short circuit). Currents of negligible quantity have values $\leqq$ 0.5 A; examples are capacitive charging currents for bushings, busbars, connections, very short lengths of cable and currents of voltage transformers.

Isolating distances are gaps of specified dielectric strength in gases or liquids in the open current paths of switching devices. They must comply with special conditions for the protection of personnel and installations and their existence must be clearly perceptible when the switching device is open.

Switches are mechanical switching devices, which not only make, carry and interrupt currents under normal conditions in the network but also must carry for a specific time and possibly make currents under specified abnormal conditions in the network (e.g. short circuit).

Switch disconnectors are switches which satisfy the requirements for an isolating distance specified for a disconnector in their open position.

Circuit-breakers are mechanical switching devices able to make, carry and interrupt currents occurring in the circuit under normal conditions, and can make, carry for a specified time and break currents occurring in the circuit (e.g. short circuit) under specified abnormal conditions.

Earthing switches are mechanical switching devices for earthing and short-circuiting circuits. They are capable of carrying currents for a specified time under abnormal conditions (e.g. short circuit). They are not required to carry normal operating currents. Earthing switches for transmission networks may also be required to make, carry and break induced currents (capacitive and inductive) under normal circuit conditions. Earthing switches with short circuit making capability shall be able to make the short-circuit current.

Fuses are switching devices that open the circuits in which they are installed by the melting of one or more parts specified and designed for the purpose of breaking the current when it exceeds a given value for a sufficiently long period.

Auxiliary switches must be rated for a continuous current of at least 10 A and be capable to break the current of the control circuits. The manufacturer must provide details. In the absence of such information, they must be capable of breaking at least 2 A at 220 V d.c. at a minimum circuit time constant of 20 ms. The terminals and wiring in auxiliary circuits must be designed for at least 10 A continuous current. The auxiliary switches that are actuated in connection with the main contacts must be directly actuated in both directions.

Electrical characteristics

(Peak) making current: peak value of the first major loop of the current in one pole of a switching device during the transient period following the initiation of current during a making operation.

Peak current: peak value of the first major loop of current during the transient period following initiation.

Breaking current: current in one pole of a switching device at the instant of initiation of an arc during a breaking process.

Breaking capacity: value of the prospective breaking current that a circuit-breaker or load switch can break at a given voltage under prescribed conditions for application and performance; e.g. overhead line (charging current) breaking capacity.

Short-line fault: short circuit on an overhead line at a short but not negligible distance from the terminals of the circuit-breaker.

Out of phase (making or breaking) capacity: making or breaking capacity for which the specified conditions for use and behaviour include the loss or the lack of synchronism between the parts of an electrical system on either side of the circuit-breaker.

Applied voltage: voltage between the terminals of a circuit-breaker pole immediately before making the current.

Recovery voltage: voltage occurring between the terminals of a circuit-breaker pole after interruption of the current.

Opening time: interval of time between application of the auxiliary power to the opening release of a switching device and the separation of the contacts in all three poles.

Closing time: interval of time between application of the auxiliary power to the closing circuit of a switching device and the contact touch in all poles.

Break time: interval of time between the beginning of the opening time of a switching device and the end of the arcing time.

Make time: interval of time between application of the auxiliary power to the closing cuircuit of a switching device and the instant in which the current begins to flow in the main circuit.

Rated value: value of a characteristic quantity used to define the operating conditions for which a switching device is designed and built and which must be verified by the manufacturer.

Rated normal current: the current that the main circuit of a switching device can continuously carry under specified conditions for use and behaviour. See below for standardized values.

Rated short-time withstand current: current that a switching device in closed position can carry during a specified short time under prescribed conditions for use and behaviour. See below for standardized values.

Rated voltage: upper limit of the highest voltage of the network for which a switching device is rated. See below for standardized values.

Additional rated values:
rated withstand current,
rated making current,
rated short-circuit breaking capacity etc.

Standard value: rated value based on official specifications to be used for designing a device.

Standardized rated voltages: 3.6; 7.2; 12; 17.5; 24; 36; 52; 72.5; 100; 123; 145; 170; 245; 300; 362; 420; 550; 800 kV.

Standardized rated normal currents: 200; 250; 400; 500; 630; 800; 1000; 1250; 1600; 2000; 2500; 3150; 4000; 5000; 6300 A.

Standardized rated short-time currents: 6.3; 8; 10; 12,5; 16; 20; 25; 31,5; 40; 50; 63; 80; 100 kA.

Rated insulation level: standardized combination of the rated values for the lightning impulse withstand voltage, the switching impulse withstand voltage (if applicable) and the short-time power frequency withstand voltage assigned to a rated voltage. As standardized insulation level, only combinations of values from one and the same line of Table 10-1 are valid.

Rated short-duration power frequency withstand voltage: rms value of the sinusoidal a.c. voltage at operating frequency that the insulation of a device must withstand under the specified test conditions for 1 minute.

Rated lightning impulse withstand voltage: peak value of the standard voltage surge 1.2/50 µs that the insulation of a device must withstand.

Rated switching impulse withstand voltage: peak value of the unipolar standard voltage surge 250/2500 µs which the insulation of a device with a rated voltage of 300 kV and above must withstand.

Note:

For disconnectors and specific (asynchronous) circuit-breakers for rated voltages of 300 kV and above, the isolating distances or breaker gaps are tested with combined voltage so that the power frequency test voltage (Table 10-1, peak values in parentheses) is applied at one terminal and the counterpolar test surge voltage (lightning or switching) occurs in the time range of the maximum voltage at the other terminal. The test with combined voltage was originally known as the bias test.

Table 10-1

Standardized rated insulation level for disconnectors, switches, circuit-breakers and earthing switches according to IEC 62271-1 (VDE 0670 Part 1000)

Rated voltage kV (rms value)	Rated short-duration power frequency withstand voltage kV (rms value)		Rated lightning impulse withstand voltage kV (peak value)	
	Phase to earth, between the phases and across the open breaker gap	Across the isolating distance	Phase to earth, between the phases and across of the open breaker gap	Across the isolating distance
1	*2*	*3*	*4*	*5*
3.6	10	12	20	23
			40	46
7.2	20	23	40	46
			60	70
12	28	32	60	70
			75	85
17.5	38	45	75	85
			95	110
24	50	60	95	110
			125	145
36	70	80	145	165
			170	195
52	95	110	250	290
72.5	140	160	325	375
100	150	175	380	440
	185	210	450	520
123	185	210	450	520
	230	265	550	630
145	230	265	550	630
	275	315	650	750
170	275	315	650	750
	325	375	750	860
245	360	415	850	950
	395	460	950	1 050
	460	530	1 050	1 200

(continued)

Table *10-1 (continued)*

Rated voltage kV (rms value)	Rated short-duration power frequency withstand voltage kV (rms value)		Rated lightning impulse withstand voltage kV (peak value)		Rated switching impulse withstand voltage kV (peak value)		
	Phase to earth and between the phases	Across the open breaker gap and/or isolating distance	Phase to earth and between the phases	Across the open breaker gap and/or isolating distance	Phase to earth and across the open breaker gap	Between the phases	Across the isolating distance
1	*2*	*3*	*4*	*5*	*6*	*7*	*8*
300	380	435	950	950 (+ 170)	750	1 125	700 (+ 245)
			1 050	1 050 (+ 170)	850	1 275	
362	450	520	1 050	1 050 (+ 205)	850	1 275	800 (+ 295)
			1 175	1 175 (+ 205)	950	1 425	
420	520	610	1 300	1 300 (+ 240)	950	1 425	900 (+ 345)
			1 425	1 425 (+ 240)	1 050	1 575	
550	620	800	1 425	1 425 (+ 315)	1 050	1 680	900 (+ 450)
			1 550	1 550 (+ 315)	1 175	1 760	
800	830	1 150	1 800	1 800 (+ 455)	1 300	2 210	1 100 (+ 650)
			2 100	2 100 (+ 455)	1 425	2 420	

The values in parentheses are the peak values of the a.c. voltage applied to the opposite terminal.

10.2 Disconnectors and earthing switches

Disconnectors are used for galvanic isolation of networks or sections of switchgear installations. As an independent air-insulated device, they form a visible isolating distance in their open position. They are suitable for switching small currents (< 0.5 A) or also larger currents if the voltage does not change significantly between the contacts of a disconnector pole during switching (commutation currents).

Disconnectors can carry currents under operating conditions continuously and under abnormal conditions, such as short circuit, for a specified time (1s, 3s).

More than 10 different designs are in use around the world. The most important are rotary disconnectors, two-column vertical break disconnectors and single-column disconnectors.

Earthing switches are used for earthing and short-circuiting deenergized station components. Earthing switches can withstand currents during a specified time (1s, 3s) under abnormal conditions, such as a short circuit, but they are not required to carry continuous operating currents.

In general, earthing switches are combined with the adjacent disconnectors to form one unit. However, earthing switches can also be installed separately.

The applicable standard for disconnectors and earthing switches is IEC 62271-102 (VDE 0671 Part 102). IEC 61128 is specifically applicable for switching commutation currents with disconnectors.

Selection of the disconnector design is primarily guided by the layout of the installation (structural design), see Section 11.3.3. The commercially available disconnector range can cover virtually all important layout variations in the ranges 72.5 to 800 kV, (rated voltage), 1250 to 4000 A (rated current) and 63 to 160 kA (rated peak withstand current).

10.2.1 Rotary disconnectors

Two-column rotary disconnectors

This disconnector type is used for rated voltages of 72.5 to 420 kV (in individual cases also for 525 kV), preferably in smaller installations and also in larger switchgear installations as incoming feeder or sectionalizing disconnector. An earthing switch can be installed on both sides.

As shown in Fig. 10-1, the two rotating bases are mounted on a sectional steel frame and connected by a braced tie-rod. The insulators (post insulators) are fixed to the rotating bases and carry the swivel heads with the arms and the high-voltage contacts. Both arms swivel 90 degrees with their insulators during the switching movement.Two-column rotary disconnectors in their open position form a horizontal isolating distance. The rotary bases should be weather protected and should have maintenance-free ball bearings. The rotary bases are fastened on stay bolts, which allow precise adjustment of the contact system after the lines have been rigged and also compensate the insulator tolerances.

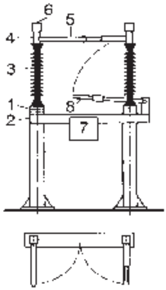


Fig. 10-1

Two-column rotary disconnector for 123 kV, 1 Rotating base, 2 Frame, 3 Post insulator, 4 Rotating head, 5 Contact arm, 6 High-voltage terminal, 7 Mechanism, 8 Earthing switch

The swivel arms are normally an aluminium-welded construction with non-corroding contact joints, thereby eliminating any long-term changes in resistance. Disconnectors ≥ 170 kV have an interlocking mechanism (pawl and pin). This prevents the contacts from opening at high short-circuit currents. The current in the maintenance-free swivel heads, which are protected against external influences, is transferred via contact fingers arranged in a tulip shape around two contact pins, or for operating currents > 2500 A via tapered roller contacts. The high-voltage contacts can be rotated 360 degrees, allowing the tube or wire runs to be connected in any direction. The contact system has separately sprung contact fingers with no exposed springs.

The disconnectors and earthing switches have mostly an operating mechanism with dead-centre interlocking. This prevents its position from being changed by extreme external influences, such as short circuits, earthquake or high winds. Disconnectors and earthing switches have separate mechanisms. For rated voltages of up to 300 kV, a three-pole disconnector or earthing switch group is generally actuated with one mechanism each. The individual poles of one group are mechanically linked by a connecting rod. The torque is transferred by the mechanism to a rotating base and rotates it by 90 degrees. The tie-rod rotates the second rotating base simultaneously. The contacts make both a rotary and a sliding movement when opening and closing the disconnector. This easily breaks heavy icing. The torque of the earthing switch is transferred to the shaft of the earthing switch. On closing, the arm of the earthing switch swivels upwards and meets the earthing contact attached to the swivel arm.

Three-column rotary disconnectors

These disconnector-types are primarily used outside Europe with a side-by-side configuration of the three poles of a group. In comparison to two-column rotary disconnectors, they allow smaller pole spacings and higher mechanical terminal loads.

The two outer insulators are fixed to the base frame and carry the contact system (Fig. 10-2). The middle insulator is fastened to a rotating base and carries the one-piece arm, which rotates approximately 60 degrees during a switching operation and engages the contact systems on the outer insulators. The earthing contacts of the earthing switches, which can be mounted on either side, are located at the fixed contact system.

The three-column rotary disconnectors have the same components as the two-column rotary disconnectors described above. The same information applies for contact arm, swivel bases, contact system and interlocking mechanism, centre-point interlock, earthing switch and mechanical connection of the poles.

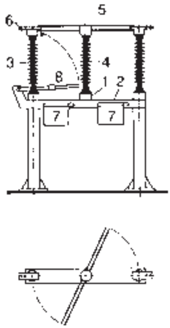


Fig.10-2

Three-column rotary disconnector, 145 kV, 1 Swivel base, 2 Frame, 3 Post insulator, 4 Rotating insulator, 5 Contact arm, 6 High-voltage terminal, 7 Mechanisms, 8 Earthing switch

10.2.2 Single-column (pantograph) disconnectors

In installations for higher voltages (≥ 170 kV) and multiple busbars, the single-column disconnector (also referred to as pantograph or vertical-reach disconnector) shown in Fig. 10-3 requires less space than other disconnector designs. For this reason and because of the clear station layout, it is used in many switchgear installations. The switch status is clearly visible with the vertical isolating distance.

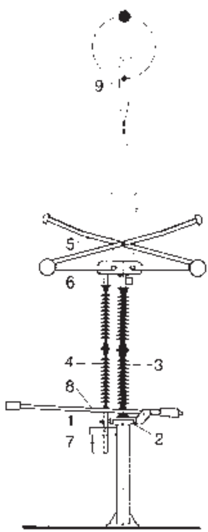


Fig.10-3

Single-column disconnector for 245 kV, 1 Rotating bearing, 2 Frame, 3 Post insulator, 4 Rotating insulator, 5 Pantograph, 6 Gearbox, 7 Mechanism, 8 Earthing switch, 9 Fixed contact

The base of the disconnector is the frame, which holds the post insulator carrying the head piece with the pantograph and the gearbox. The actuating force is transferred through the rotating insulator to the gearbox. The suspended contact is mounted on the busbar situated above the disconnector. On closing, it is gripped between the pantograph arms. During the closing movement, the pantograph arms swivel through a wide range and are therefore capable of carrying the fixed contact even under extreme position changes caused by weather conditions. The feeder line is connected to the high-voltage terminal of the gearbox. In general, the single-column disconnector allows higher mechanical terminal loads than the two-column rotary disconnector.

The frame with the rotary bearing for the rotating insulator is fastened to the support with four stay bolts. They allow the disconnector to be accurately adjusted relative to the suspended contact.

The pantograph is normally a welded aluminium construction. It is fixed to the gearbox with the pantograph shaft by pins, preventing the pantograph unit from moving during the entire lifetime. This also ensures long-term high contact pressure between the contacts of the pantograph and the fixed contact. A contact force of 700 to 1500 N (depending on the pantograph design) not only ensures secure current transfer but also breaks heavy icing. Tapered roller contacts transfer current from the gearbox to the lower pantograph arms and make the connection from the lower to the upper pantograph arm.

The contact bars on the top of the pantographs and the fixed contact are silver-coated copper, for heavy duty or special cases they have a fine silver inlay. This results in low contact erosion, good current transfer and long service intervals.

Disconnectors for high short-circuit currents have normally a damping device between the arm joints. In the event of a short circuit, it prevents any reduction in the contact pressure and damps the oscillations of the pantograph caused by the short-circuit current.

The single-column disconnectors have a centre-point interlock in the gearbox and therefore cannot change their position spontaneously. It retains the switch position in any case, even if the rotating insulator breaks or if the disconnector is subjected to extreme vibrations caused by earthquakes or short-circuit forces. Anti-corona fittings on the ends of the arms act as a stop for the suspended contact if it moves in a vertical direction. Even under high tensile forces, it is securely held in the contact zone in the event of a short circuit.

Special designs of single-support disconnectors have been used in installations for high-voltage direct current transmission (HDVC) for many years.

A rotary-linear earthing switch (Section 10.2.4) can be installed on every disconnector pole.

In general, single-column disconnectors and the associated earthing switches are actuated by one mechanism each per pole.

Suspended contact for commutating current switching with single-column disconnector (bus-transfer current switching)

When switching between busbars without current interruption in outdoor switchgear installations, commutation currents occur during the switching operation and cause increased contact erosion on the contact bars of the disconnector and on the suspended contact. The height of the currents depends on the distance of the switching location from the power supply and the type of switchover, i.e. whether between busbars or switch bays, with the latter causing the higher stress. The commutation voltage can be calculated.

Commutation processes occur both on closing and opening. Closing causes bouncing between the contact bars and the suspended contact, which causes only slight arcing and a low degree of contact erosion. However, opening causes arcing between the opening contact bars that continues until the inverse voltage for quenching the arc has been generated. Because of the slow start of the movement of the contact bars, this process lasts for several cycles and causes significant stress on the disconnector contacts. Heavy-duty 420-kV outdoor switchgear installations can have commutation voltages up to 300 V and commutation currents to approximately 1500 A.

The ABB-developed commutation suspended contact for single-column disconnectors has two independently operating enclosed auxiliary switching systems. This ensures proper function in every case, regardless of which of the two contact bars on the pantographs is first to touch or last to leave the suspended contact. The most important components are illustrated in Figs. 10-4 and 10-5. The auxiliary switching system built into an anti-corona hood consists of a spring contact – connected to the auxiliary contact bar by a toggle lever – and a deion arc-quenching device. The spring contact is opened and closed independently of the switching speed at a defined position of the auxiliary contact bar.

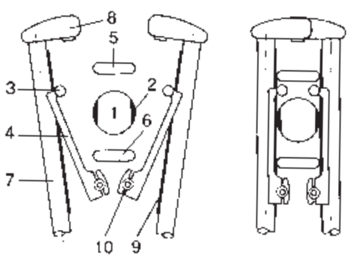


Fig.10-4

Commutating suspended contact, operating principle of guide strips,
1 Main contact support, 2 Main contact bar, 3 Auxiliary contact bar, 4 Toggle lever, 5 Upper guide strip, 6 Lower guide strip, 7 Pantograph arm, 8 Catch device, 9 Pantograph contact bar, 10 Insulated pivot with reset spring

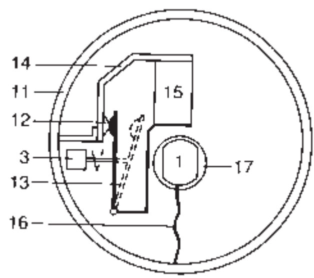


Fig.10-5

Commutating suspended contact, schematic diagram of auxiliary switching chamber,
1 Main contact support, 3 Auxiliary contact bar, 11 Anti-corona hood, 12 Fixed contact, 13 Spring contact, 14 Arc-deflecting baffle, 15 Deion arc-quenching plates, 16 Flexible connection for equipotential bonding, 17 Rotary bearing

Because the arc only lasts for about 25 ms on average during opening, the contact erosion on the spring contact system remains slight and the current is safely interrupted before the pantograph contact bar separates. Separating the main and auxiliary contact systems keeps the latter completely free from the effects of forces resulting from a short circuit. Short-circuit testing has confirmed a peak withstand current strength of 200 kA. Each switching system can take at least 350 switching cycles at commutation currents up to 1600 A and commutation voltages up to 330 V.

Installing commutation suspended contacts provides the system operator with flexibility and reliability of operation. Older installations can be upgraded by replacing the suspended contacts.

10.2.3 Two-column vertical break disconnectors

This type of disconnector is preferred for higher voltages (≥ 170 kV) as a feeder or branch disconnector (at 1 1/2 circuit-breaker structure, Section 11.3.3). It differs from two-column rotary disconnectors by smaller phase spacings (with side-by-side configuration) and higher mechanical terminal loads. In its open state, there is a horizontal isolating distance with the contact arm open upwards.

As shown in Fig. 10-6, the two post insulators are mounted on a frame. The gearbox with contact arm and high-voltage terminal and the fixed contact with high-voltage terminal are mounted on them. The rotating insulator fastened to the rotary bearing transfers the actuating force to the gearbox, which transmits the force into a torque for opening the contact arm.

Each side of the disconnector can be fitted with an earthing switch (Section 10.2.4) depending on the requirements. The associated earthing contacts are installed on the gearbox or on the fixed contact.

For rated voltages of up to 245 kV one mechanism per three-phase disconnector or earthing switch group is sufficient, at higher nominal voltages one mechanism per pole is generally used.

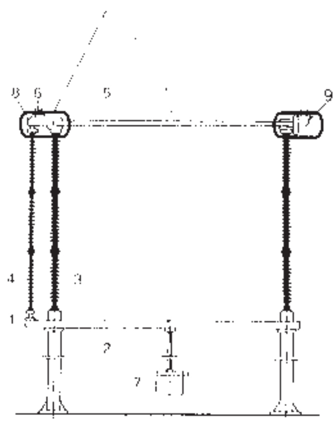


Fig.10-6

Vertical break disconnector for 525 kV, 1 Rotary bearing, 2 Frame, 3 Post insulator, 4 Rotating insulator, 5 Contact arm, 6 High-voltage terminal, 7 Mechanism, 8 Gearbox, 9 Fixed contact

As with the other disconnector types, the post insulators are also fixed to stay bolts, which enable precise adjustment of the contact arm and equalization of the insulator tolerances after the lines have been fastened.

The contact arm of the vertical break disconnectors is also a welded aluminium design. The contacts are silver-coated copper. The current in the gearbox is carried by tapered roller contacts.

A tie-rod transmits the actuating force from the mechanism to the contact arm with rotary bearings, rotating insulator and gearbox. This tie-rod, like the tie-rods in the gearbox, passes though the centre point shortly before reaching the end position,ensuring that the centre-point is interlocked against spontaneous changes of position under extreme external conditions. At high voltages and high short-circuit currents, or when ice loads have to be broken, a rotary movement of the contact arm around the longitudinal axis (approx. 25°) after reaching the “On” position provides a higher contact pressure, an additional interlock or frees the contacts from ice.

10.2.4 Single-column earthing switches

In outdoor switchgear installations, earthing switches are required not only directly adjacent to the disconnectors but also at other positions in the installation, e.g. for earthing individual busbar sections. Single-column earthing switches are used for this purpose, and they can be simultaneously used as supports for tubular busbars.

The components of the earthing switches are the same for mounting on disconnectors or separate single-column configuration. The only exceptions are the frame and support for the earthing contact.

The insulator is supported by a base frame with the operating mechanism (Fig. 10-7). It supports the contact holder with the earthing contact.

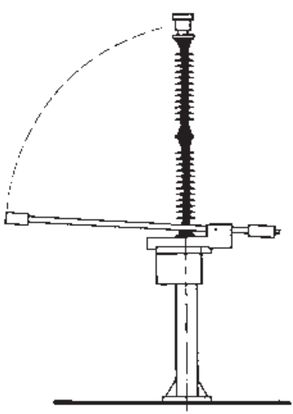


Fig.10-7

Single-column earthing *switch, 420 kV*

Two designs are available for the different requirements: a) Vertical-reach earthing switches for low rated voltages and rated currents, b) rotary-linear earthing switches for higher rated voltages and currents. They differ in the design of the earthing mechanism and hence in the switching movement of the contact arm.

On the vertical-reach earthing switch, the contact arm swivels on the shaft and only rotates around a switching angle of about 90 degrees. In the closed position, the earthing contact is situated between the contact fingers and these are against a spring stop. On the other hand, the rotary-linear earthing switch has a more complex mechanism. The contact arm first executes a rotary movement similar to that of the vertical-reach earthing switch and towards the end of the rotary movement moves on a straight line into the earthing contact. The contact blade on the contact arm is fixed in the earthing contact so the connection can withstand even high peak currents.

10.2.5 Operating mechanisms for disconnectors and earthing switches

Disconnectors are almost entirely actuated by motor-driven operating mechanisms, but manual mechanisms are also used for earthing switches. The operating mechanism is either mounted directly on the base frame of the disconnector or earthing switch or placed at operator level (1.20 m above ground level). Motor-operated mechanisms may also have an emergency manual actuator in case of failure of auxiliary power or for adjustments.

The operating mechanism housing has the position indicator switches for showing the switching position and for control and interlocking, and the motor-operated mechanisms also have contactors, etc. for controlling the actuators. The controllers are designed so that only one switching impulse is necessary to start the mechanism. They shut down automatically when the end position is reached. In the event of an emergency manual operation, the control circuit of the motor-operated mechanism is interrupted by a safety contact, making a simultaneous actuation from the control room impossible. The motor-operated mechanisms can also be fitted with pushbuttons for local control.

The mechanisms of the disconnectors and earthing switches can be interlocked relative to each other and to the associated circuit-breakers to prevent maloperation. Motor-operated mechanisms have an indicator switch contact for the relevant device incorporated into the control circuit of the mechanism. Manual and motor-operated mechanisms can also be fitted with a locking solenoid, which prevents manual switching when there is no power and also breaks the control circuit of the motor mechanism with a separate auxiliary contact. Mechanical interlocking between disconnectors and earthing switches is also possible with directly mounted earthing switches.

The mechanical actuation energy is transmitted from the motor to the actuation shaft by a spindle gear, which has an increased torque on closing and opening the main contact point to break ice loads.

Disconnectors and earthing switches have an operating mechanism with centre-point interlocking, which prevents any spontaneous changes of position under extreme external influences, such as short circuits, earthquakes or hurricanes.

Future generations of mechanisms will be motor-operated mechanisms with semiconductor controls and electronic indication of switch position.

10.3 Switch disconnectors

High-voltage switch disconnectors are switching devices that make, carry and break operating currents and also carry and in part also make short-circuit currents. In their open position, they also form an isolating distance.

The relevant standards are the following:

- IEC 62271-103 for rated voltages of 1 kV to 52 kV
- IEC 62271-104 for rated voltages of 52 kV and above

  Note: the standards also cover switches, i.e. devices whose open switching gap does not meet the special requirements of an isolating distance. In practice, equipment of this type is no longer used in central Europe.

The two above standards classify the switch disconnectors into the following by their usage:

- general-purpose switch disconnectors,
- switch disconnectors for limited applications and
- switch disconnectors for special applications.

General-purpose switch disconnectors must be capable of making and breaking the load current for which their current path is designed (rated current) and of carrying and making (at the same level) short-circuit currents for a specified time (1s, 3s). These devices have a very wide application. They are encountered with rated voltages of 12 kV, 24 kV and 36 kV in varying designs, primarily for operating currents to 630 A, but also for 1250 A (Section 8.1.2). Switch disconnectors with this versatility are found in the area of transmission voltages only as integrated devices in SF_6-insulated switchgears.

While the switch disconnector is the most common switching device in many distribution networks, it is much less common in transmission networks, in spite of its much lower costs compared to circuit-breakers.

10.4 Circuit-breakers

10.4.1 Function, selection

High-voltage circuit-breakers are mechanical switching devices capable of making, carrying continuously and breaking electrical currents, both under normal circuit conditions and, for a limited period, abnormal circuit conditions, such as in the event of a short circuit. Circuit-breakers are used for switching overhead lines, cable feeders, transformers, reactor coils and capacitors. They are also used in bus ties in installations with multiple busbars to allow power to be transmitted from one busbar to another.

Specially designed breakers are used for specific duties such as railways, where they have to extinguish longer-burning arcs (longer half-wave) in 16 $^2/_3$-Hz networks. Breakers used with smelting furnaces frequently operate with reduced actuating force and lower breaking capacity. This leads to less wear in spite of the high switching frequency and to long service intervals.

The following points are important when selecting circuit-breakers:

– maximum operating voltage on location
– installation height above sea-level
– maximum load current occurring on location
– maximum short-circuit current occurring on location
– network frequency
– duration of short-circuit current
– switching cycle
– special operational and climatic conditions

Important standards:

IEC

62271-1	General and definitions
62271-100	Classification
	Design and construction
	Type and routine testing
	Selection of circuit-breakers for service
	Information in enquiries, tenders and orders
62271-101	Synthetic testing

ANSI (**A**merican **N**ational **S**tandards **I**nstitution)

C 37 04	–1979	Rating structure
C 37 06	–1979	Preferred ratings
C 37 09	–1979	Test procedure
C 37 010	–1979	Application guide
C 37 011	–1979	Application guide for transient recovery voltage
C 37 012	–1979	Capacitance current switching

10.4.2 Design of circuit-breakers for high-voltage (> 52 kV)

Fig. 10-8 shows the basic design of HV outdoor circuit-breakers with the following components: operating mechanism, insulators, interrupting chamber and grading capacitor. HV circuit-breakers have a modular design. Higher voltages and higher capacities are dealt with by increasing the number of interrupting chambers. Self-blast interrupting chambers with low operating energy requirements are used for voltages of up to 550 kV and breaking currents of up to 50 kA (see Section 10.4.4). Single-chamber breakers are used for voltages of up to 300 kV and breaking currents of 50 kA. Multiple-chamber breakers are used for higher currents of up to 80 kA in this voltage range. Multiple-chamber breakers are used for voltages > 300 kV. Two-chamber breakers are used up to 550 kV and a breaking current of 63 kA.

In the lower voltage range and for three-phase autoreclosure, it is best to mount the three poles on a common base frame. Single-pole mounting and a separate mechanism for each pole are standard for voltages above 245 kV. HV circuit-breakers can also be mounted on trolleys with sprocket or plain rollers. Fig. 10-8 shows examples from the ABB outdoor breaker range.

The outdoor circuit-breaker design shown in Fig. 10-8 is the current type preferred in Europe. In America, the “dead tank” design is also common (Fig. 10-7a). This design, which is based on the earlier oil tank breaker, has the interrupting unit in an earthed metal tank filled with SF_6. The terminals of the interrupting unit are connected on both sides to SF_6-air bushings.

The same interrupting chambers and mechanisms as in outdoor circuit-breakers are also used with the integrated circuit-breakers of gas-insulated switchgear installations (GIS). An example of such breakers is shown in Fig. 10-9 with the section through the circuit-breaker of the SF_6-insulated switchgear installation EXK-01 for 123 kV and 40 kA. The self-blast interrupting chamber is identical to that of the outdoor circuit-breaker type LTB-D1; the three-pole circuit-breaker is operated by the HMB-1 mechanism.

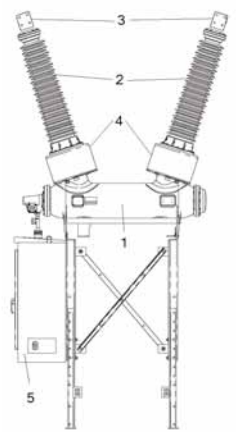


Fig. 10-7a

Dead Tank Breaker mit SF_6 self-blast interrupting chamber and spring mechanism.

1 metal-enclosed interrupting chamber,
2 bushing, 3 HV-connections
4 toroidal-core C.T., 5 drive

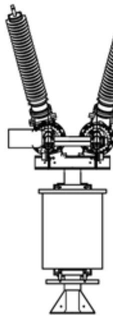
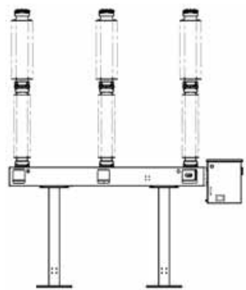
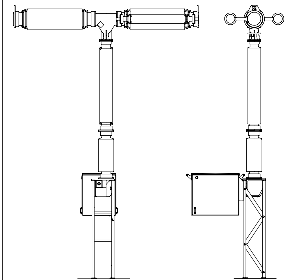
Rated voltage kV	123 (16 ⅔ Hz)	123-170	245-300	420-(550)
Rated short-circuit breaking current kA	31,5	40	50	50/63
Breaker arrangement				
Breaker type	PASS MO 16 ⅔ Hz	LTB-D1	LTB E1 / HPL-B1	LTB E2 / HPL-B2
Mechanism type	Motordrive	BLK / Motordrive	BLK / BLG	BLG / HMB-8

Fig.10-8

ABB SF_6 outdoor circuit-breaker, standard types for the central European region

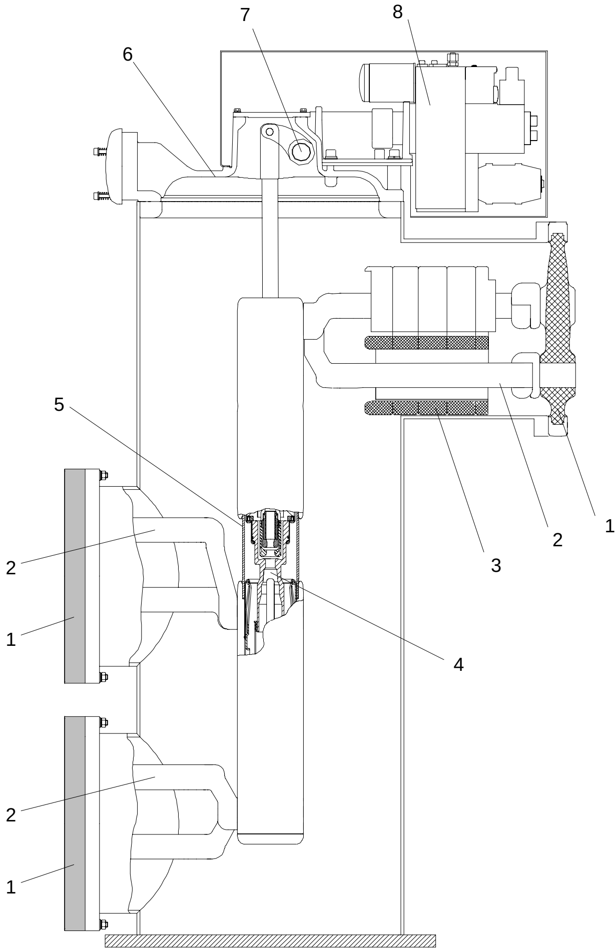


Fig.10-9

GIS circuit-breaker EXK-01 with SF_6 self-blast interrupting chamber and hydraulic spring mechanism HMB-1

1 Barrier insulator
2 Feed conductor
3 Current transformer
4 Interrupting chamber
5 Chamber insulator
6 Cover
7 Rotary feed
8 Mechanism

10.4.3 Interrupting principle and important switching cases

There are two basic arc-extinction processes.

Direct current extinction, Fig. 10-10

A d.c. arc can only be extinguished by forcing a current zero. This means that the arc voltage U_s must be higher than the voltage at the breaker LS. A sufficiently high arc voltage can be built up – by reasonable means – only in low and medium voltage d.c. circuits (magnetic blow-out breakers). In high-voltage d.c. circuits, the voltage must be lowered appropriately to extinguish the d.c. arc and/or artificial current zeros must be created by inserting a resonant circuit (see Fig. 11-39).

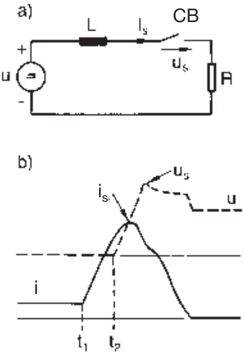


Fig.10-10

Direct current extinction a) simplified equivalent circuit, b) curves of current i_s and arc voltage u_s, t_1 initiation of short circuit, t_2 contact separation

Alternating current extinction, Fig. 10-11

A.C. arcs may extinguish at every current zero. In high-voltage circuits and without special measures, the arc re-ignites immediately after passing zero crossing, so that the arc continues to burn. The arc plasma is intensively cooled in the interrupting chambers of HV circuit-breakers with the result that it loses its electrical conductivity at current zero and the recovery voltage is not sufficient for re-ignition.

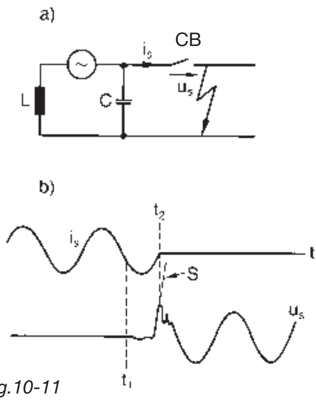


Fig.10-11

Alternating current extinction, a) simplified equivalent circuit, b) curves of short-circuit current i_s and recovery voltage u_s, t_1 contact separation, t_2 arc extinction, S rate of rise of recovery voltage

10

Voltage stress of the breaker, Fig. 10-12

When interrupting an inductive load (Fig. 10-12a), the breaker voltage oscillates to the peak value of the recovery voltage. The breaker must be able to withstand the rate of rise of the recovery voltage and its peak value. Once the arc is quenched, the dielectric strength between the contacts must build up more quickly than the recovery voltage to prevent re-ignition.

When interrupting a purely resistive load (Fig. 10-12b), current zero and voltage zero coincide. The recovery voltage at the breaker rises sinusoidally with the operating frequency. The breaker gap has sufficient time to recover dielectric strength.

When switching a capacitive load (Fig. 10-12c), the supply-side voltage (infeed breaker terminal) oscillates at system frequency after current interruption between ± û, while the capacitor-side terminal remains charged at + û.

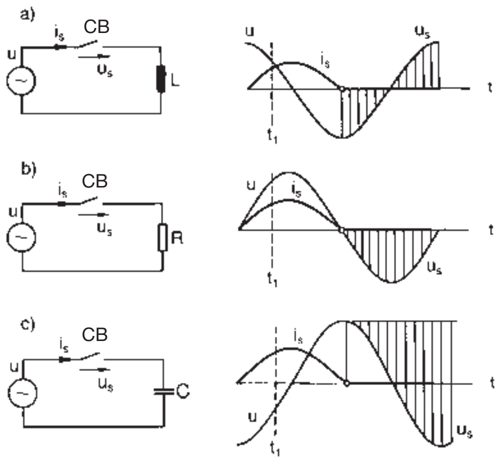


Fig.10-12

Recovery voltage u_S when breaking a) inductive load, b) resistive load, c) capacitive load

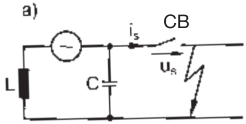
Various switching cases

Circuit-breakers must handle various switching cases that place different requirements on the breaker depending on their location.

Terminal fault (symmetrical short-circuit current), Fig. 10-13

The terminal fault is a short circuit on the load side of a breaker in the immediate vicinity of the breaker terminals. The short-circuit current is symmetrical if the fault begins at the voltage maximum. The recovery voltage oscillates to the value of the driving voltage. Rate of rise and amplitude of the transient voltage are determined by the network parameters. The values to be used in testing are defined in the relevant standards (Section 10.4.1).

Terminal fault (asymmetrical short-circuit current), Fig. 10-13



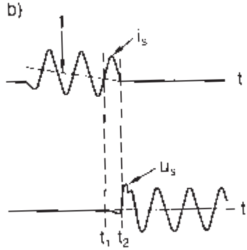
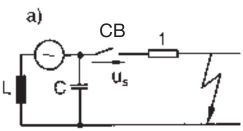


Fig.10-13

Terminal fault, a) simplified equivalent circuit, b) curves of recovery voltage u_s and short-circuit current i_s, 1 decaying d.c. current component

A more or less high d.c. current component must be switched in addition to the symmetrical short-circuit current depending on the opening time of the breaker. The d.c. current component of the short-circuit current depends on the moment of short-circuit initiation (max. at voltage zero) and on the time constants of the network supply-side components, such as generators, transformers, cables and HV lines. In accordance with IEC and DIN VDE, a time constant of 45 ms is set as standard. This means a d.c. current component of about 40% to 50% with the usual opening times of modern SF_6 outdoor breakers.

Short-line fault, Fig. 10-14



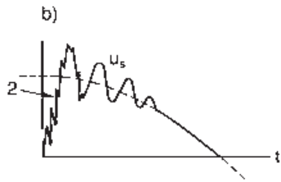


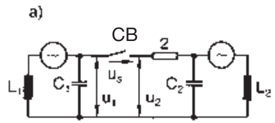
Fig.10-14

Short-line fault, a) simplified equivalent circuit, b) recovery voltage u_s across the breaker, 1 Line, 2 Sawtooth shape of u_s

Short line faults are short circuits on overhead lines at a short distance (up to a few kilometres) from the breaker. They impose a particularly severe stress on the breaker because two transient voltages are superimposed: the transient voltage of the supply network and the transient voltage on the line side. The superimposition results in a particularly high rate of rise of the voltage with only a minor reduction of the short-circuit current. The critical distance of the short circuit depends on the current, voltage and arc-quenching medium.

Switching under out-of-phase conditions (phase opposition), Fig. 10-15

The (power-frequency) voltage stress is severe if the phase angle of the systems on either side of the breaker are different (system components fall out of step because of overload or incorrect synchronization of generator circuit-breakers).



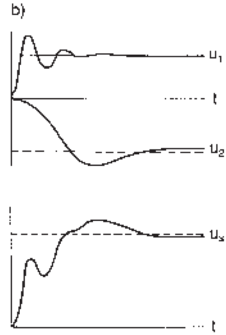


Fig.10-15

Switching under out-of-phase conditions, a) simplified equivalent circuit,
b) voltage stress on circuit-breaker

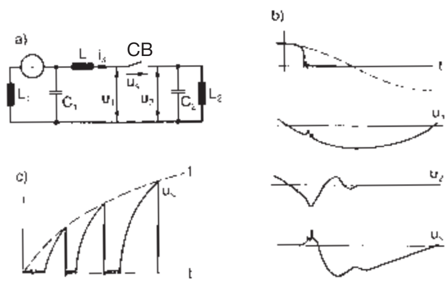
Interruption of small inductive currents, Fig. 10-16

Depending on the network configuration, interruption of small inductive currents, such as reactor coils or magnetizing currents from transformers, causes a rapid rise of the recovery voltage and under some circumstances high overvoltage resulting from current chopping before the natural zero crossing.

The overvoltages are also heavily dependent on the individual properties of the load circuit (inductance L_2 and capacitance C_2). There is no generally applicable test circuit that covers all load cases occurring in the network. However, in transmission networks an overvoltage of 2.5 pu is normally not exceeded.

Fig.10-16

Interruption of small inductive currents,
a) simplified equivalent circuit, b) curve of current and voltages with current chopping without restriking,
c) voltage curve when restriking occurs

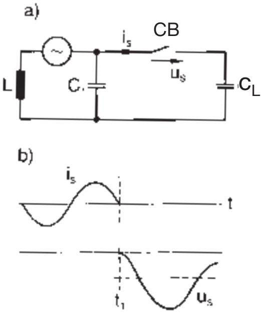


Switching of capacitive currents, Fig. 10-17

Since breakers that prevent restriking are generally available, this switching case does not cause extreme stress (see Fig. 10-12c). However, theoretically, repeated restriking can increase the voltage load to several times the peak value of the driving voltage.

Switching of unloaded lines and cables:

The capacitance per unit length of line or cable imposes a similar situation as with the switching of capacitors



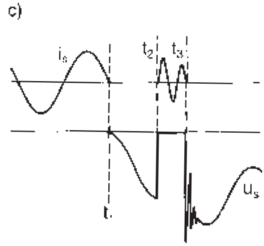


Fig.10-17

Breaking capacitive currents, a) Simplified equivalent circuit, b) Curves of current and voltage, c) Current and voltage characteristics when restriking occurs

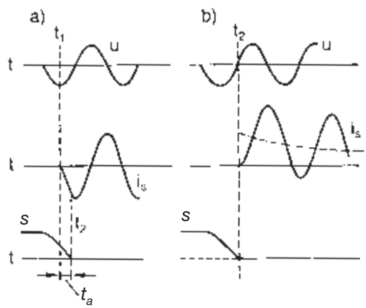
Closing of inductive currents, Fig. 10-18

The most important switching case of this type for switchgear technology is the closing on short circuit. The timing of the contact making with reference to the driving voltage determines the effects on the contact system. Fig. 10-18a shows the closing operation with pre-arcing on contact proximity in the area of the peak value of the persistent voltage and the associated symmetrical fault current curve. Fig. 10-18b shows the curve on contact making in the area of the zero crossing of the persistent voltage with the peak value increased to almost double the value (1.8 times) by a transient direct current component in the current path.

One breaker pole nearly always reaches this curve during three-pole switching with simultaneous closing time of the three breaker poles.

Fig.10-18

Making inductive currents:
t_1 = instant of pre-arcing
t_2 = instant of contact touch
S = contact path
a) symmetrical current with pre-arcing
t_a = pre-arcing duration
b) asymmetrical current with maximum peak current



Closing of unloaded overhead lines

Overhead lines can be shown in the electrical equivalent circuit diagram as combinations of series-connected inductances and capacitances to earth. During closing of long overhead lines, due to reflections of the voltage at the open end of the line, voltage increase of about 100% can occur. For this reason, at high transmission voltages and very long lines (> 300 km) circuit-breakers are fitted with closing resistors or closing is single-phase synchronized at the instant of zero crossing of the persistent voltage.

Short-circuit making and breaking tests

Making and breaking tests of circuit-breakers are performed in high-power test laboratories. The short-circuit current for the test is supplied by specially designed generators. The single-phase breaking power of a 420 kV circuit-breaker with a rated short-circuit current of 63 kA is approximately 15 000 MVA, which cannot be performed in a direct test circuit even by the most powerful test laboratory. Therefore, as early as the 1940s synthetic test circuits were developed for testing breakers with high short-circuit switching capability.

The basic reasoning behind a synthetic breaking test is that in the event of a short circuit, the short-circuit current and the recovery voltage do not occur simultaneously. This allows current and voltage to be supplied from two different sources. Fig. 10-19a shows the simplified test circuit for a synthetic test with current injection.

When test- and auxiliary-breakers are closed, the short circuit is initiated by closing the making switch. Auxiliary-breaker and test-breaker open at approximately the same time. Shortly before current zero of the current that is to be interrupted, the spark gap is ignited and an oscillating current of high frequency with an amplitude of some kA is superimposed on the short-circuit current in the test-breaker (Fig. 10-19b). The test-circuit elements must be selected so that the rate of current rise of the oscillating current at zero crossing coincides with the rate of rise of the high current.

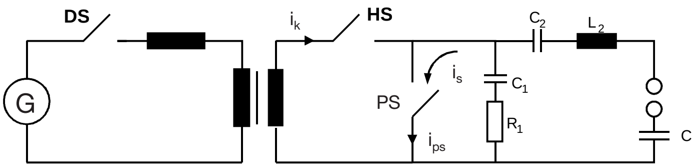


Fig.10-19a:

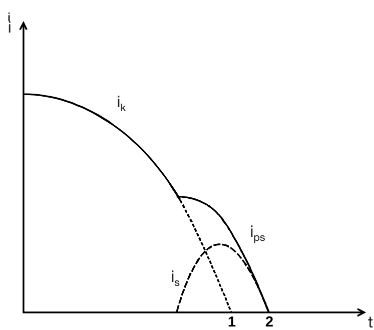
Synthetic test circuit with current injection
G: short-circuit generator, DS: making switch, HS: auxiliary breaker, PS: test breaker, i_k: short-circuit current, i_s: injection current, $i_{ps} = (i_k + i_s)$: test current through the test breaker, C, C_1, C_2, R_1, L_2: element of the synthetic circuit

An oscillogram of a make (c)/break (o) operation in a synthetic test circuit is shown in Fig. 10-19c.

Fig.10-19b:

Current versus time in the synthetic test circuit

The auxiliary breaker interrupts the short-circuit current i_k at zero crossing 1, the test breaker interrupts the test current i_{ps} at zero crossing 2, i_s is the injection current.



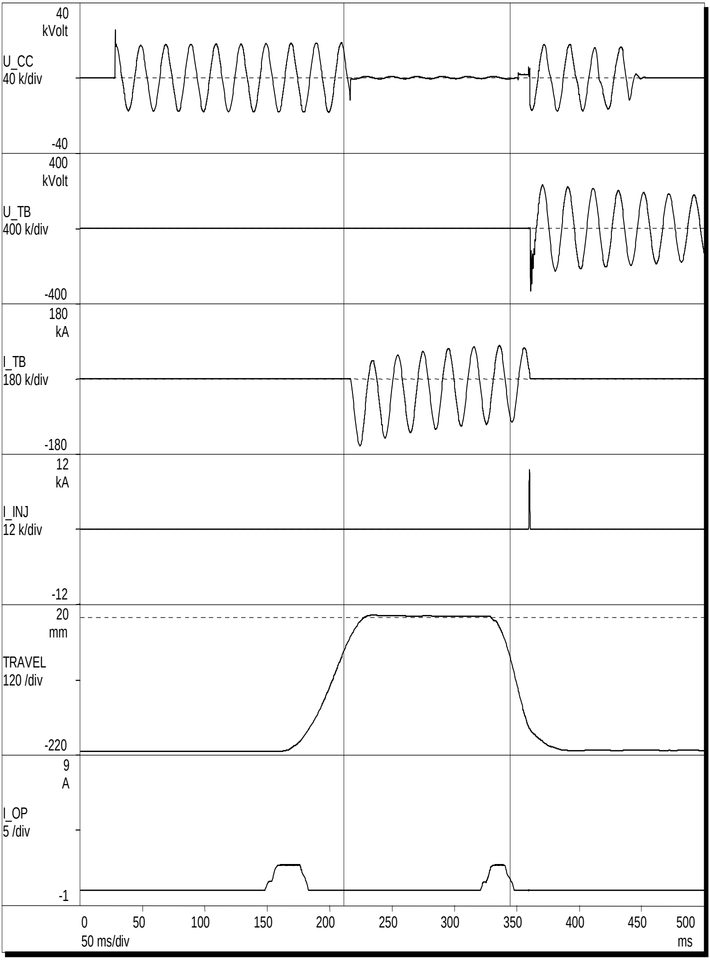


Fig.10-19c:

Oscillogram of a CO operation in the synthetic test circuit (half-pole test)

U_{CC}	*Generator voltage*	I_{INJ} (= i_S)	*injected oscillating current*
U_{TB}	*recovery voltage across the breaker gap*	*Travel*	*contact travel of breaker contacts*
I_{TB} (= i_{ps})	*current through the test object*	I_{OP}	*closing command and opening command*

10.4.4 Quenching media and operating principle

SF_6 gas

High-voltage circuit-breakers with SF_6 gas as the insulation and quenching medium have been in use throughout the world for more than 30 years. This gas is particularly suitable as a quenching medium because of its high dielectric strength and thermal conductivity (see also Section 11.2.2). Puffer-type breakers are used for high breaking capacity, while the self-blast technique is used for medium breaking capacity.

Puffer (piston) principle

Fig. 10-20 shows the design and operation of the interrupting chamber of the puffer principle. The extinction unit consists of the fixed contact and the moving contact with the blast cylinder. During the opening movement, the volume of the blast cylinder is steadily reduced and thereby increases the pressure of the enclosed gas until the fixed contact and the movable contact separate. The contact separation causes an arc to be drawn, which further increases the pressure of the SF_6 gas in the blast cylinder. At sufficiently high pressure, the compressed gas is released and blows the arc, depleting its energy and causing it to be extinguished. The nozzle shape of the two contacts provides optimum flow and quenching properties.

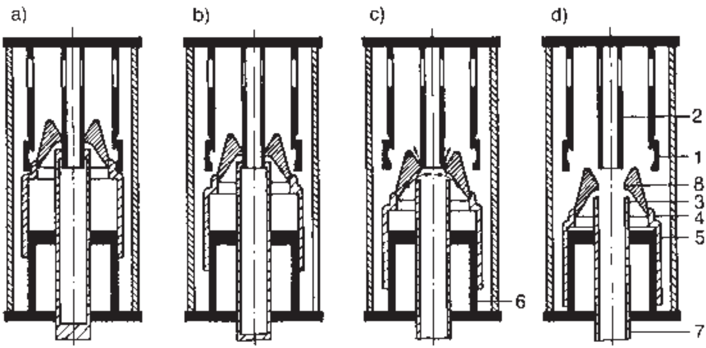


Fig.10-20

Puffer (piston) method showing the 4 stages of the opening process, a) closed position, b) beginning of the opening movement, c) arcing contacts separate, d) open position,
1 fixed continuous current contact, 2 fixed arcing contact, 3 movable arcing contact, 4 movable continuous current contact, 5 compression cylinder, 6 compression piston, 7 actuating rod, 8 quenching nozzle

Self-blast principle

In 1985, ABB introduced the self-blast quenching principle, which has been in use with SF_6 medium-voltage breakers for many years (see Fig. 8-15), in a modified form for HV circuit-breakers, without any need for a magnetic coil to rotate the arc. Fig. 10-21 shows the design and operation of the self-blast interrupting chamber up to 170 kV, 40 kA.

For small currents, the required extinction pressure is generated by compressing the gas in volume 5 as with a puffer-type breaker during the opening movement (Fig. 10-21 c). In contrast, for short-circuit currents the energy of the high-amp arc heats the quenching gas and increases its pressure in the heating volume 6 (Fig. 10-21 d). This overpressure does not affect the mechanism in any way. Its energy only needs to be dimensioned for switching normal operating currents.

Compared to the puffer principle, the self-blast principle only requires about 20% of the actuating energy for the same circuit-breaker performance data. The operational advantages are the compact mechanisms, low mechanical stresses on the overall system, low dynamic foundation loads, low noise level and generally improved reliability.

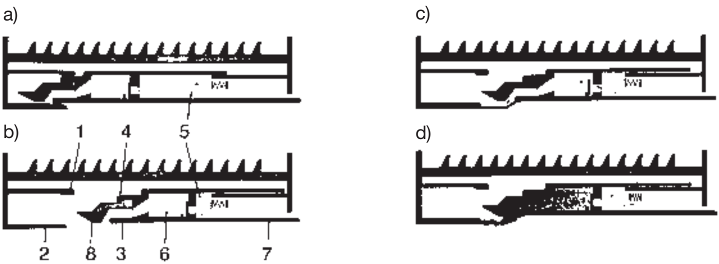


Fig.10-21

Self-blast principle for high-voltage circuit-breakers, a) closed position, b) open position, c) interruption of small currents (by the puffer method), d) interruption of short-circuit currents (by the self-blast method)
1 fixed continuous current contact, 2 fixed arcing contact, 3 movable arcing contact, 4 movable continuous current contact, 5 compression volume, 6 heating volume, 7 actuating rod, 8 quenching nozzle

The dielectric behaviour of the insulating media SF_6 gas, transformer oil, compressed air and air at atmospheric pressure is shown in Fig. 10-22.

The external dielectric strength of the interrupting chamber depends on the pressure of the ambient air, but not on the SF_6 gas pressure inside the chamber. The SF_6 gas pressure and the contact distance determine the dielectric strength inside the chamber.

Fig. 10-23 shows the current status of interrupting chamber breaking capacity of the ABB outdoor circuit-breakers

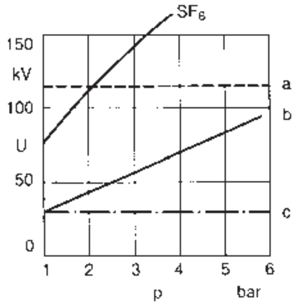


Fig.10-22

General dielectric behaviour of various insulation materials; breakdown strength U (a.c. voltage) with electrode distance 38 mm in function of the pressure p, a transformer oil, b compressed air, c reference line of air at atmospheric pressure

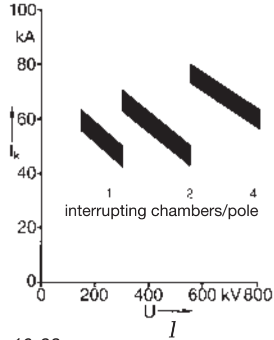


Fig.10-23

Interrupting chamber switching capacity U = rated voltage I_k = rated short-circuit breaking current

Oil

Up to about 1930, HV circuit-breakers were exclusively of the bulk-oil circuit-breaker type. The oil was used for insulation and arc extinction. The breaking arc heats the oil in its vicinity, induces an oil flow and causes the arc extinction. The minimum-oil breakers with a small volume of oil in the quenching chamber provided great advantages compared with the bulk-oil circuit-breakers with their large volume of oil. The arc also heats the oil in this type of breaker and extinguishes the arc in this way. When breaking small currents, the arc extinction is supported by pump action.

Compressed air

Until the end of the 1970s, air-blast breakers using compressed air as a quenching, insulation and actuating medium were widely used. They contain the quenching medium at a pressure of up to around 30 bar in the breaker tank and inside the breaker. At the instant of contact separation, compressed air is forced through the nozzle-shaped contacts thereby extinguishing the arc and establishing the insulating distance. Compressors, storage and distribution systems supply the air-blast breaker with clean and dry compressed air.

10.4.5 Operating mechanism and control

Operating mechanisms for circuit-breakers consist of energy storage unit, controller unit and power-transmitter unit. The energy-storage unit must be suited for storing energy for an autoreclosure cycle (OCO). This can be performed with different actuating systems.

Spring-operated mechanism

The spring-operated mechanism is a mechanical actuating system using a powerful spring as energy storage. The spring is tensioned with an electric motor and held by a latch system. When the breaker trips, the latch is released by magnetic force, and the spring energy moves the contacts by mechanical power transmission.

Pneumatic operating mechanism

The pneumatic operating mechanism operates by compressed air, which is fed directly to the breaker from a compressed air tank used as energy storage. Solenoid valves allow the compressed air into the actuating cylinder (for closing) or into the atmosphere (for opening). The compressed-air tank is replenished by a compressor unit. Compressed-air mechanisms have not been used for ABB circuit-breakers for many years.

Hydraulic operating mechanism

The hydraulic operating mechanism has a nitrogen accumulator for storing the actuation energy. The hydraulic fluid is pressurized by a compressed cushion of nitrogen. A hydraulic piston transmits the power to actuate the breaker contacts.

The mechanism operates on the differential piston principle. The piston rod side is permanently under system pressure. The piston face side is subject to system pressure for closing and pressure is released for opening. The system is recharged by a motor-driven hydraulic pump, which pumps oil from the low-pressure chamber to the nitrogen storage chamber. The hydraulic mechanisms from ABB were replaced by the hydraulic spring-operated mechanism in 1986.

Hydraulic spring -operated mechanism

The hydraulic spring-operated mechanism is an operating mechanism combining hydraulics and springs. Energy is stored in a spring set which is tensioned hydraulically. Power is transmitted hydraulically with the actuating forces for the circuit-breaker contacts being generated as with a hydraulic mechanism by a differential piston integrated into the actuation unit. As an example, Fig. 10-24 shows a section through the hydraulic spring operating mechanism type HMB-1.

The hydraulic stored energy spring mechanisms from ABB are available in various sizes (Fig. 10-25). Circuit-breakers for three-phase autoreclosing are fitted with a common operating mechanism for all three poles. With the mechanism of the “HMB-S” series, the individual poles of the circiut-breaker can be operated separately, with no need for each pole to have its own mechanism. All the operating mechanisms are designed in such a way that there are no external tube connections whatsoever.

The hydraulic spring operating mechanism offers the following advantages:

- temperature-independent disc-spring set, allowing the lowest possible oil volume (example: < 1.5 litres for the HMB-1)
- compact
- high repeat accuracy of operating times
- integrated hydraulic damping
- high mechanical endurance
- easily adaptable to different breaker types.

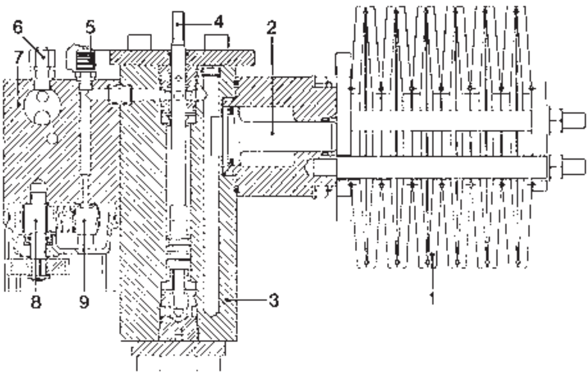


Fig.10-24

Section through the hydraulic spring operating mechanism for SF_6 self-blast breakers, 1 Springs, 2 Spring piston, 3 Actuating cylinder, 4 Piston rod, 5 Measuring connection, 6 Oil filler connection, 7 Pump block, 8 Pump drive shaft, 9 Pump unit

Motorized operating mechanism

The MOTOR DRIVE motorized operating mechanism is the result of over 100 years of experience at ABB in the development, production and servicing of hight voltage circuit-breakers and operating mechanism in use worldwide and meeting the highest demands:

A digitally controlled motor moves the contacts in the interrupter. The only remaining mechanical part is the crank which transforms the rotary motion of the motor into a thrust motion of the circuit-breaker contacts. This also provides for dead centre locking of the closed circuit-breaker, ensuring that it remains closed if the mechanism's energy is lost.

The energy of the MOTOR DRIVE operating mechanism is stored electrically in a capacitor bank. On tripping of the circuit-breaker, a power electronics unit applies the stored energy to the motor. A high resolution optical position encoder which continuously feeds the position of the operating mechanism back to the controller is integrated in the motor, ensuring that the motorized mechanism exactly follows the digitally programmed motion curve. At the end of the motion, the motor is electrically braked and the energy fed back into the system.

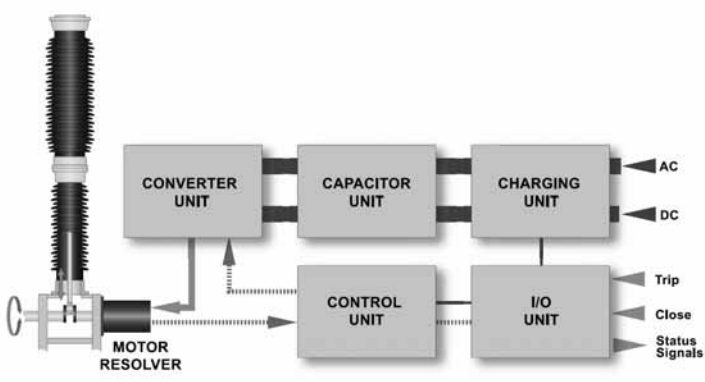


Fig. 10-25

Control circuit of the MOTOR DRIVE operating mechanism

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All processes, such as the charging of the capacitor by the universal voltage power pack, and the charging condition of the energy store, are permanently monitored.

Advantages of the MOTOR DRIVE motorized operating mechnism:

- Minimum number of moving parts
- precise, programmed contact movement
- Continuous and active self-monitoring
- Very quiet and wear-free function
- Low and even energy consumption

Requirements for electrical control of circuit-breakers

Phase-discrepancy monitoring

Breakers with a single-phase mechanism are fitted with phase-discrepancy monitoring.

If the three breaker poles are in different positions during a three-pole closing, the phase-discrepancy monitoring detects the differential position. All three breaker poles are tripped together after a preset waiting time of 2 seconds.

Anti-pumping control

The anti-pumping control prevents repeated, undesired operation of one or more breaker poles if an existing OFF command is followed by several ON commands. The breaker must then close only once followed by a lockout, i.e. it must remain in the OFF position regardless of whether and how long control commands are applied.

Non-stop motor operation

Depending on the design and the type of switching cycle performed, the pump or the compressor requires a specific period to restore the consumed energy. If there is a leak in the pressure system, the motor will run more often or will run continuously. Continuous running is detected and reported as a fault.

SF_6 gas monitoring

The breaking capacity of a circuit-breaker is dependent on the gas density in the breaker chamber. This is measured by a temperature-compensated pressure gauge. If the gas pressure falls to a specified value, an alarm is triggered, and if it falls further to a lower limit value, the breaker is blocked.

Local/remote control

To allow work on the breaker, it can generally be controlled from the local control cubicle; control can be switched from remote to local by a selector switch.

Monitoring of the operating mechanism energy

In pneumatic and hydraulic operating mechanisms the air pressure or fluid pressure is monitored and controlled by a multiple pole pressure switch. The pressure switch performs the following functions:

- control of the compressor or pump motor
- OFF blocking, ON blocking and autoreclosure blocking, depending on the instantaneous mechanism pressure

Pressure control is not required in hydraulic stored energy spring mechanisms. Instead, they are fitted with a gate controller which monitors and controls the charging condition of the spring (spring travel) as a measure of the current energy content.

In mechanical stored energy spring mechanisms, the condition of the energy stored is signalled to the controller can measure the charging condition of the energy store directly.

Autoreclosing

A single- or three-pole autoreclosing is selected depending on the type of system earthing, the degree of interconnection, the length of the lines and the amount of infeed from large power plants. The trip commands of the network protection (overcurrent and line protection, Section 14.2) are accordingly evaluated differently for the tripping action of the circuit-breaker.

Circuit-breakers for three-pole autoreclosing only require one hydraulic spring mechanism with one actuation cylinder, allowing *one* tripping initiates the closing and opening of all poles.

For single phase autoreclosing these breakers are fitted with a separate operating mechanism for each pole, which can then be switched separately. When a hydraulic stored energy spring mechanism is used, one of type HMB-S with three operating cylinders which are activated separately can be fitted. In this way, each pole can be switched independently, even with only one mechanism. Single-phase autoreclosing is intended to trip short-time faults and restrict them in time and place without allowing larger system units to fail for any length of time. Single-pole tripping improves network stability and prevents the network from going out of phase. At the same time, breakers with single-pole autoreclosing can be operated as three-pole autoreclosing by opening and closing the three poles together.

Circuit-breakers with separate poles and single-pole actuation are equally suited for both single-pole and three-pole autoreclosing.

Synchronized switching

Synchronized switching of circuit-breakers in which every breaker pole is synchronously actuated by a suitable control unit at the instantaneous value of the current or the phase-to-earth voltage are becoming increasingly important. Examples of applications of synchronized switching include closing overhead lines under no load without closing resistors and switching capacitor banks in transmission networks.

10.5 Instrument transformers for switchgear installations

Instrument transformers are transformers used to feed measuring instruments, electricity meters, protection relays and similar equipment.

Their function is to transform high voltages and currents to values that can be unified or measured safely with low internal losses. With current transformers, the primary winding carries the load current, while with voltage transformers, the primary winding is connected to the service voltage. The voltage or the current of the secondary winding is identical to the value on the primary side in phase and ratio except for the transformer error. Current transformers operate almost under short-circuit conditions while voltage transformers operate at no-load. Primary and secondary sides are nearly always electrically independent and insulated from one another as required by the service voltage. Above a service voltage of 110 kV, instrument transformers are frequently manufactured as combined current and voltage transformers.

In modern substation and bay control systems, current and voltage transformers can be replaced by sensors. They offer the same accuracy as conventional instrument transformers. The output signal, A/D-converted, is processed by the digital bay control unit.

10.5.1 Definitions and electrical quantities

A distinction is made between transformers for measurement purposes used to connect instruments, meters and similar devices and transformers for protection needs for connection of protection devices.

Instrument transformers are classified according to their measurement precision and identified accordingly. They are used as shown in Table 10-2.

Table 10-2

Selection of instrument transformers by application

Application	VDE class	IEC class	ANSI class
Precision measurements and calibration	0.1	0.1	0.3
Accurate power measurement and tariff metering	0.2	0.2	0.3
Tariff metering and accurate measuring instruments	0.5	0.5	0.6
Industrial meters: voltage, current, power, meters	1	1	1.2
Ammeters or voltmeters, overcurrent or voltage relays	3	3	1.2
Current transformer protective cores	5P, 10P	5P, 10P	C, T
Combined CT / VT protective cores	3P, 6P	3P, 6P	1, 2

CAUTION: In Germany, transformers for billing purposes require PTB type approval and must be calibrated.

Definitions

Current transformer – IEC 60044-1

- Rated primary current: the value of the primary current on which the performance of the transformer is based.
- Rated secondary current: the value of the secondary current on which the performance of the transformer is based.
- Burden: impedance of the secondary circuit in ohms and power factor. The burden is usually expressed as apparent power in volt amperes, absorbed at a specified power factor and at the secondary rated current.
- Rated burden: the value of the burden on which the accuracy requirements of this specification are based.
- Rated output: the value of the apparent power (in volt amperes at a specified power factor), which the current transformer is intended to supply to the secondary circuit at the rated secondary current and with rated burden connected to it.
- Rated transformation ratio: the value of the rated primary current to the rated secondary current.
- Current error (ratio error): the error which a transformer introduces into the measurement of the current and which arises from the fact that the actual transformation ratio is not equal to the rated transformation ratio.

$$\text{Current error in \%} = \frac{(K_n \cdot I_s - I_p) \cdot 100}{I_p}$$

Here:

K_n rated transformation ratio
I_s actual primary current
I_p actual secondary current when I_p is flowing under the conditions of measurment

- Phase displacement: the difference in phase between the primary and secondary current vectors, the direction of the vectors being so choosen that the angle is zero for a perfect transformer.

  Note: the definition is strictly correct for sinusoidal currents only.

- Composite error: in its stationary state, the composite error ε_c based on the rms value of the primary current is the difference between
  a) the instantaneous values of the primary current
  b) the instantaneous values of the secondary current intensities multiplied by the rated transformation.

The positive signs of the primary and secondary current must be specified in accordance with the agreement on connection labels.

The composite error in general is expressed as a percentage of the rms values of the primary current intensity as given by the following equation.

$$\varepsilon_c = \frac{100}{I_p} \sqrt{\frac{1}{T} \int_0^T (K_N \cdot i_s - i_p)^2 \, d\,t}$$

Here:

K_n Rated transformation ratio of the current transformer
I_p r.m.s. value of the primary current
i_p Instantaneous value of the primary current
i_s Instantaneous value of the secondary current
T Duration of one cycle

- Rated instrument limit primary current (IPL): the value of the minimum primary current at which the composite error of the measuring current transformer is equal to or greater than 10 %, the secondary burden being equal to the rated burden.

  Note: the composite error should exceed 10 % to protect the device fed from the current transformer against the high current values occurring if there is a fault in the network.

- Instrument security factor (FS): the ratio of the rated instrument limit current to the rated primary current.

  Note: if a short-circuit current flows through the primary winding of the current transformer, the load on the instruments connected to the current transformer is smaller in proportion to smallness of the overcurrent limit factor.

- Accuracy limit factor: the ratio of the primary rated accuracy limit current to the primary rated current.
- Thermal rated continuous current: unless otherwise specified, the thermal rated continuous current intensity is equal to the primary rated current.
- Current transformer with extended current measuring range: the thermal rated continuous current must be equal to the extended primary rated current. Standard values: 120 %, 150 % and 200 %.
- Rated short-time thermal current: the rated short-time thermal current (I_{th}) must be given for every current transformer. (see definition in Section 2.1.28 in IEC 60044-1).

  Note: if a current transformer is a component of another device (e.g. switchgear installation), a time different from one second may be given.

- Rated peak short-circuit current: the value of the rated peak short-circuit current (I_{dyn}) must in general be 2.5 I_{th}. Only in the event of deviation from this value must I_{dyn} be given on the nameplate. (see definition in Section 2.1.29 in IEC 60044-1).

Voltage transformer – IEC 60044-2

- Rated primary voltage: the value of the primary voltage which appears in the designation of the transformer and on which its performance is based.
- Rated secondary voltage: the value of the secondary voltage which appears in the designation of the transformer and on which its performance is based.
- Rated transformation ratio: the ratio of the rated primary voltage to the rated secondary voltage.
- Burden: the admittance of the secondary circuit expressed in siemens and power factor lagging or leading.

  Note: The burden is usually given as apparent power in volt amperes, which is assumed at a specified power factor and secondary rated voltage.

- Rated burden: the value of the burden on which the accuracy requirements of this specification are based.
- Rated output: the value of the apparent power (in volt amperes at a specified power factor), which the transformer is intended to supply to the secondary circuit at the rated secondary voltage and with rated burden connected to it.
- Thermal limiting output: the value of the apparent power referred to rated voltage which can be taken from a secondary winding, at rated primary voltage applied, without exceeding the limits ot temperature rise of 5.4.

  Note 1: In this condition the limits of error may be exceeded.

  Note 2: In this case of more than one secondary winding, the thermal limiting output is to be given separately.

  Note 3: the simultaneous use of more than one secondary winding is not admitted unless there is an arrangement between manufacturer and purchaser.

- Rated thermal limiting output of windings for ground fault detection: the rated thermal limiting output of the winding for ground fault detection must be given in volt-amperes; the values must be 15, 25, 50, 70, 100 VA and their decimal multiples, based on the secondary rated voltage and a power factor of 1.

  Note: because the windings for ground fault detection are connected in the open delta, they are subject to load only in the event of malfunction.

The thermal rated burden rating of the winding for ground fault detection should be based on a load duration of 8 h.

- Rated voltage factor: the multiplying factor to be applied to the rated primary voltage to determine the maximum voltage at which a transformer must comply with the relevant thermal requirements for a specified time and with the relevant accuracy requirements.

– Voltage error (ratio error): the deviation of a voltage transformer when measuring a voltage resulting from the deviation of the actual transformation from the rated transformation. The voltage error is given by the equation below and expressed as a percentage.

$$\text{Voltage error in \%} = \frac{(K_n \cdot U_s - U_p) \cdot 100}{U_p}$$

Here:

K_n rated transformation ratio
U_p actual primary voltage
U_s actual secondary voltage when U_p is subject to measuring conditions.

– Phase displacement: the angular difference between the primary and secondary voltage vectors. The direction of the vector is specified so on an ideal voltage transformer the phase displacement is equal to zero. The phase displacement is considered positive when the secondary vector is ahead of the primary vector. It is usually expressed in minutes or in centiradians.

Note: the definition is strictly speaking only applicable to sinusoidal voltage

10.5.2 Current transformer

Current transformers must be capable of withstanding the rated voltages and overvoltages at the location where they are installed. Test voltages and procedures, dependent on the maximum equipment voltage, to which the current transformers are subjected in type or routine tests, are defined to demonstrate that capability. In addition, current transformers must withstand the current flowing in the network. The primary rated current which characterizes the current transformer should be selected at a level around 10% - 40% above the expected operating current. The rated current must be selected from the standard levels available.

Primary reconnection: Current transformers can be designed to be switchable for two or more primary currents. With primary reconnection, this is effected by series and/or parallel connection of two or more partial primary windings. The advantage is that the number of ampere turns remains constant at all ratios, which also leads to unchanged rated outputs and accuracy class ratings. It should however be noted that with series connection the rated short-time current for smaller transformation ratios is reduced relative to parallel connection.

Secondary tappings: For high primary currents and high rated short-time thermal currents, switchover can take place on the secondary side with additional tappings. In this case, the number of ampere turns is reduced, leading to reduced rated output, although the rated short-time current remains unchanged.

Selection of current transformers

The choice of a current transformer is based on the values of the primary and secondary rated current, the rated output of the transformer cores at a given accuracy class rating and the overcurrent limit factor (FS) or accuracy limit factor.

Selection of the values for the primary and secondary rated currents should be based on the standard levels (e.g. to IEC 60044). Secondary rated currents of 1A, 2A or 5A are available. Modern protection devices and measuring instruments have a relatively low burden, and so 1A is becoming the most frequently used secondary current. This secondary current, lower than 5A, reduces cable losses by a factor of 25 and allows smaller and less expensive current transformer cores to be used.

When selecting the burden and accuracy class, each transformer should be matched to the relevant application, so as to avoid overdimensioning. The required output data are dependent on the application and type of load:

Measuring instruments or meters, for instance for kW, kVar, A or kWh, measure under normal load conditions as a rule. These devices require high accuracy, a low burden and low saturation. They normally function in a range of 5-120% of the rated current in accordance with accuracy classes 0.2 or 0.5 (to IEC) and 0.3 or 0.6 (IEEE).

For protection relays and disturbance recorders, the information about the fault on the primary side has to be transmitted to the secondary side. Measurement under fault conditions in the overcurrent range requires lower accuracy, but the ability to transmit high fault currents which enable the protection relay to measure and selectively shut down the fault. Typical classes are 5P, 10P or TP (IEC) and C100-800 (IEEE).

Several measuring and protection cores can be combined in each transformer.

Measuring and metering cores: In order to protect measuring and metering devices from damage in the case of a fault, measuring cores should go into saturation as early as possible. Typical overcurrent limit factors (FS) are, for example, 5 or 10. As the overcurrent limit factor only applies at rated burden, and in reality rises in approximately inverse proportion at lower burdens or lower transformer loads, it should be ensured that the operating burden of the connected instruments including the connecting lines required is equal to the rated burden of the transformer where possible, so as to protect the measuring devices from destruction. Otherwise, an additional burden should be connected in the secondary circuit.

See IEC 60044-1 for further details on the selection of classes, accuracy limits, rated outputs and designations.

Protective cores: Current transformers for protection purposes are operated at currents above the rated current. In contrast to measuring cores, they are to be selected in such a way that their composite error does not become too great in relation to the relay settings, even with short-circuit currents in the range in which the protection relays are intended to function precisely, e.g. at 6 – 8 times the rated current. It is therefore necessary to dimension the protective core in such a way that the product of rated output and overcurrent limit factor is at least equal to the product of the power requirement of the secondary transformer circuit at rated current and the required overcurrent limit factor. This is particularly important when verification of the thermal short-circuit stress indicates a large primary conductor cross-section. In this case, either a current transformer for higher rated current can be selected, where the primary winding number and also the output will be lower because the load current is less than the rated current, or a special transformer can be used.

Selection of current transformers to international standards (e.g. ANSI) in principle follows similar criteria.

Transformer dimensioning is made easier under the above specifications by using the following short overview with tables 10-3 to 10-3.

Definition and standardized values to IEC 60044-1

Measuring cores	Rated output:	2.5 – 5.0 – 10 – 15 – 30 VA;
	Burden power factor cos φ = 0.8	
	Classes:	0.1 – 0.2 – 0.5 – 1: valid in the range of 25 % and 100 % of the rated burden.
		0.2 s and 0.5 s: For special applications (electricity meters which measure correctly between 50 mA and 6 A, i.e. between 1% and 120% of the rated current of 5A
		3 – 5: Valid in the range 50% to 100% of the rated burden
	Label:	Measuring cores are identified by a combination of the rated output with the overcurrent limit factor and with the class, e.g.
		15 VA class 0.5 FS 10 15 VA class 0.5 ext. 150% (extended current measuring range)
Protective cores	Rated output:	preferably 10 – 15 – 30 VA
	Classes:	5 P and 10 P: The numbers identify the maximum permissible total error with rated accuracy limit current; the letter P stands for "protection”.
	Accuracy limit factors: 5 – 10 – 15 – 20 – 30	

When the current to be measured contains an exponentially falling direct current component with a set time constant, i.e. when asymmetrical short-circuit currents are to be transmitted, normal current transformer cores can no longer be used. Special current transformer cores with low rated induction, or with an air gap in the transformer core, are used for these applications. The selection is made by the user on the basis of the protection relays used. The applicable classes are defined in the standards (IEC 60044-6).

TPS: Closed core with low leakage flux. The transmission behaviour is defined by the secondary excitation characteristics and turns ratio error limits. No limit for remanent flux.

TPX: Closed core. Accuracy limit defined by peak instantaneous error during specified transient duty cycle. No limit for remanent flux.

TPY: Core with small air gap. Accuracy limit defined by peak instantaneous error during specified transient duty cycle. Remanent flux not to exceed 10% of the saturation flux.

TPZ: Core with large air gap. Accuracy limit defined by peak instantaneous alternating current component error during single energization with maximum d.c. offset at specified secondary loop time constant. Remanent flux to be practically negligible.

All the selection criteria named above also apply to current transformers in enclosed switchgear installations.

Table 10-3

Error limits for measuring cores as per DIN VDE 0414-1

Accuracy class	Current error in % at rated current percentage value						± phase displacement at rated current percentage value									
							in minutes					in centiradians				
	1	5	20	50	100	120%	1	5	20	100	120%	1	5	20	100	120%
0.1	–	0.4	0.2	–	0.1	0.1	–	15	8	5	5	–	0.45	0.24	0.15	0.15
0.2	–	0.75	0.35	–	0.2	0.2	–	30	15	10	10	–	0.9	0.45	0.3	0.3
0.5	–	1.5	0.75	–	0.5	0.5	–	90	45	30	30	–	2.7	1.35	0.9	0.9
1	–	3	1.5	–	1.0	1.0	–	180	90	60	60	–	5.4	2.7	1.8	1.8
3	–	–	–	3	–	3	–	–	–	–	–	–	–	–	–	–
5	–	–	–	5	–	5	–	–	–	–	–	–	–	–	–	–
0.2S	0.75	0.35	0.2	–	0.2	0.2	30	15	10	10	10	0.9	0.45	0.3	0.3	0.3
0.5S	1.5	0.75	0.5	–	0.5	0.5	90	45	30	30	30	2.7	1.35	0.9	0.9	0.9

NOTE: the limit values given for current error and phase displacement are generally applicable for any position of an outside conductor with a distance no less than the insulation distance in air for the maximum voltage for equipment (U_m).

Special application conditions, enclosed low service voltages in connection with high current values should be subject to separate agreement between manufacturer and purchaser.

The values for accuracy classes 0.2 S and 0.5 S only apply to current transformers with a secondary rated current of 5 A.

Table 10-4

Error limits for protective cores as per DIN VDE 0414-1

Accuracy class	Current error in % at primary Rated current	Phase displacement at primary rated current in minutes	in centiradians	Composite error in % at Rated accuracy limits
5 P	± 1	± 60	± 1.8	5
10 P	± 3	–	–	10

Definition and standardized values to ANSI/IEEE - Standard C 57.13

Table 10-5

Error limits for measuring cores to IEEE C57.13

Class	Times rated current	Power error %	Designation	Ohm	Power factor (PF)
0.3	1.0	0.3	B-0.1	0.1	0.9
	0.1	0.6	B-0.2	0.2	0.9
0.6	1.0	0.6	B-0.5	0.5	0.9
	0.1	1.2	B-0.9	0.9	0.9
1.2	1.0	1.2	B-1.8	1.8	0.9
	0.1	2.5			

Measuring core classes: 0.3 – 0.6 – 1.2
Designation: Measuring cores are identified by a combination of the class with the burden designation, e.g.
0.3 B-0.1 or 0.6 B-0.5

Table 10-6

Error limits for protective cores to IEEE C57.13

Class	Times rated current	Ratio error	Sec. terminal voltage	Designation	Power factor (PF)
C100* T100	20	10	100	B-1.0	0.5
C200 T200	20	10	200	B-2.0	0.5
C400 T400	20	10	400	B-4.0	0.5
C800 T800	20	10	800	B-8.0	0.5

*) C Calculated
T Tested

Classes / Error limits:

"C" and "T" at max. total error ~ 10% in the range 1–20 x primary rated current (corresponding to IEC Class 10 P 20).

With "C" transformers, the magnetic flux in the transformer core does not influence the transformation ratio. With "T" transformers, magnetic flux influence at a limited level is permissible, but must be verified by testing.

Secondary terminal voltage

The transformer must supply this voltage at the rated burden at 20 times the secondary rated current without exceeding the max. ratio error of 10%.

Secondary terminal voltage (V)	Rated burden
100	B-1
200	B-2
400	B-4
800	B-8

Designation

Protective cores are identified by class and secondary terminal voltage, e.g. C 100, a C transformer with secondary terminal voltage 100 V for rated burden B-1.

Design features of current transformers:

The primary winding is incorporated in the line and carries the current flowing in the network. It has various secondary cores. The current transformers are designed to carry the primary current with respect to magnitude and phase angle within preset error limits. The main source of transmission errors is the magnetizing current. To ensure that this and the resulting transmission errors remain small, the current transformers without exception are fitted with high-grade core magnets. The core materials are made of silicon-iron or high-alloy nickel-iron.

Depending on the design of the primary winding, current transformers are divided into various types. This basically depends on the application (high, medium or low voltage) and the service conditions (e.g. short-circuit current carrying capacity).

Table 10-7

Designs of current transformers

Insulation	Type	Voltage range	Application
Dry	Slipover, wound and cable current transformer	Low voltage	Indoor switchgear
Cast resin	Post-type and bushing transformer	Medium voltage	Indoor and SF_6 installations
Oil-paper / porcelain	Tank and top-core type transformers	High and extra-high voltage	Outdoor installations
SF_6/composite*)	Top-core type transformers	High and extra-high voltage	Outdoor installations

*) Composite material of fiberglass and silicone rubber

High voltage transformers are as a rule designed with oil-paper or SF6 insulation. Medium voltage transformers are preferably manufactured as post-type current transformers with standardized dimensions and as cast resin transformers for special applications.

Figure 10.26 shows the structures of various high voltage current transformers.

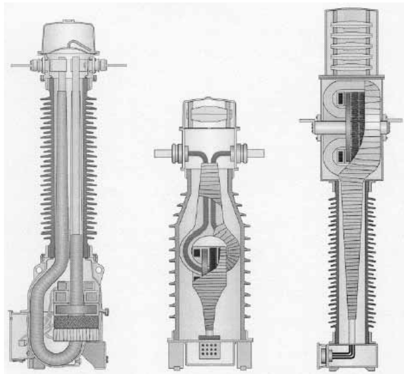


Fig. 10.26:

Tank current transformer, hybrid of top-core and tank-type current transformer, and top-core current transformer

Top-core current transformers are designed with a short primary conductor with low thermal losses, relatively high current and short-circuit current carrying capacity, and slim insulators. The location of the secondary cores at the top makes the centre of gravity very high, which leads to increased stress on the insulator with large cores.

Tank-type current transformers have a long primary conductor with higher thermal losses and limitations to the short-circuit current carrying capacity. The location of the secondary cores in the tank makes the centre of gravity very low, which is advantageous with large cores.

10.5.3 Voltage transformers

As with current transformers, voltage transformers also have to withstand the rated voltages and overvoltages at the service location. Test voltages and procedures, dependent on the maximum equipment voltage, to which the voltage transformers are subjected in type or routine tests, are defined to demonstrate that capability.

The decisive factors in selection of voltage transformers are the values of the primary and secondary rated voltage, the rated output and accuracy class of the transformer windings, and the rated voltage factor.

Selection of the values for the primary and secondary rated voltages should be based on the standard levels (e.g. to IEC 60044-2). Secondary rated voltages of 100/√3 or 110/√3 are generally used.

The rated voltage factor is dependent on the method of neutral point connection in the network. Standard values can be found in the specifications (IEC 60044-2). These are generally 1.5/30s in effectively earthed networks and 1.9/8h in isolated-neutral or compensated systems when earth faults are not automatically interrupted.

For earth fault detection, windings from a set of single-phase voltage transformers can be connected in an open delta to supply a displacement voltage.

Selection of voltage transformers

All voltage transformers must be suitable for measuring purposes. Certain types are also suitable for protection purposes. The burden and accuracy class are normally selected as follows:

1. If the burden consists of measuring and protection components, the higher accuracy class rating for the measuring equipment must be selected.

2. The selected burden must correspond to the total burden of the connected components.

Classes for measuring windings are specified in IEC 60044-2 for 80-120% of the rated voltage and 25-100% of the rated burden. Classes for protective windings are specified for 5% of rated voltage to rated voltage x rated voltage factor and 25-100% of the rated burden. The letter P is appended in these cases.

Transformer dimensioning is made easier under the above specifications by using the following short overview with tables 10-8 to 10-9.

Definition and standardized values to IEC 60044-2

Measuring windings	Rated output: 10 – 25 – 50 – 100 – 200 – 500 VA; Burden power factor cos $\varphi = 0.8$ Classes: 0.1 – 0.2 – 0.5 – 1 – 3.0
Label:	Measuring windings are identified by a combination of the rated output and the class, e.g. 100 VA class 0.5

10

Protective windings: All voltage transformers for protection purposes (except windings for earth fault detection) must comply with one of the accuracy classes for voltage transformers for measuring purposes, and also one for protection purposes. The standard values for voltage transformers for protection purposes are those of classes 3P and 6P.

Table 10-8

Limit values for voltage error and phase displacement for voltage transformers

		Phase displacement ±		
Class	Voltage error ± %	Minutes	Centiradians	Application
0.1	0.1	5	0.15	Measurement
0.2	0.2	10	0.3	Measurement
0.5	0.5	20	0.5	Measurement
1.0	1.0	40	1.2	Measurement
3.0	3.0	not specified	not specified	Measurement
3P	3.0	120	3.5	Protection
6P	6.0	240	7.0	Protection

Definition and standardized values to ANSI/IEEE – Standard C57.13

Table 10-9

Accuracy classes for voltage transformers to IEEE C57.13

Class	Range		Power error at metered load PF 0.6-1.0	Application
	Burden %	Voltage %		
0.3	0-100	90-110	0.3	Revenue metering
0.6	0-100	90-110	0.6	Revenue metering
1.2	0-100	90-110	1.2	Revenue
Standard burdens		VA	Power factor (PF)	
M		35	0.20	
W		12.5	0.10	
X		25	0.70	
Y		75	0.85	
Z		200	0.85	
ZZ		400	0.85	

Design features of voltage transformers:

Voltage transformers can fundamentally be divided into two groups: inductive and capacitive voltage transformers. Inductive voltage transformers are the most economical solution for voltages up to 145 kV, and above that level capacitive transformers have advantages.

High voltage transformers are generally designed as oil-paper insulated transformers. Medium voltage transformers are usually designed as post-type voltage transformers in single-pole (phase-earth) or two-pole (phase-phase) versions with standardized dimensions, or manufactured in cast resin for special applications.

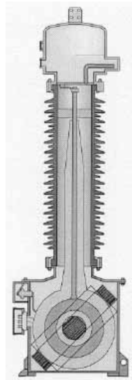


Figure 10.27

shows the structure of an inductive voltage transformer.

Apart from inductive voltage transformers, capacitive voltage transformers are available for higher system voltages up to 765 kV. They fundamentally consist of a capacitive divider and an inductive medium voltage transformer. The structure of a capacitive voltage transformer can be seen in the schematic diagram of figure 10.28.

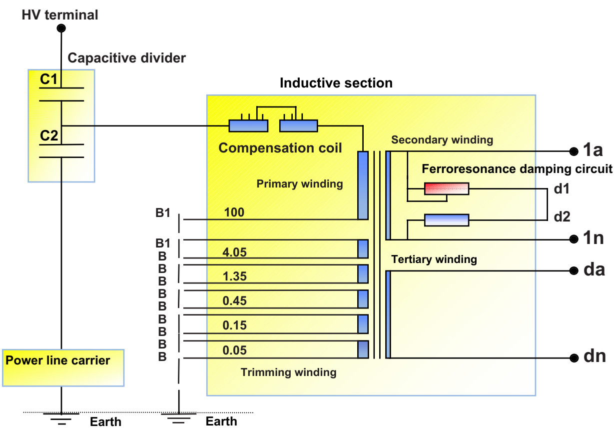


Fig. 10.28:

Schematic diagram of a capacitive voltage transformer

Capacitive voltage transformers are often the more cost-effective solution, especially for relatively high voltages, and at the same time have the advantage of permitting conducted high frequency applications, e.g. telephone, telecontrol and similar systems, to be connected. The additional components required (reactors, surge arresters) are accommodated in the terminal box.

Capacitive voltage transformers make no contribution to line discharge. Inductive voltage transformers have clear advantages here.

When selecting capacitive voltage transformers, primary and secondary rated voltage, rated frequency, rated output and class are the essential features. In addition, the rated thermal limiting output of a ground-fault detector winding, rated voltage factor and the specified load duration at increased voltage must be considered.

10.5.4 Combination transformers

Combination transformers: As an alternative to the use of individual current and voltage transformers, combination transformers in which the current and voltage transformer are accommodated in a common enclosure are often used, especially in 110 kV networks. Combination transformers are frequently less expensive, both in terms of equipment costs and the costs of installation (space required, bench and foundation).

The limits for measuring errors must be equivalent to those defined for individual transformers. The mutual influence of the current and voltage transformer must not lead to the error limits for voltage (or current) and phase angle of the class for the equipment concerned being exceeded within stipulated ranges (see IEC 60044-3).

The structure of a typical combination transformer for a rated voltage of 110 kV can be seen in figure 10.29.

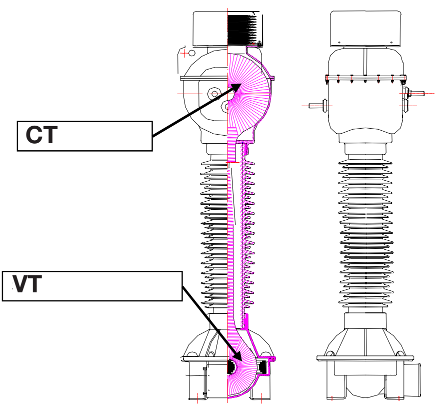


Fig. 10.29:

Schematic diagram of a combination transformer

10.5.5 Non-conventional transformers

In contrast to conventional transformers, non-conventional current and voltage transformers are distinguished by compact size and low weight. They are generally not saturable and have high transmission bandwidths. The measured values are best transmitted by fibre-optic cables, which are practically immune to electromagnetic fields (EMC). The non-conventional type of measured value acquisition and transmission requires only limited output in the area of 0.1 ... 5 VA on the secondary side.

Non-conventional transformers consist of a measurement recorder, a measured value transmission line bridging the potential difference between high voltage and ground potential and an electronic interface at ground potential for measured-value processing and connections to protection devices in the station control system.

Measurement recorders can be divided into active and passive systems depending on the method used.

Active non-conventional transformers

Current sensors based on the Rogowski coil principle are generally used for current detection. The sensor consists of an air-cored coil without ferrous core, and therefore undergoes no saturation. It is linear over the entire measuring range.

Advantages:

- High linearity
- Large dynamic range
- No saturation
- Small and light
- Only a few types for the entire range
- Simplified engineering and logistics

The output signal is a voltage which is proportional to the current. This voltage is integrated digitally and thus produces a signal equivalent to the current measured.

The current sensors are used for both measurement and protection. Three different sensor types (80 A, 300 A and 800 A) cover the range from 4 to 1600 A, i.e. 5...200 percent of rated current.

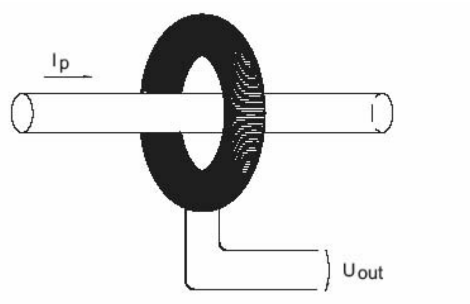


Fig. 10.30:

Rogowski coil

Voltage detection is generally performed with the aid of ohmic or capacitive voltage dividers.

Advantages:

- High linearity
- Large dynamic range
- No ferroresonance
- Small dimensions and light weight
- Only one type for the entire product range
- Simplified engineering and logistics

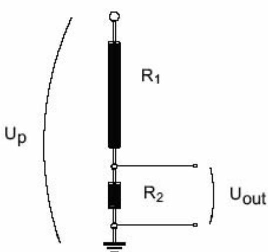


Fig. 10.31: Ohmic divider

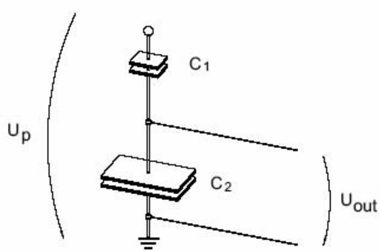


Fig. 10.32: Capacitive divider

Passive non-conventional transformers

Passive measurement recorders do not require auxiliary energy at high-voltage potential. They are normally completely constructed of dielectric materials, and are preferably used in high voltage applications.

Passive optical voltage transformers

Linear electro-optic effects (Pockel effect) linked to specific classes of crystals are used for voltage measurement with optical voltage transformers. The physical principle of the Pockel effect is a change of the polarization state of light that is sent within an electrical field through a transparent material. The change in polarization is linearly proportional to the electrical field applied.

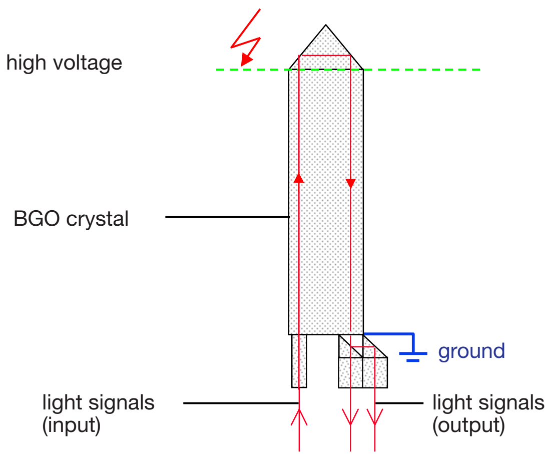


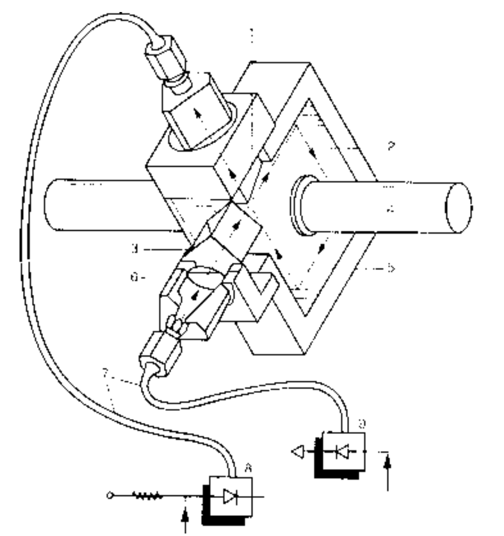
Fig. 10-33

Principle of light conduction in a crystal (BGO) for passive optical voltage measurement using the Pockel effect

Passive optical current transformer

An optical current transformer like the ABB-developed MOCT (magneto optical current transducer) uses the Faraday effect in crystalline structures for passive measurement of currents. Here, monochromatic light is sent polarized into a solid body of glass, which surrounds the current carrying conductor. Reflection from the bevelled corners of the glass container directs the light beam around the conducting line before it exits again on one side (Fig. 10-34).

The magnetic field around the conductor rotates the polarization plane of the light, whose phase difference is proportional to the magnetic field intensity H. The phase difference at the end of the path in the glass body is directly proportional to the current.



Legend

1 Analyzer
2 Light path in sensor
3 Polarizer
4 Primary conductor
5 Faraday sensor
6 Lens
7 fibre-optic cable
8 Detector
9 Light source

Fig. 10-34

Passive non-conventional current transformer (MOCT). The Faraday sensor around the conductor line is structured as a glass block.

Comparison of a non-conventional current transformer (left in the picture) with a conventional outdoor transformer with oil-paper insulation

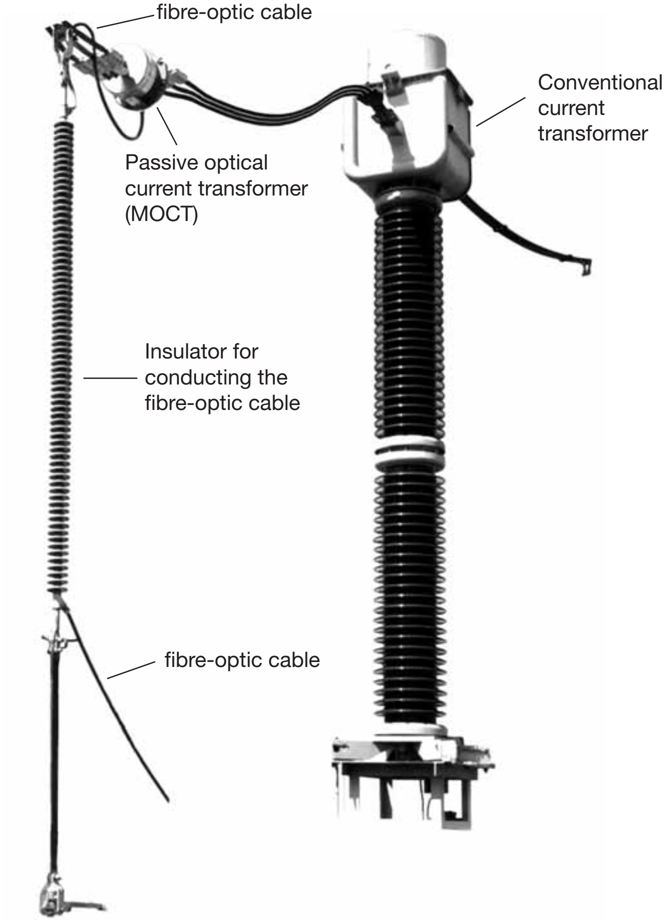


Fig. 10-35:

Comparison of size between non-conventional and conventional current transformers

10

Connection to protection technology

Devices and systems in conventional secondary technology are generally directly linked to the primary quantity with standardized current and voltage ports (typically 100 V or 1 A). The former specification of these ports is based on the requirements of analog secondary devices with high power requirements and the attempt to attain security with regard to electromagnetic interference by relatively high signal levels.

However, modern secondary devices, in general digital, only require a small part of the input power that was formerly required (typically 0.1 VA to 1 VA).

In non-conventional instrument transformers, the processing device sends a small signal that is generally suitable for digital secondary devices. However, if necessary, supplementary amplifier inserts can generate current and voltage signals suitable for the interfaces of conventional secondary technology.

10.6 Surge arresters

10.6.1 Design, operating principle

Today arresters are based on metal oxide (MO) resistors, which have an extremely non-linear U/I characteristic and a high energy-absorption capability. They are known as metal oxide surge arresters, MO arresters for short.

IEC 60 099-4 contains detailed information on the new arrester technology.

The MO arrester is characterized electrically by a current/voltage curve (Fig. 10-34). The current range is specified from the continuous operating range (range A of the curve, order of magnitude 10^{-3} A) to a minimum of the double value of the rated discharge current (order of magnitude 10^3 A). The MO arrester corresponding to the characteristic is transferred from the high-resistance to the low-resistance range at rising voltage without delay. When the voltage returns to the continuous operating voltage U_c or below, the arrester again becomes high-ohmic.

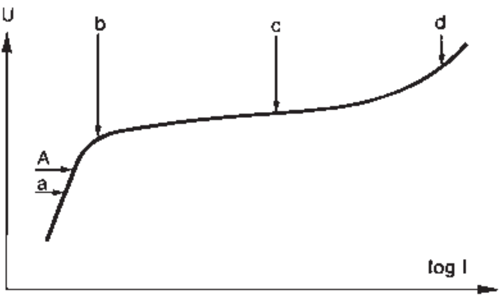


Fig. 10-34

Current-voltage characteristic of a metal oxide resistor; a Lower linear part, b Knee point, c Strongly non-linear part, d Upper linear part ("turn up" area), A Operating point (continuous persistent voltage)

The protective level of the MO arrester is set by its residual voltage U_P. The residual voltage is defined as the peak value of the voltage at the terminals of the arrester when a surge current flows. A surge current with a front time of about 1 µs, a time to half-value of up to 10 µs and a current of up to 10 kA represents very steep overvoltage waves, and the associated residual voltage is comparable to the front sparkover voltage of spark-gapped arresters.

A surge current with a front time of about 8 μs and a current intensity of up to 40 kA yields a residual voltage that is approximately equal to the protection level with lightning surge voltage. The current wave with a front time between 30 μs and 100 μs corresponds to a switching voltage pulse. The residual voltage with this wave form at 3 kA yields the protection level for switching voltages.

Surge arresters are protective devices that may be overloaded under extreme fault conditions. In such cases, e.g. when voltage leaks from one network level to the other, a single-phase earth fault occurs in the resistor assembly of the arrester. The pressure relief ensures that porcelain housings do not explode. The earth-fault current of the network at the arrester site must be less than the guaranteed current for the pressure relief of the relevant arrester. Fig. 10-35 shows the structural design of an MO arrester with a polymer housing.

Today, MO arresters for protection of medium-voltage equipment almost always have composite housings of silicon polymer. This insulation material allows the metal oxide resistors to be directly surrounded without gas inclusions. This type, in contrast to arresters with porcelain or other tube material, does not require a pressure-relief device for a possible overload. Because the polymeric arresters are substantially lighter, have a better response under contamination layer conditions and the arrester cannot fall apart in the event of an overload, this new technology is becoming more and more common even for arresters for high voltage.

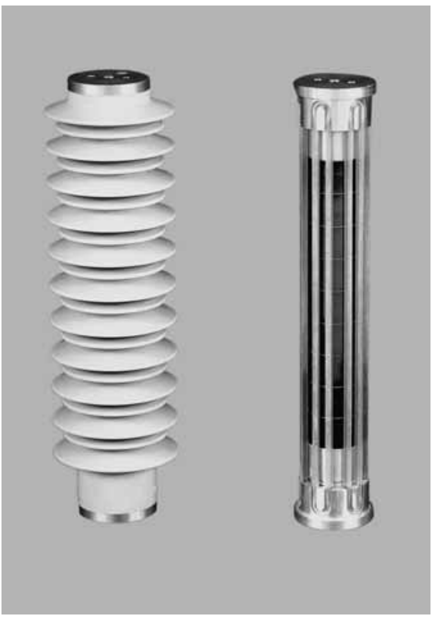


Fig.10-35

Cutaway view (principle design) of a metal oxide surge arrester, type POLIM-H

10.6.2 Application and selection of MO surge arresters

Surge arresters are used for protection of important equipment, particularly transformers, from atmospheric overvoltages and switching overvoltages. MO arresters are primarily selected on the basis of two basic requirements:

- the arrester must be designed for stable continuous operation,
- it must provide sufficient protection for the protected equipment.

Stable continuous operation means that the arrester is electrically and mechanically designed for all load cases that occur under standard operation and when system faults occur. This requires that the electrical and mechanical requirements are known as precisely as possible. The magnitude of the maximum power-frequency voltage, magnitude and duration of the temporary overvoltages and the anticipated stresses caused by switching and lightning overvoltages must all be known. In addition, the stress caused by short-circuit current forces and special environmental conditions, e.g. pollution, ambient temperatures over 45 °C, installation in earthquake regions etc., are very important.

When selecting the arrester by its electrical data, there must be an appropriate margin between the protection level of the arrester and the insulation levels standardized for the applicable operating voltage to meet the requirements of the insulation coordination as per IEC 60 071-1 (VDE 0111 Part 1) (Fig. 10-36).

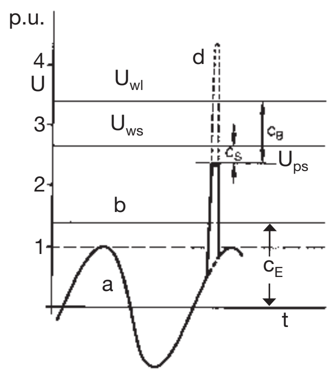
Parallel connecting of MO resistor columns allows every technically necessary dimension of the energy-absorption capability to be implemented at equivalent protection levels. Doubling the number of columns can reduce the protection level and almost double the energy-absorption capability.

IEC 60099-5 (VDE 0675 Part 5) outlines the correct selection of MO arresters.

Fig.10-36

Arrester selection for a low-resistance earthed network (c_E = 1,4) in range II (U_m ≥ 245 kV) as per IEC 60099-5 (VDE 0675 Part 5)

- *a* *maximum power frequency conductor-ground voltage in the normally operating network (1 p.u. = peak value)*
- *b* *peak value of the maximum temporary power frequency conductor-ground voltage at earth fault in an adjacent phase*
- c_E *earth fault factor (= 1.4)*
- *d* *switching impulse overvoltage (limited by arrester to U_{ps})*
- U_{ps} *switching impulse protection level of the arrester*
- U_{wL} *rated lightning impulse voltage for equipment-standardized values*
- U_{wS} *rated switching impulse voltage for equipment-standardized values*



C_B, C_S *safety margins*

For MO arresters, the *continuous operating voltage* U_c is defined as the maximum power frequency voltage that the arrester can withstand continuously. The peak value of the continuous operating voltage of the arrester must be higher than the peak value of the operating voltage. On one hand, it is determined by the power-frequency voltage that corresponds to the maximum voltage in the network; but on the other hand, possible harmonics of the voltage must be considered. In normal networks, a safety margin of 5% over the power frequency system voltage is sufficient.

The *rated voltage* U_r of an MO arrester is the reference value to the power frequency voltage versus time characteristic and is decisive for the selection of the arrester with reference to temporary overvoltages. During the operating duty test of an MO arrester type, a test voltage of U_r is applied immediately following the surge current for a period of 10 s to the test object.

U_r is the 10 s value in the power frequency voltage versus time characteristic of the arrester. Peak values of the permissible power-frequency alternating voltage for other periods (U_t , T_t) are taken from the characteristic submitted by the manufacturer or derived approximately for period T_t in s between 0.1 s and 100 s by calculation as in the following equation:

$$U_t = \sqrt{2}\, U_r \left(\frac{10}{T_t}\right)^m$$

m = arrester-specific exponent, average value 0.02

Possible causes of the occurrence of temporary overvoltages include

- Earth fault
- Load shedding
- Resonance phenomena and
- Voltage increases over long lines

The following selection recommendations can be formulated based on the neutral treatment in networks:

Arresters between line and earth

- In networks with automatic earth-fault interruption, the continuous operating voltage U_c of the arrester should be equal to or greater than the peak value of the maximum operating voltage of the network against ground divided by $\sqrt{2}$
- In networks with earth-fault neutralizing or isolated neutral point without automatic fault disconnection, the continuous operating voltage should be greater than or at least equal to the maximum operating voltage of the network.

Arresters between phases

- The continuous operating voltage must be at least 1.05 times the maximum service voltage.

Neutral-point arresters

- For networks with low-resistance neutral-point configuration, the continuous operating voltage U_c of the arresters is derived from the dielectric strength specified for the neutral point of the equipment.
- For networks with earth-fault compensation or with insulated neutral point, the continuous operating voltage should be at least equal to the maximum service voltage divided by $\sqrt{3}$

Table 10-13 shows recommended standard values for selecting MO arresters (under the asumption that no additional temporary overvoltages occur) for some current nominal system voltages and the earth-fault factors appearing there.

Table 10-13

Recommended values for MO arresters according to the continuous operating voltage U_c and the associated rated voltage U_r

Nominal system voltage kV	Phase arrester				Neutral-point arrester			
	at $C_E = 1.4$		at $C_E = \sqrt{3}$		at $C_E = 1.4$		at $C_E = \sqrt{3}$	
	U_c kV	U_r kV	U_c kV	U_r kV	U_c kV	U_r kV	U_c kV	U_r kV
6	–	–	7,2	9	–	–	> 4,7	> 5,9
10	–	–	12	15	–	–	> 7,8	> 9,75
20	–	–	24	30	–	–	> 15,6	> 12,5
30	–	–	36	45	–	–	> 23,4	> 29,3
110	75	126	123[1)]	144[1)]	50	78	72	84
220	160	216[2)]	–	–	60	108	–	–
380	260	360[2)]	–	–	110	168	–	–

1) Lower values are possible if the duration of the earth fault is accurately known.

2) Higher values are set for generator transformers.

After specifying the continuous operating voltage and the rated voltage of the arrester that is to be used, selection is based on the energy-absorption capability required by the system conditions (rated discharge current and line discharge class). The following selection recommendation for rated discharge current can be set as a general guideline:

Distribution networks of up to 52 kV

– sufficient under standard conditions	5 kA
– at higher lightning intensity, cable units, capacitors, specially important analogues	10 kA
– specially high lightning loads	20 kA
Transmission networks of up to 420 kV	10 kA
Transmission networks over 420 kV	20 kA

In specially supported cases, it may be necessary to determine the required energy-absorption capability more accurately, e.g. as follows

- Closing or reclosing long lines,
- Switching capacitors or cables with non-restrike-free switching devices,
- Lightning strikes in overhead lines with high insulation level or back flashovers near the installation site.

If the calculated energy content exceeds the energy quantity absorbed at the duty test of the arresters, an arrester with higher rated discharge current or parallel connected arresters must be selected.

Surge arresters are preferably installed parallel to the object to be protected between phase and earth. Because of the limited protection distance with steep lightning impulse voltages, the arresters must be installed immediately adjacent to the equipment that is to be protected (e.g. transformer) as much as possible. The size of the protection distance of an arrester is dependent on a whole series of influencing parameters. It increases as follows:

– the difference between rated lightning impulse voltage of the equipment and the protection level (U_{pl}) of the arrester,
– the limitation of the peak value of the incoming lightning surge voltage wave by the mast type of the overhead line before the substation (e.g. grounded cross-arms or timber masts),

but also from the point of view of the insulation coordination with

– the decrease of the lightning strike rate of the overhead line (e.g. shielding by overhead ground wire) and with

– the increase of the fault rate that is still considered acceptable for the equipment that must be estimated.

Examples for the size of protection ranges in outdoor switchgear installations for various rated system voltages under practice-relevant conditions are shown in Table 10-14. Permissible fault rates of 0.25% per year for the equipment and lightning strike rates of 6 per 100 km x year for the 24 kV overhead lines and of 2 per 100 km x year for the high-voltage lines are assumed.

Table 10-14

Guidance values for the protection range of MO arresters

Network nominal voltage kV	Arrester protection level kV	Rated lightning impulse withstand voltage kV	Protection distance m
24	80	125	3[1)]/15[2)]
123	350	550	24
420	900	1425	32

[1)] Overhead line with timber masts (without grounding)

[2)] Overhead line with grounded cross-arms

The ABB travelling wave program for testing larger switchgear installations can be used to calculate the temporal course of the voltage at all interesting points of the installation.

In overhead lines with cable feed, the travelling wave through the cable with overvoltages must be calculated by reflection in spite of the depression. Arrester A1 is to be provided for protection of the cable in short cable units ($l_k \leq 5$ m) and arrester A3 for protection of the transformer, see fig. 10-37. however, if $l_k > 5$ m, the cable must be protected on both sides with arresters A1 and A2. In this case, arrester A3 can only be omitted with the transformer if the protection range of arrester A2 is greater than l_1.

Cable units within an overhead line should be protected immediately adjacent to the two end seals with arresters.

Monitoring sytems (surge counters, tell-tale spark gap, leakage current measuring instrument) may be used to monitor surge arresters. They are installed in the ground conductor of the arrester that is to be monitored; the arresters must be installed insulated against ground.

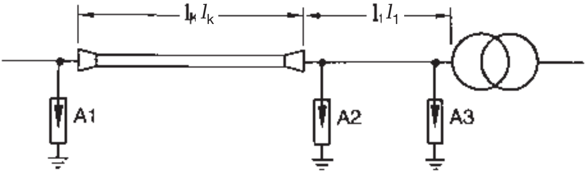


Fig.10-37

Overvoltage protection of the cable link of overhead lines, l_K: length of cable unit, l_1: distance cable / transformer, A1 & A2 arresters for protection of the cable, A3 arrester for protection of the transformer

11 High-Voltage Switchgear Installations

11.1 Summary and circuit configuration

11.1.1 Summary

A switchgear installation contains all the apparatus and auxiliary equipment necessary to ensure reliable operation of the installation and a secure supply of electricity. Three-phase a.c. high-voltage switchgear installations with operating voltages of up to 800 kV are used for distributing electricity in towns and cities, regions and industrial centres, and also for power transmission. The voltage level employed is determined by the transmission capacity and the short-circuit capacity of the power system.

Distribution networks are operated predominantly up to 123 kV. Power transmission systems and ring mains round urban areas operate with 123, 245 or 420 kV, depending on local conditions. Over very large distances, extra high powers are also transmitted at 765 kV or by HVDC (high-voltage direct-current) systems.

Switchgear installations can be placed indoors or outdoors. SF_6 gas-insulated switching stations have the important advantage of taking up little space and being unaffected by pollution and environmental factors.

Indoor installations are built both with SF_6 gas-insulated equipment for all voltage ratings above 36 kV and also with conventional, open equipment up to 123 kV. SF_6 technology, requiring very little floor area and building volume, is particularly suitable for supplying load centres for cities and industrial complexes. This kind of equipment is also applied in underground installations.

Outdoor switching stations are used for all voltage levels from 52 to 765 kV. They are built outside cities, usually at points along the cross-country lines of bulk transmission systems. Switchgear for HVDC applications is also predominantly of the outdoor type.

Transformer stations comprise not only the h.v. equipment and power transformers but also medium- and low-voltage switchgear and a variety of auxiliary services. These must additionally be accounted for in the station layout.

Depending on the intended plant site, the construction of a switchgear installation must conform to IEC requirements, VDE specifications (DIN VDE 0101) or particular national codes.

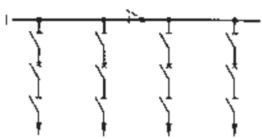
The starting point for planning a switchgear installation is its single-line diagram. This indicates the extent of the installation, such as the number of busbars and branches, and also their associated apparatus. The most common circuit configurations of high and medium-voltage switchgear installations are shown in the form of single-line diagrams in Section 11.1.2.

11.1.2 Circuit configurations for high- and medium-voltage switchgear installations

The circuit configurations for high- and medium-voltage switchgear installations are governed by operational considerations. Whether single or multiple busbars are necessary will depend mainly on how the system is operated and on the need for sectionalizing, to avoid excessive breaking capacities. Account is taken of the need to isolate parts of the installations for purposes of cleaning and maintenance, and also of future extensions.

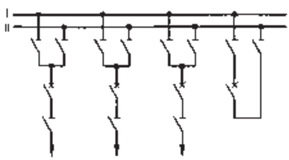
When drawing up a single line-diagram, a great number of possible combinations of incoming and outgoing connections have to be considered. The most common ones are shown in the following diagrams.

Common circuit configurations



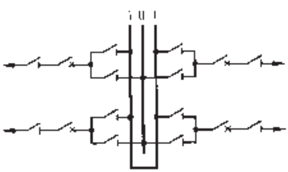
Single busbars

Suitable for smaller installations. A sectionalizer allows the station to be split into two separate parts and the parts to be disconnected for maintenance purposes.



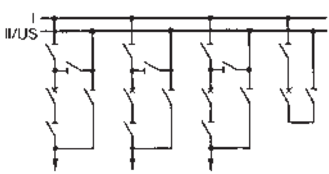
Double busbars

Preferred for larger installations. Advantages: cleaning and maintenance without interrupting supply. Separate operation of station sections possible from bus I and bus II. Busbar sectionalizing increases operational flexibility.



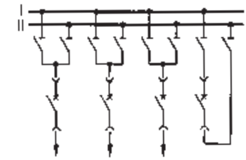
Double busbars in U connection

Low-cost, space-saving arrangement for installations with double busbars and branches to both sides.



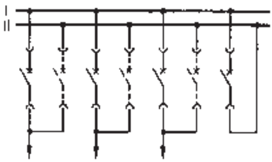
Composite double bus/bypass bus

This arrangement can be adapted to operational requirements. The station can be operated with a double bus, or with a single bus plus bypass bus.



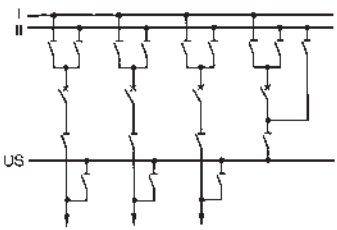
Double busbars with draw-out circuit-breaker

In medium-voltage stations, draw-out breakers reduce downtime when servicing the switchgear; also, a feeder isolator is eliminated.



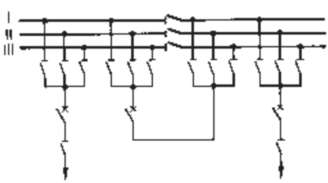
Two-breaker method with draw-out circuit-breakers

Draw-out circuit-breakers result in economical medium-voltage stations. There are no busbar isolators or feeder isolators. For station operation, the draw-out breaker can be inserted in a cubicle for either bus I or bus II.



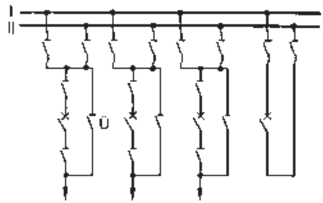
Double busbars with bypass busbar (US)

The bypass bus is an additional busbar connected via the bypass branch. Advantage: each branch of the installation can be isolated for maintenance without interrupting supply.



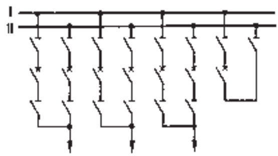
Triple (multiple) busbars

For vital installations feeding electrically separate networks or if rapid sectionalizing is required in the event of a fault to limit the short-circuit power. This layout is frequently provided with a bypass bus.



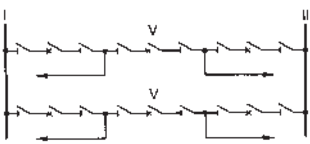
Double busbars with shunt disconnector

Shunt disconnector “U” can disconnect each branch without supply interruption. In shunt operation, the tie breaker acts as the branch circuit-breaker.



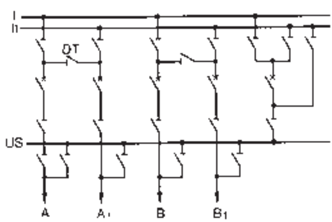
Two-breaker method with fixed switchgear

Circuit-breaker, branch disconnector and instrument transformers are duplicated in each branch. Busbar interchange and isolation of one bus is possible, one branch breaker can be taken out for maintenance at any time without interrupting operation.



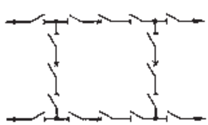
1 ½-breaker method

Fewer circuit-breakers are needed for the same flexibility as above. Isolation without interruption. All breakers are normally closed. Uninterrupted supply is thus maintained even if one busbar fails. The branches can be through-connected by means of linking breaker V.



Cross-tie method

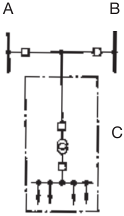
With cross-tie disconnector “DT”, the power of line A can be switched to branch A_1, bypassing the busbar. The busbars are then accessible for maintenance.



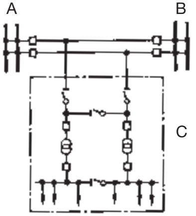
Ring busbars

Each branch requires only one circuit-breaker, and yet each breaker can be isolated without interrupting the power supply in the outgoing feeders. The ring busbar layout is often used as the first stage of 1 ½-breaker configurations.

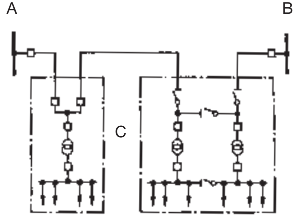
Configurations for load-centre substations



Single-feed station



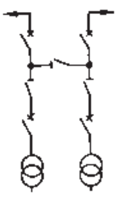
Double-feed station



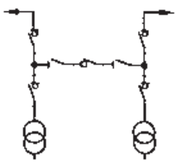
Ring stations

A and B = Main transformer station, C = Load-centre substation with circuit-breaker or switch disconnector. The use of switch-disconnectors instead of circuit-breakers imposes operational restrictions.

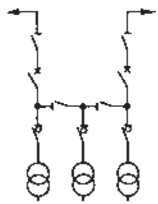
Switch-disconnectors are frequently used in load-centre substations for the feeders to overhead lines, cables or transformers. Their use is determined by the operating conditions and economic considerations.



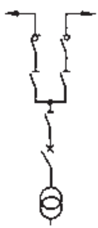
H connection with circuit-breakers



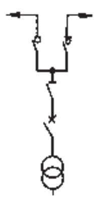
H connection with switch-disconnectors



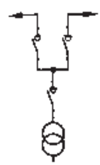
H connection with 3 transformers



Ring main cable connection allowing isolation in all directions

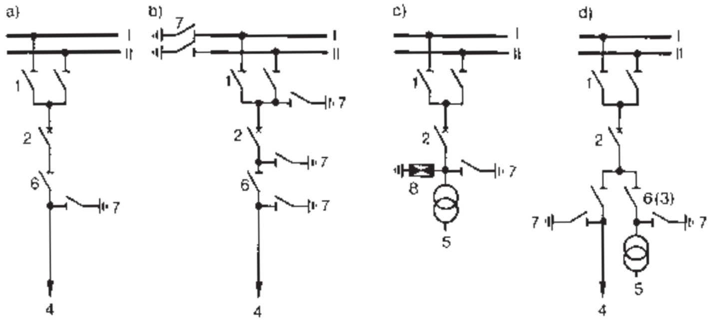


Simple ring main cable connection



Cable loop

Branch connections, variations a) to d)



1 Busbar disconnector, 2 Circuit-breaker, 3 Switch-disconnector, 4 Overhead-line or cable branch, 5 Transformer branch, 6 Branch disconnector, 7 Earthing switch, 8 Surge arrester

a) Overhead-line and cable branches

Earthing switch (7) eliminates capacitive charges and provides protection against atmospheric charges on the overhead line.

b) Branch with unit earthing

Stationary earthing switches (7) are made necessary by the increase in short-circuit powers and (in impedance-earthed systems) earth-fault currents.

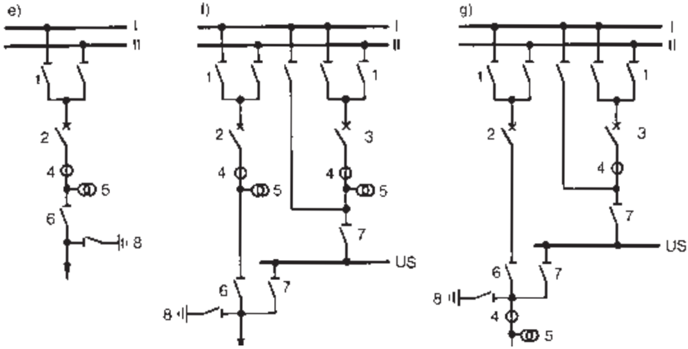
c) Transformer branches

Feeder disconnectors can usually be dispensed with in transformer branches because the transformer is disconnected on both h.v. and l.v. sides. For maintenance work, an earthing switch (7) is recommended.

d) Double branches

Double branches for two parallel feeders are generally fitted with branch disconnectors (6). In load-centre substations, by installing switch-disconnectors (3), it is possible to connect and disconnect, and also through-connect, branches 4 and 5.

Connections of instrument transformers, variations e) to g)



1 Busbar disconnectors, 2 Branch circuit-breaker, 3 Bypass circuit-breaker, 4 Current transformers, 5 Voltage transformers, 6 Branch disconnector, 7 Bypass disconnectors, 8 Earthing switch

e) Normal branches

The instrument transformers are usually placed beyond the circuit-breaker (2), with voltage transformer (5) after current transformer (4). This is the correct arrangement for synchronizing purposes. Some kinds of operation require the voltage transformer beyond the branch disconnectors, direct on the cable or overhead line.

f) Station with bypass busbar (US)

Instrument transformers within branch.

The instrument transformers cease to function when the bypass is in operation. Line protection of the branch must be provided by the instrument transformers and protection relays of the bypass. This is possible only if the ratios of all transformers in all branches are approximately equal. The protection relays of the bypass must also be set for the appropriate values. Maintenance of the branch transformers is easier and can be done during bypass operation. If capacitive voltage transformers are used which also act as coupling capacitors for a high-frequency telephone link, this link is similarly inoperative in the bypass mode.

g) Station with bypass busbar (US)

Instrument transformers outside branch.

In bypass operation, the branch protection relays continue to function, as does the telephone link if capacitive voltage transformers are used. It is only necessary to switch the relay tripping circuit to the bypass circuit-breaker (3). Servicing the transformers is more difficult since the branch must then be out of operation.

The decision as to whether the instrument transformers should be inside or outside the branch depends on the branch currents, the protection relays, the possibility of maintenance and, in the case of capacitive voltage transformers, on the h.f. telephone link.

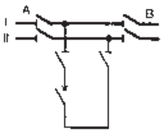
Busbar coupling connections

A and B = Busbar sections, LTr = Busbar sectioning disconnector

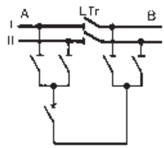
In the configurations earlier in this chapter, the tie-breaker branches are shown in a simple form. Experience shows, however, that more complex coupling arrangements are usually needed in order to meet practical requirements concerning security of supply and the necessary flexibility when switching over or disconnecting. This greater complexity is evident in the layouts for medium- and high-voltage installations.

Division into two bays is generally required in order to accommodate the equipment for these tie-breaker branches.

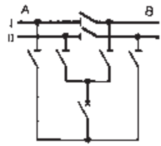
Double busbars



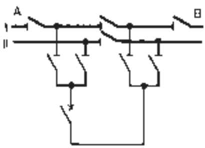
Bus coupling SSI/II for A or B



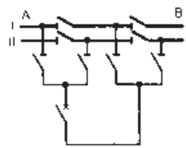
Section coupling for A-B Bus coupling SSI/II via disconnector LTr



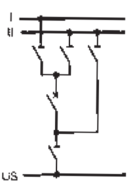
6-tie coupling Section coupling for A-B Bus coupling SSI/II for A or B



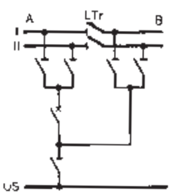
Section coupling for A-B Bus coupling SSI/II for A or B via tie-breaker bus II



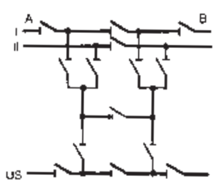
8-tie coupling Section coupling for A-B Bus coupling SSI/II for A or B



Bus coupling SSI/II Bypass (US) coupling SSI or II to bypass

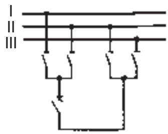


Section coupling for A-B Bus coupling SSI/II via LTr Bypass coupling A direct, B via LTr to bypass

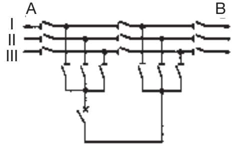


13-tie coupling Most flexible method of section, bus and bypass coupling

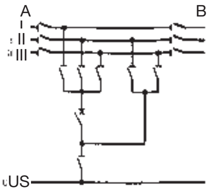
Triple busbars



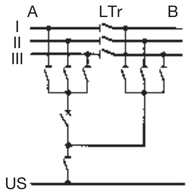
Bus coupling SSI/II/III



Section- and bus coupling for all possible ties between the 6 sections A-B



Bus coupling SSI/II/III for A or B
Bypass coupling SSI/II/III
to bypass (US) for A or B



Section coupling for A-B,
Bus coupling SSI/II/III via LTr,
Bypass coupling A SSI/II/III
to bypass,
Bypass coupling B/ bypass via LTr

11.2 SF_6 gas-insulated switchgear (GIS)

11.2.1 General

The range of application of SF_6 gas-insulated switchgear extends from voltage ratings of 72.5 up to 800 kV with breaking currents of up to 63 kA, and in special cases up to 80 kA. Both small transformer substations and large load-centre substations can be designed with GIS technology.

11

The distinctive advantages of SF_6 gas-insulated switchgear are: compactness, low weight, high reliability, safety against touch contact, low maintenance and long life. Extensive in-plant preassembly and testing of large units and complete bays reduces assembly and commissioning time on the construction site.

GIS equipment is usually of modular construction. All components such as busbars, disconnectors, circuit-breakers, instrument transformers, cable terminations and joints are contained in earthed enclosures filled with sulphur hexafluoride gas (SF_6).

The "User Guide for the application of GIS for rated voltages of 72.5 kV and above" issued by CIGRÉ Study Committee B3 includes comprehensive application information.

Up to ratings of 170 kV, the three phases of GIS are generally in a common enclosure, and at higher voltages the enclosures may be single-phase, three-phase or the two used in combination. The encapsulation consists of nonmagnetic and corrosion-resistant cast aluminium or welded aluminium sheet.

Table 11-1

Rating data and dimensions of the GIS range from 72.5 to 800 kV

Series	EXK-0	ELK-0	ELK-14	ELK-3	ELK-4
Service voltage in kV	72.5 – 145	123 – 170	245 – 362	362 – 550	800
Lightning impulse voltage in kV	650	750	1050	1550	2000
Breaking current in kA	40	40 – 63	40 – 63	40 – 63	40 – 50
Load current in A	2500	4000	4000	5000	6300
Bay width in m	1.0	1.2	1.7	3.1	4.5
Bay height in m	2.8	3.0	3.9	6.0	7.5
Bay depth in m	3.6	4.9	5.0	7.5	8.0
Bay weight in t	2.5	3.7	7.3	17.0	34.0

11.2.2 SF_6 gas as an insulating and quenching medium

Sulphur hexafluoride gas (SF_6) is employed as insulation in all parts of the installation, and in the circuit-breaker also for arc-quenching. SF_6 is an electronegative gas, its dielectric strength at atmospheric pressure is approximately three times that of air. It is incombustible, non-toxic, odourless, chemically inert with arc-quenching properties 3 to 4 times better than air at the same pressure. See also section 10.4.4.

Commercially available SF_6 is not dangerous, and so is not subject to the Hazardous Substances Regulations or Technical Regulations on Hazardous Substances (TRGS). SF_6 gas for switchgear must be technically clean and comply with IEC 60376. Gas returned from SF_6 installations and apparatus is dealt with in IEC 60480. SF_6 released into the atmosphere is a greenhouse gas with a very high potential effect. It is therefore mentioned in the UNFCCC Kyoto Protocol and is subject to national regulations on handling and documentation. With its contribution to the greenhouse effect below 0.1%, the proportion of SF_6 is low compared to that of the better known greenhouse gases (carbon dioxide, methane, nitrous oxide etc.). To prevent any increase of SF_6 in the atmosphere, its use should be confined to closed systems. Devices suitable for processing and storing SF_6 gas are available for this purpose. The gas pressure is monitored in the individually sealed gas compartments. GIS for high voltage is a sealed pressure system to IEC 60694.The low gas losses (below 0.5 % per year) are taken into account with the first gas filling. Automatic topping-up facilities are not necessary.

The insulating gas pressure is generally 350 to 450 kPa at 20 °C. In some cases this can be up to 600 kPa. The quenching gas pressure is 600 to 700 kPa. Outdoor apparatus exposed to arctic conditions contains a mixture of SF_6 and N_2, to prevent the gas from liquefying.

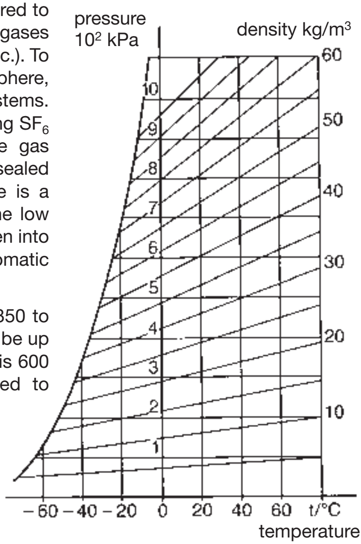


Fig. 11-1

p-t diagram for pure SF_6 gas

Arcing causes the decomposition of very small amounts of SF_6 gas. The decomposition products react with water, therefore the gas's moisture content, particularly in the circuit-breaker, is controlled by drying (molecular) filters. Careful evacuation before first gas filling and avoidance of moisture ingress during manufacture and installation greatly reduces the initial moisture content. Apart from its favourable physical and chemical properties, SF_6 is highly suitable for reuse. Used SF_6 is either reprocessed at site using the servicing equipment or returned to the manufacturer. Details can be found in the CIGRÉ B 3.02 "SF_6 Recycling Guide". Special steel cylinders and large containers are available for transport of used SF_6, marked with orange shoulders and labels.

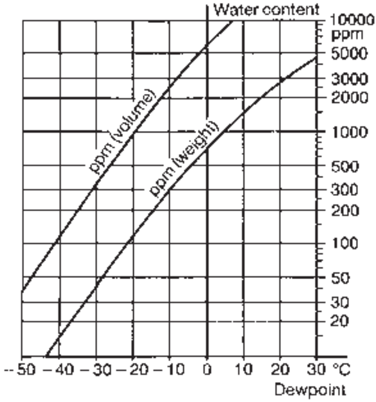


Fig. 11-2

Conversion of water vapour content into dewpoint for SF_6 gas at atmospheric pressure

11.2.3 GIS for 72.5 to 800 kV

SF_6 switchgear type EXK/ELK

For voltages from 72.5 to 800 kV ABB has five graduated module sizes of the same basic design available. The modular construction offers the advantages of quantity production, standard components, simple stocking of spares and uniform performance. By combining the various components of a module size, it is possible to assemble switching installations for all the basic circuit configurations in section 11.1.2.They are thus able to meet every layout requirement.

As a general recommendation, the intended location for totally enclosed equipment should comply with the requirements of DIN VDE 0101 for indoor switchgear installations. The buildings can be of lightweight construction, affording some protection against the outdoor elements. With minor modifications, GIS apparatus can also be installed outdoors.

Components

The busbars are segregated by barrier insulators at each bay and form a unit with the busbar disconnectors and the maintenance earthing switches. Assembly, conversion and repair work is assisted by elastic bellows or telescopic joints between the bays.

The circuit-breaker for relatively small rated voltages operates on the self-blast principle. The self-blast breakers use the thermal energy of the short-circuit switching arc to generate the breaker gas stream, saving up to 80% of the actuation energy. Depending on their size, the breakers have one to four breaker gaps per pole. They have single- or triple-pole actuation with hydraulic spring mechanisms. See also sections 10.4.4 and 10.4.5.

The disconnectors used are predominantly rod-type disconnectors. They are generally combined with maintenance earthing switches to ensure safe working conditions during maintenance of the circuit-breaker. The enclosures can be fitted with optional sight glasses if a visible contact gap is required.

The positively making earthing switch can close safely on the full short-circuit current. A stored-energy mechanism with charging motor gives it a high closing speed. Manual mechanisms are also available. Maintenance earthing switches, required for example for the performance of inspection work, are normally located on both sides of the circuit-breaker, mostly combined with disconnectors. They are switched by manual or motor-operated mechanisms, and only when de-energized. If a positively making earthing switch is fitted on the line side, the maintenance earthing switch behind the circuit-breaker is frequently omitted.

The current transformers for measuring and protection purposes are of the toroidal core type and can be arranged before or after the circuit-breaker, depending on the protection concept. Primary insulation is provided by SF_6 gas, so it is resistant to ageing. The secondary wiring is routed via a bushing plate into a terminal box.

Voltage transformers for measurement and protection can be equipped on the secondary side with two measuring windings and an open delta winding for detecting earth faults. Inductive voltage transformers are contained in a housing filled with SF6 gas. Foil-insulated voltage transformers are used, with SF_6 as the main insulation. The secondary windings are connected to a secondary terminal box with earthing terminals.

The cable sealing end can accommodate any kind of high voltage cable with conductor cross-sections up to 2000 mm^2, in accordance with specification IEC TS 60859. Isolating contacts and connection facilities are provided for testing the cables with d.c. voltage. If there is a branch disconnector, it is sufficient to open this during testing.

Plug-in cable sealing ends are available for connection of XLPE cables. They consist of gas-tight plug-in sockets, which are installed in the switchgear installation, and prefabricated plugs with grading elements of silicone rubber. Plug-in cable sealing ends do not have insulating compound. They are approximately half as long as the compound-filled end seal.

SF_6 outdoor bushings allow the enclosed switchgear to be connected to overhead lines or the bare terminals of transformers. To obtain the necessary air clearances at the outdoor terminals, the bushings are splayed using suitably shaped enclosure sections.

SF_6 oil bushings enable transformers to be connected directly to the switchgear, without outdoor link. The bushing is bolted straight to the transformer tank. A flexible bellows takes up thermal expansion and erection tolerances and prevents vibration of the tank due to the power frequency from being transmitted to the switchgear enclosure.

The surge arresters contain non-linear metal oxide resistors and therefore do not require spark quenching gaps. If the installation is bigger than the protected zone of the line-side arrester, arresters can also be arranged inside the installation. It is generally advisable to study and optimize the overvoltage protection system, particularly with distances of more than 50 m.

Each bay has a control cubicle containing all the equipment needed for control, signalling, supervision and auxiliary power supply.

The enclosure surrounds all the live components, which are supported by cast resin insulators and insulated from the enclosure by SF_6 gas. It consists of high-grade aluminium is of low weight so that only light foundations are required.

Barrier insulators divide the bay into separate gas compartments sealed off from each other. This minimizes the effects on other components during plant extensions, for example, or in case of faults, and also simplifies inspection and maintenance. The flanged joints contain non-ageing gaskets.

The circuit-breaker in figure 11-3 has one quenching chamber per phase. Depending on the rated voltage and breaking capacity, a breaker pole can have up to four quenching chambers connected in series, with parallel capacitors ensuring even voltage distribution. The breakers can handle breaking currents of up to 63 kA, and in special cases up to 80 kA.

Each switching device is provided with an easily accessible operating mechanism located outside the enclosure with emergency manual operation. The contact position can be seen on reliable mechanical position indicators.

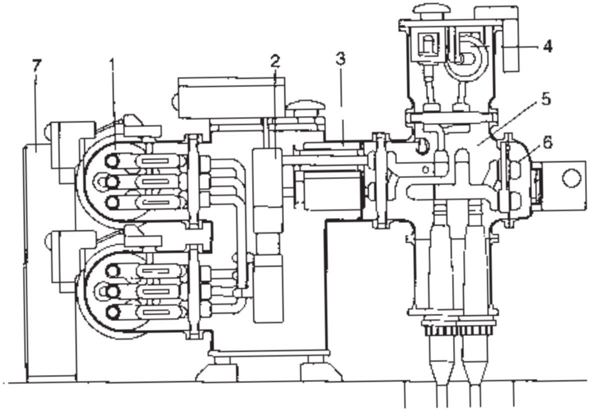


Fig. 11-3

SF_6 GIS for 72.5 to 145 kV, section through a bay, double busbar and cable branch 1 Busbar with combined disconnector and earthing switch, 2 Circuit-breaker, 3 Current transformer, 4 Voltage transformer, 5 Combined disconnector and earthing switch with cable sealing end, 6 Positively making earthing switch, 7 Control cubicle

11.2.4 SMART-GIS

A characteristic feature of SMART GIS is the use of digital bay control and protection units instead of conventional secondary technology. The digital bay control and protection unit performs the functions of protection, measurement, control and monitoring. Components which have already proved themselves in other applications and are manufactured in large numbers are preferably used here.

The digital bay control and protection unit allows the condition of the switchgear installation and its devices to be monitored. In this way, the maintenance requirement can be brought in line with the condition of the system and downtime significantly reduced. Data and parameters can be transmitted to the central automation system for analysis and processing. The diagnosis system therefore has up to date information at all times, and the scope and timing of necessary functional checks and inspections can be reliably determined.

Network faults can be recorded by the fault recorder function module. This facilitates clarification of the cause and development of faults and allows suitable preventive measures to be implemented where necessary.

A defined interface with the switchgear is required for performance of the protection, measurement and control functions. Both analog signals such as current and voltage, and binary signals such as switch positions, have to be transmitted.

Following the stipulations of the comprehensive IEC 61850 standard, intelligent electronic devices from various manufacturers can also be integrated in the system. Adapted combinations with older systems and, for example, protocol converters, are being used in a transitional period until all equipment to the current IEC standard is available.

11.2.5 Station arrangement

Gas supply

The final filling of the switchgear installation with technically clean SF_6 gas to IEC 60376 takes place after installation at site. This includes allowance for any minor leakage during operation (less than 0.5 % per year is guaranteed, and experience shows that the actual rate is lower). All the gas compartments have vacuum couplings, making sampling or occasional topping up very easy to perform while the station remains in operation. The gas is monitored by density relays mounted directly on the components. There are therefore no pipe connections or fittings.

Electrical protection system

A reliable protection system and safe electrical or mechanical interlocks provide protection for service staff when carrying out inspections and maintenance or during station extension, and safeguard the equipment against failure and serious damage.

The fast-response busbar protection system is recommended for protecting the equipment internally.

Earthing

Being electrically connected throughout, the switchgear enclosure acts as an earth bus. It is connected at various points to the station earthing system. 120 mm_ copper is laid for short-circuit currents up to 40 kA and 1 s short-circuit duration, and 2 x 120 mm_ for 3 s. For inspection or during station extension, parts of the installation can be earthed with suitably positioned maintenance earthing switches. Protective earthing for disconnected cables, overhead lines or transformers is provided by short-circuit make-proof earthing switches located at the outgoing feeders.

By short-circuiting the insulation between the earthing switch and metal enclosure during operation, it is possible to use the earthing switch to supply low-voltage power or to measure switching times and resistances. Thus there is no need to intervene inside the enclosure.

Erection and commissioning

Only lightweight cranes and scaffolding are required. Cranes of 5000 kg capacity are recommended for complete bays, and lifting gear of 1000 to 2500 kg capacity is sufficient for assembling prefabricated units.

Cleanliness on site is very important, particularly when erecting outdoors, in order to avoid dirt on the exposed parts of joints.

The completely installed substation undergoes a voltage test before entering operation. In accordance with IEC 62271-203, various procedures are recommended, depending on the rated voltage. Up to 170 kV procedure A: Power frequency voltage testing with 0.36 x rated lightning impulse withstand voltage Up. Over 245 kV procedure B (power frequency voltage testing with 0.36 x rated lightning impulse withstand voltage Up and partial discharge measurement with $1.2/\sqrt{3}$ times rated power frequency withstand voltage) or alternatively procedure C (power frequency voltage testing with 0.36 x rated lightning impulse withstand voltage Up and lightning impulse test with 0.8 x Up). For large switchgear installations and rated voltages above 245 kV, resonance test equipment is also frequently used.

11.2.6 Station layouts

The modular construction of SF_6 switchgear means that station layouts of all the basic circuit configurations shown in section 11.1 are possible.

For layout engineering, attention must be paid to DIN VDE 0101. Sufficiently dimensioned gangways must allow unhindered access to the components for erection and maintenance. Minimum gangway distances must be observed even when the control cubicle doors are open. A somewhat larger floor area, if necessary at the end of the installation, facilitates erection and later extensions or inspection.

A separate cable basement simplifies cable installation and distribution. Where outdoor lines terminate only at one side of the building, the required clearances between bushings determine the position of the switchgear tee-offs. These are usually at intervals of three to four bays. If overhead line connections are brought out on both sides of the building or are taken some distance by means of SF_6 tube connections, the respective feeder bays can be next to each other.

Installations of the model ranges EXK-01 for 72.5/123 kV and ELK-0 for 123/170 kV as shown in figure 11-4 are extremely compact because of the three-phase encapsulation of all components. Combining busbar, disconnector and earthing switch into one assembly reduces the depth of the building.

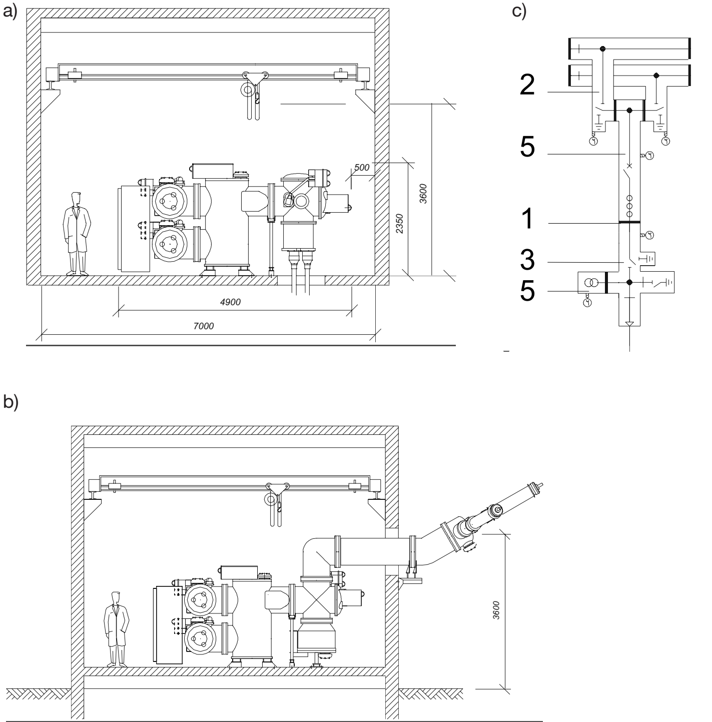


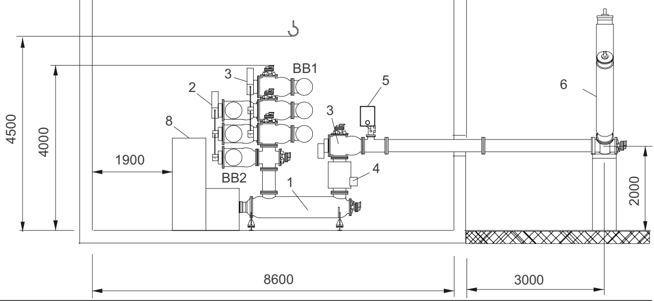
Fig. 11-4

SF_6 switchgear for 123 to 170 kV with double busbar

a) Section at cable bay, b) Section at overhead line bay, c) Circuit and gas diagram at a), 1 Barrier insulator, 2 Busbar gas compartment, 3 Feeder gas compartment, 4 Circuit-breaker gas compartment, 5 Voltage transformer

Installations for rated voltages of 245 kV or more are mostly single-phase encapsulated. This makes the components smaller and easier to handle. The busbars are partitioned at each bay so that if access to the busbar compartment is necessary (e.g. for station extension) only small amounts of gas have to be extracted and stored. Partitioning each bay avoids damage to adjacent bays in the event of a fault.

a)



b)

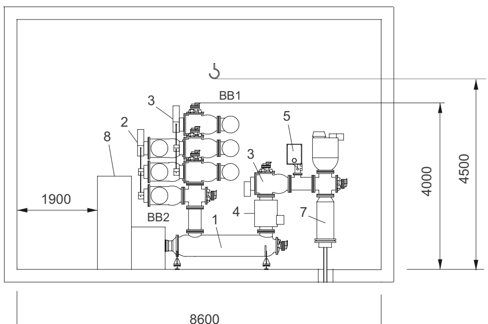


Fig. 11-5

SF6 switchgear for 245 to 362 kV with double busbar

a) Overhead line tee-off, b) Cable tee-off 1 Circuit-breaker, 2 Disconnector, 3 Disconnector and earthing switch, 4 Current transformer, 5 Positively making earthing switch, 6 Bushing, 7 Cable sealing end, 8 Control cubicle

The structural type with standing breaker is preferred in all installation layouts with three-phase encapsulation. This allows the interrupters to be easily removed from the circuit-breakers with a crane or lifting gear for inspection. In the single-phase enclosed designs, preference is given to horizontal circuit-breakers, as this arrangement has a favourable influence on the standardized components which can be used.

Single busbars, formerly used only for small installations, have become more important owing to the high reliability of the electrical apparatus and its outstanding availability. System operation has become less complicated by dividing the station into sections by means of sectionalizers.

Bypass buses with their disconnectors add another busbar system to stations with single or double busbars. The further busbar system can be activated by means of bypass coupler circuit-breakers. The bypass bus enables any circuit-breaker to be isolated without interrupting the feeders.

A special form of the single busbar is the H connection or double H connection. It is employed chiefly for load centres in urban and industrial areas.

Combined busbars: In GIS stations with double busbars the second busbar is occasionally used as a bypass bus with the aid of an additional disconnector, mounted in a space-saving manner, resulting in a so-called combined busbar. This greatly improves the station availability at little extra cost.

11.3 Outdoor switchgear installations

11.3.1 Requirements, clearances

The minimum clearances in air and gangway widths for outdoor switching stations are as stated in DIN VDE 0101 or specified by IEC. They are listed in the rated insulation levels as per IEC 60071-1 (VDE 0111 Part 1) (see Table 4-10 in Section 4.6.1). Where installation conditions are different from the standardized atmospheric conditions, e.g. installations at high altitudes, they must be taken into account by the atmospheric correction factor by determining the required withstand voltage in the course of the insulation coordination (compare Section 4.1).

Where phase opposition cannot be ruled out between components having the same operating voltage, the clearances must be at least 1.2 times the minimum values. The minimum distance between parts at different voltage levels must be at least the value for the higher voltage level.

When wire conductors are used, the phase-to-phase and phase-to-earth clearances during swaying caused by wind and short-circuit forces are allowed to decrease below the minimum values. The values by which the clearances are permitted to extend below the minima in this case are stated in DIN VDE 0101, Para. 4.4.

Equipment for outdoor switching stations is selected according to the maximum operating voltage on site and the local environmental conditions. The amount of air pollution must be taken into account, as on outdoor insulators, it can lead to flashovers. The hazard these represent can be influenced by the shape of the insulator, by extending the creepage distance, by siliconizing and by cleaning. IEC 60815 defines various degrees of contamination and specifies minimum creepage distances in relation to the equipment's maximum voltage U_m (see Table 11-3).

Table 11-3

Degree of contamination		Examples	Minimum creepage distance mm/kV
I	slight	Predominantly rural areas without industry and far from sea air	16
II	moderate	Areas in which little severe pollution is expected	20
III	severe	Industrial areas with relatively severe pollution, sea air, etc.	25
IV	very severe	Areas with heavy industry and much dust, fog, sea air	31

11.3.2 Arrangement and components

Surge arresters

Surge arresters for limiting atmospheric and switching overvoltages are described in Section 10.6. The protection zone of an arrester is limited. For rated voltages of 123 kV, the arrester should therefore not be further than approx. 24 m distant from the protected object, and for 245 to 525 kV, not further than approx. 32 m. The minimum distances from neighbouring apparatus must conform to the arrester manufacturer's specific instructions.

PLC communication

The power line carrier (PLC) system is a means of communicating over high-voltage lines. A PLC link requires a line trap and capacitor or capacitive voltage transformer in one or two phases of the incoming lines, positioned as shown in Fig. 11-14.

Control cubicles and relay kiosks

In outdoor switchyards, the branch control cubicles are of steel or aluminium sheet or of plastic (GFR polyester-reinforced resin). The cubicles contain the controls for local operation, auxiliary equipment and a terminal block for connecting the control, measuring and auxiliary cables. The size depends on how much equipment they have to contain. In large switchyards, the cubicles are replaced by relay kiosks containing all the equipment for controlling and protecting two or more high-voltage branches.

Busbars and connections

Busbars and the necessary connections to the equipment can be of wire or tube. Busbars are usually of aluminium/steel wire strung between double dead-end strings of cap-&-pin type or long-rod insulators with means of arc protection. Bundle conductors are employed for high voltages and high currents, and when single-column disconnectors are used. The tension of the wires is selected to be as small as possible to reduce stresses on the gantries. The choice of tension is further governed by the variation in sag.

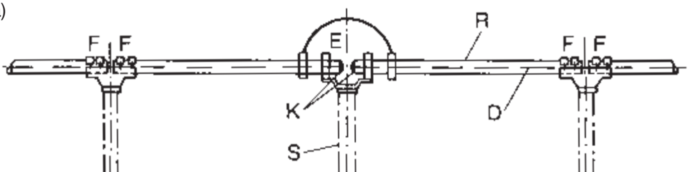
In the case of spans carrying the stirrup contacts of single-column disconnectors, account must be taken of the difference in sag at temperatures of –5 °C plus additional load and +80 °C. The change in sag can be reduced by means of springs located at one end of the span between the dead-end string and the portal structure.

Wires with cross sections of at least 95 mm^2 are used for installations with a rated voltage of 123 kV. At higher operating voltages, wires of not less than 300 mm^2 or two parallel wires forming a bundle-conductor are employed in view of the maximum permissible surface voltage gradients (see Section 4.3.3). Tensioned conductors are usually of aluminium/steel and rarely of aluminium. Aluminium wire is used for connections to HV equipment where the conductors are not tensioned, but only strung loosely. Wires are selected on the basis of mechanical and thermal considerations, see Sections 4.2.2, 4.2.3, 4.3.1 and 13.1.4.

Tubes are more economical than wires with busbar currents of more than 3000 A. Suitable diameters of the aluminium tubes are 100 mm to 250 mm, with wall thicknesses from 6 to 12 mm. For the same conductor cross-section area, a tube of larger diameter has greater dynamic strength than one of smaller diameter. Tubular conductors can be mounted on post insulators in spans of up to 20 m or more. To avoid costly joints, the tubes are welded in lengths of up to 120 m. Aluminium wires are inserted loosely into the tubes to absorb oscillation. Dampers of various makes are another method of suppressing tube oscillations. Tubular conductors for busbars and equipment interconnections are sized according to both thermal and dynamic considerations, see Sections 4.2.1, 4.3.2, 4.4.6 and 13.1.2.

Common tubular conductor arrangements for busbars and equipment links are shown in Fig. 11-7.

a)



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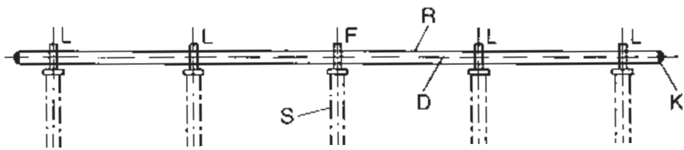


c)

Tube dia. mm	Max. span without damping wire m	Aluminium wire mm^2
100	4.5	240
120	5.5	300
160	7.5	500
200	9.5	625
250	12.0	625

Fig. 11-7

Use of tubular conductors for busbars and equipment interconnections
a) Tubes and damping wires cut at each support, b) Tubes welded across several supports, damping wire continuous, c) Recommended damping wires
L = Sliding tube support, F = Fixed tube support, E = Expansion joint, D = Damping wire, K = End cap, S = Support insulator, R = Tube

High-voltage terminals (connectors, clamps)

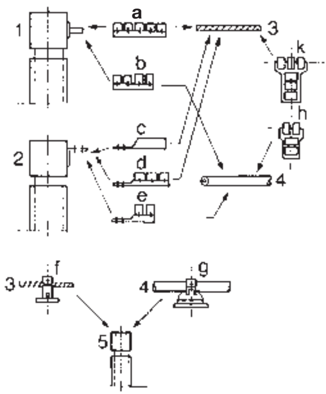
High-voltage HV terminals connect high-voltage apparatus to electrical conductors.

Their purpose is to provide a permanent, corona-free connection of sufficient thermal/ mechanical strength for continuous and short-circuit currents at the maximum operating voltage.

Unless specified otherwise, HV terminals conform to DIN 48084 and 46206 Parts 2 and 3.

Besides current conducting terminals, the conductors require purely mechanical supports attaching them to the insulators, see Fig. 11-7.

The principal kinds of terminal connection are shown in Fig. 11-8.



1 HV apparatus with connection bolt
2 HV apparatus with flat pad
3 Stranded wire conductor
4 Tubular conductor
5 Support insulator
a Screw type terminal, bolt/wire
b Screw type terminal, bolt/tube
c Compression terminal with flat pad
d Screw type terminal flat pad / wire
e Screw type terminal flat pad / tube
f Conductor support for wire
g Conductor support for tube
h Tube connector
k Wire connector

Fig. 11-8

High-voltage terminals, alternative connections for outdoor switchgear installations

Depending on the installation site, straight, 45° angle or 90° angle HV terminals are used. With stranded wire connections, terminals are used for both a single stranded wire and for bundled wires.

HV terminals have to satisfy a number of technical requirements. To select the correct terminal, the following points need to be considered:

– design, e.g. screw type flat terminal
– material of body, screws
– conductor type, e.g. stranded wire Al 400 mm^2 to DIN 48201, dia. 26.0 mm
– contact area or surface of pin, e.g. flat terminal to DIN 46206 Part 3
– rated voltage, e.g. 380 kV
– surface voltage gradient
– rated current, e.g. 2000 A
– peak short-circuit current, e.g. I_s = 80 kA
– total opening time or short-circuit duration
– ambient temperatures
– ultimate temperatures terminal/conductor
– mechanical stress
– specific environmental factors

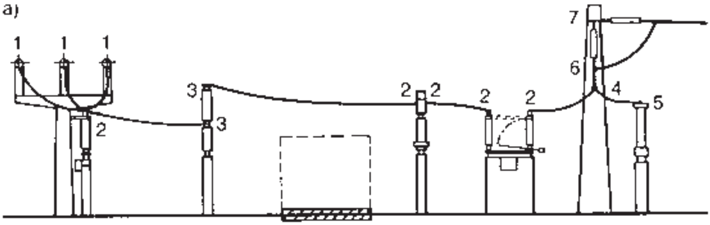
When connecting different materials, e.g. terminal bolt of Cu to stranded wire conductor of Al, a cover or plate of Cupal (a Cu/Al bimetal) is usually inserted between terminal and apparatus connector. Two-metal (Al/Cu) terminals are used where the local climate is unfavourable. The two different materials of these terminals are factory-bonded to prevent corrosion.

Special care is called for when selecting and using terminals and conductor supports for aluminium tubes ≧ 100 mm diameter. The following additional criteria must be considered:

– elongation in the case of lengthy tubes
– tube supports, fixed or sliding
– tube oscillation induced by wind
– connection to apparatus, fixed or flexible (expansion joint)
see also Fig. 11-7.

Fig. 11-9 shows the terminal arrangement and a terminal listing for 110 kV outdoor branches.

a)



b)

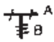
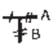
Pos.	Symbol	Mat.	Rated current (A)	Description	Total Qty.	Location	Bay 1 2 3
1		Al	850	T–terminal A = Al tube 63 dia., 2 caps B = Al wire 400 mm^2 (26.0 dia.) 3 caps	9	BB feeder	3 3 3
2		Al	850	Straight flat terminal, A = Al wire 400 mm^2 (26.0 dia.) 3 caps FL = flat term. to DIN 46206 P3	54	BB dis- connector, Current transformer, Feeder dis- connector	6 6 6 6 6 6 6 6 6
3		Al	850	90° flat terminal A = Al wire 400 mm^2 (26.0 dia.) 3 caps, FL = flat term. to DIN 46206 P3	18	Circuit- breaker	6 6 6
4		Al	850	Parallel connector A & B = Al wire 400 mm^2 (26.0 dia.), 3 screws	9	Voltage transformer drop off	3 3 3
5		Al with Cupal.	850	T–terminal A = Al wire 400 mm^2 (26.0 dia.) 3 caps B = Cu bolt 30 dia., 2 caps with Cupal cover	9	Voltage transformer connection	3 3 3
6		Al	680	T-terminal with hanger 19 dia. A = Al/St 265/35 mm^2 (22.4 dia.) 3 caps B = Al wire 400 mm^2 (26.0 dia.) 3 caps	9	Line connection	3 3 3
7		I_s =	31.5 kA/1s	110 kV V-suspension	9	Line connection	3 3 3

Fig. 11-9

Example of a) terminal arrangement and b) terminal listing for three 110 kV outdoor branches

Support structures

The steel supporting structures for outdoor switchgear are made in the form of wide-flange, frame or lattice constructions (Fig. 11-10). A conductor pull of 10 to 40 N/mm^2 max. is specified for busbar supporting structures.

The strength of supporting structures, portals and foundations is calculated in accordance with DIN VDE 0210 for overhead line construction. The structures should be fitted with a ladder so that the span fixings can be cleaned and repaired. In 525 kV installations, handrails have proved an additional safeguard for personnel.

The supporting structures for switchgear, instrument transformers and arresters are of wide-flange, frame or lattice construction, sometimes precast concrete components are used. The choice depends on economic considerations, but also appearance.

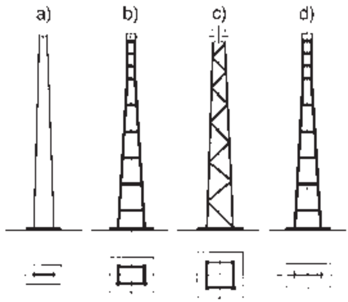


Fig 11-10

Examples of steel supporting structures for outdoor switchgear:
a) Wide-flange construction, b) Frame construction,
c) Lattice construction, d) A-tower construction

Foundations

The foundations for portals, HV switchgear and transformers are in the form of concrete blocks or rafts according to the soil's load-bearing capacity. The bottom of the foundation must be unaffected by frost, i.e. at a depth of some 0.8 to 1.2 m. The foundations must be provided with penetrations and entries for the earth wires and, where appropriate, for cables.

Access roads

Access roads in the usual sense are only rarely laid in 123 kV switchyards. The various items of switchgear, being built on the modular principle, can be brought by light means of transport to their intended position in the compound. The cable trench running in front of the apparatus serves as a footpath. It is usual to provide an equipment access route in large installations with relatively high voltages. A road or railway branch line is provided for moving the transformers.

Cable trenches, see Fig. 11-11

In outdoor installations, the cables are laid in covered trenches. Large switchyards lacking modern control facilities may require a tunnel with walking access and racks on one or both sides to accommodate the large number of control cables.

The main trenches follow the access road, the branch control cubicles being so placed that their foundations adjoin the trench. In view of the size of the covering slabs or plates, these cable trenches should not be more than 100 cm wide. Their depth depends on the number of cables. Cable supports are arranged along the sides. A descent in the lengthwise direction and drain holes ensure reliable drainage. In each branch, ducts are teed off from the control cubicle to the circuit-breaker, the instrument transformers and the isolator groups. The top of the main and branch ducts is slightly above ground level so that the trench remains dry even in heavy rain. Cable connections to individual items of equipment can also be laid in preformed troughing blocks or direct in the ground and covered with tiles.

See also civil construction requirements, Section 4.7.2.

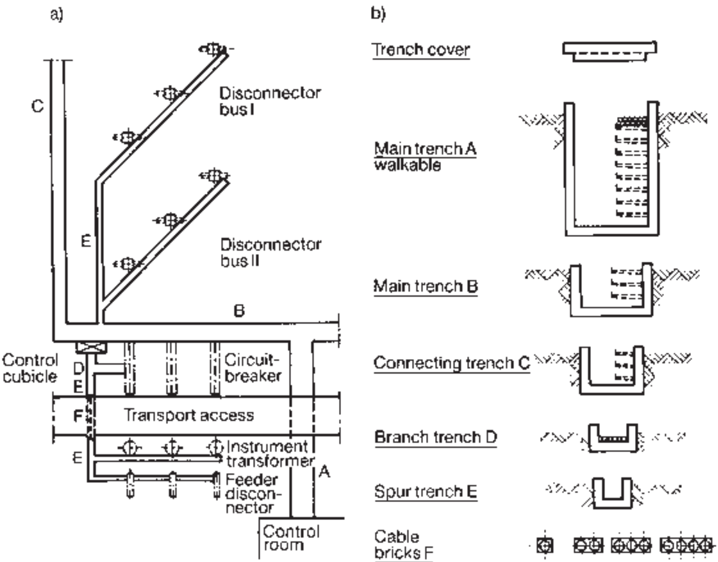


Fig. 11-11

a) Plan view of cable trench arrangement for a feeder, diagonal layout, b) Sizes of cable trenches

11

Protective screens, see Fig. 11-12

Equipment which stands low, e.g. circuit-breakers and instrument transformers on rails at 600 to 800 mm above ground level, must be provided with wire-mesh screens at least 1800 mm high, or railings at least 1100 mm high. The prescribed protective barrier distances must be observed (see Section 4.6.1).

Protective screens, railings and the like are not necessary within a switchyard if the minimum height to the top edge of the earthed insulator pedestal is 2250 mm, as specified in DIN VDE 0101, with account taken of local snow depths.

Outside of the fence of an AIS minimum elevation of EN 50341-1 are to be applied.

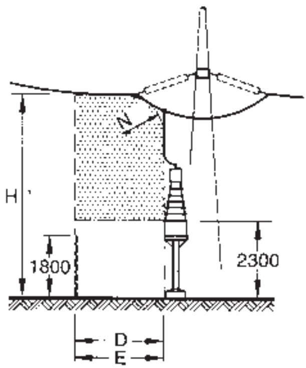


Fig. 11-12

Protective barrier clearances and minimum height H' at the perimeter fence. Distances as Table 4-11, C Solid wall, E wire-mesh screen

Perimeter fencing, see Fig. 11-13

The perimeter fence of an outdoor switching station must be at least 1800 mm high. The minimum clearance (between perimeter fence and live parts) must be observed. The perimeter fence is generally not connected to the station earth, owing to the danger of touch voltages, unless continuous separation is not possible (distance ≦ 2 m).

Station perimeter fences of conducting material must be earthed at intervals of no more than 50 m by means of driven earthrods or earthing strips at least 1 m in length, unless bonding is provided by means of a surface earth connection approximately 1 m outside the fence and about 0.5 m deep.

No special measures are required in the case of perimeter fences of plastic-coated wire mesh.

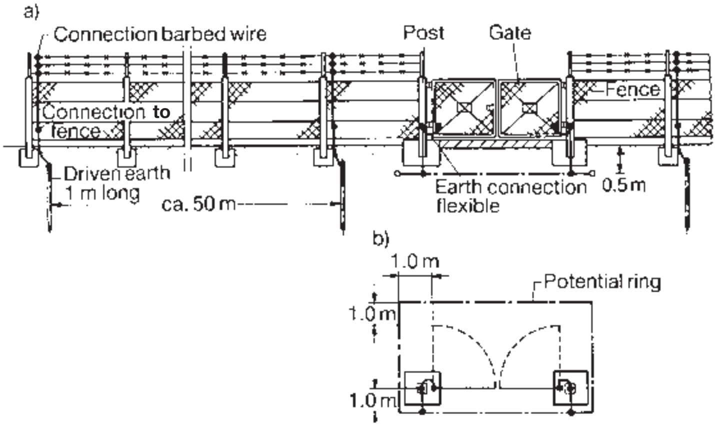


Fig. 11-13

Principle of fence earthing if distance from earth network to fence ⩽ 2 m a) Elevation, b) Plan view at gate

11.3.3 Switchyard layouts

General

The arrangement of outdoor switchgear installations is influenced by economic considerations, in particular adaptation to the space available and the operational requirements of reliability and ease of supervision. To meet these conditions, various layouts (see Table 11-4) have evolved for the circuit configurations in Section 11.1.2. Many electric utilities have a preference for certain arrangements which they have adopted as standard.

The spacing of the branches is determined by the switchyard configuration.

A span length of 50 m is economical for guyed wire (strain) busbars. The number and design of portal structures is governed by the overall length of the installation. The larger bay width T_1 and T_2 of the busbar step-down bays (starting bay, end bay) must be taken into account when planning the layout.

For stations with busbar current ratings above about 3000 A, tubular busbars offer a more economical solution than tensioned wires. In 123 kV stations, the tubular busbars are supported at each alternate bay, but at each bay with higher voltages.

The overhead lines leading from the transformer stations are generally also used for power-line carrier telephony. The necessary equipment (line trap, capacitor) is incorporated in the outgoing overhead lines as shown in Fig. 11-14.

Points in favour of rotary and vertical-break disconnectors are their mechanical simplicity and the fact that they are easier to position as feeder disconnectors. The single-column disconnector makes for a simple station layout owing to its isolating distance between the two line levels; it saves some 20% of the ground area needed for two-column disconnectors.

Table 11-4

Outdoor switchyard configurations, preferred application

Layout	≦ 145 kV	245 kV	420 kV	≧ 525 kV
Low rise (classical) layout	×	×		
In-line layout	×			
Transverse layout	×	×		
High-rise layout	×			
Diagonal layout		×	×	
1½-breaker layout		×	×	×

Each branch (bay) consists of the circuit-breaker with its disconnectors, instrument transformers and control cubicle. The apparatus is best placed at a height such that no fencing is needed. Here, it must be noted that according to DIN VDE 0101 (Fig. 4-37, Section 4.6.1), the height to the top edge of the earthed insulator base must be at least 2250 mm. The high-voltage apparatus is generally mounted directly on equipment support structures.

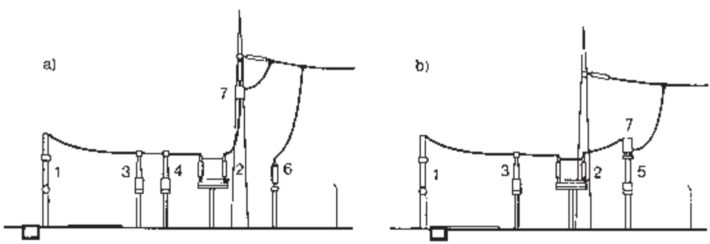


Fig. 11-14

Arrangement of overhead line bays for power-line carrier telephony:

a) Line trap suspended, capacitor standing,
b) Line trap mounted on capacitive voltage transformer,
1 Circuit-breaker, 2 Feeder disconnector, 3 Current transformer, 4 Inductive voltage transformer, 5 Capacitive voltage transformer, 6 Capacitor, 7 Line trap

Selected examples of switchyard layouts

With the *low-rise* (classical) layout (Fig. 11-15), the busbar disconnectors are arranged side by side in line with the feeder. The busbars are strung above these in a second level, and in a third plane are the branch lines, with connections to the circuit-breaker. A great advantage of this layout is that the breaker and transformer can be bypassed by reconnecting this line to the feeder disconnector. Features of this configuration are the narrow spacing between bays, but higher costs for portal structures and for means of tensioning the wires.

The classical layout is also used for stations employing the 2-breaker method.

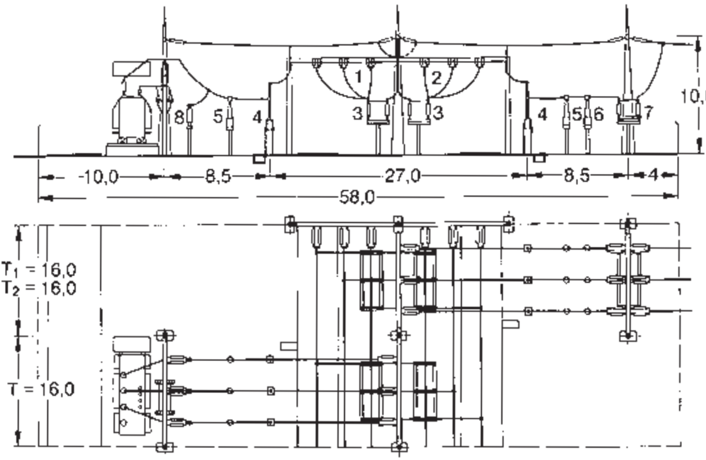


Fig. 11-15

245 kV outdoor switchyard with double busbars, low-rise (classical) layout:
1 Busbar system I, 2 Busbar system II, 3 Busbar disconnector, 4 Circuit-breaker, 5 Current transformer, 6 Voltage transformer, 7 Feeder disconnector, 8 Surge arrester; T Bay width, T_1 Width initial bay, T_2 Width final bay at busbar dead-end

An *in-line* layout with tubular busbars is shown in Fig. 11-16. It is employed with busbar current ratings of more than 3000 A. The poles of the busbar disconnectors stand in line with the busbars. Portals are needed only for the outgoing overhead lines. This arrangement incurs the lower costs for supporting steelwork and results in an extremely clear station layout.

In stations including a bypass bus, the layout chosen for the bypass bus and its disconnectors is the same as for the busbars. In stations with feeders going out on both sides, the bypass bus must be U-shaped so that all branches can be connected to it.

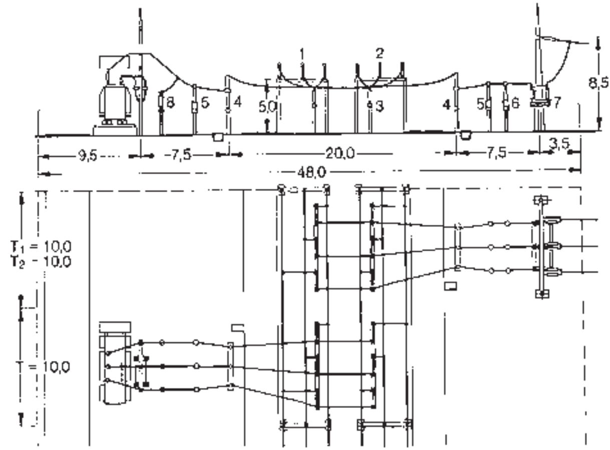


Fig. 11-16

123 kV outdoor switchyard with double busbars, in-line layout:
1 Busbar system I, 2 Busbar system II, 3 Busbar disconnector, 4 Circuit-breaker, 5 Current transformer, 6 Voltage transformer, 7 Feeder disconnector, 8 Surge arrester; T Bay width, T_1 Width initial bay, T_2 Width final bay. The busbars are tubular.

With the *transverse* layout, the poles of the busbar disconnectors are in a row at right angles to the busbar, see Fig. 11-17. With this arrangement too, the busbars can be of wire or tube. The outgoing lines are strung over the top and fixed to strain portals. Though the bay width is small, this arrangement results in a large depth of installation.

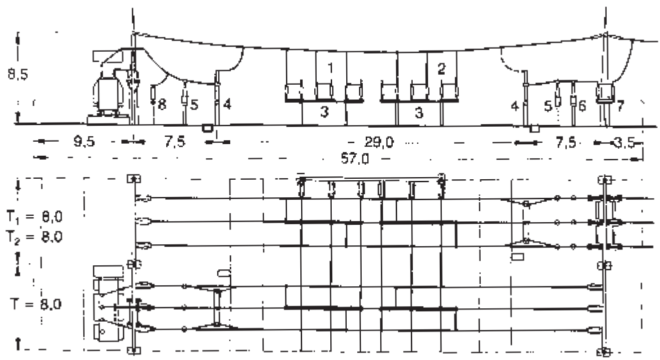


Fig. 11-17

123 kV outdoor switchyard with double busbars, transverse layout:
1 Busbar system I, 2 Busbar system II, 3 Busbar disconnector, 4 Circuit-breaker, 5 Current transformer, 6 Voltage transformer, 7 Feeder disconnector, 8 Surge arrester; T Bay width, T_1 Width initial bay, T_2 Width final bay.

Special layouts

Arrangements with draw-out breakers save a great deal of space, as the draw-out circuit-breaker does away with the need for disconnectors. The outgoing line simply includes an earthing switch. This configuration is used for stations with single busbars. The costs are low. The circuit-breaker is fitted with suitable plug-in contacts and a hydraulically operated truck.

Load-centre substations with one or two power transformers are usually in the form of simplified transformer stations. In Fig. 11-18, two incoming overhead lines connect to two transformers (H-connection). This gives rise to two busbar sections joined via two sectionalizers (two disconnectors in series). In this way, each part of the installation can be isolated for maintenance purposes. The bus sections can be operated separately or crosswise, ensuring great reliability and security of supply.

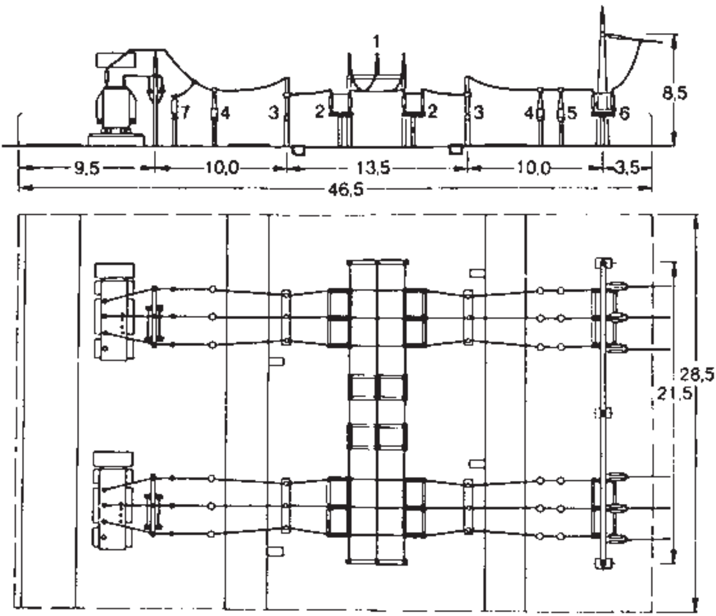


Fig. 11-18

123 kV load-centre station (H-connection): 1 Busbars, 2 Busbar disconnector, 3 Circuit-breaker, 4 Current transformer, 5 Voltage transformer, 6 Feeder disconnector, 7 Surge arrester.

Table 11-5 compares different layouts of 123-kV outdoor switchyards as regards area, foundations (volume) and steelwork (weight) for one line branch and one transformer branch with double busbar, assuming a total size of the substation of 5 bays.

Table 11-5

Comparison of different layouts for 123 kV

Type of branch (bay)	Overhead line			Transformer		
Type of layout	Area	Foundations (volume)	Steelwork	Area	Foundations (volume)	Steelwork except cable gantry on LV side
In-line (tubular busbars)	225 m^2	23.3 m^3	6.6 t	193 m^2	52.3 m^3	4.3 t
	100 %	100 %	100 %	100 %	100 %	100 %
Transverse (tubular busbars)	282 m^2	27.2 m^3	7.8 t	302 m^2	78.4 m^3	9.6 t
	125 %	117 %	118 %	156 %	150 %	223 %
Low-rise (classical, wire busbars)	192 m^2	33.9 m^3	8.4 t	201 m^2	81.3 m^3	8.8 t
	86 %	145 %	127 %	104 %	155 %	205 %

Diagonal layout

With this arrangement, the (single-column) busbar disconnectors are arranged diagonally with reference to the busbars. It is commonly used for 245 kV and 420 kV stations.

A distinction is made between two versions, depending on the position (level) of the busbars.

"Busbars above"

The advantage of this layout (Fig. 11-19) is that when a feeder is disconnected, the busbar disconnectors are also disconnected and are thus accessible.

For installations with current ratings of more than 3000 A and high short-circuit stresses, the busbars and jumper connections are made of tubes. Fig. 11-19 shows a 420 kV station in a diagonal layout and using tubes. The tubes are in lengths of one bay and mounted on the post insulators with a fixed point in the middle and sliding supports at either end. The busbars can be welded together over several bays up to about 120 m.

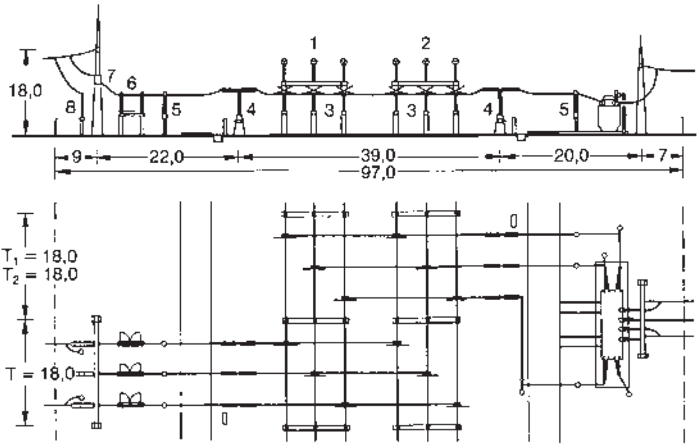


Fig. 11-19

420 kV outdoor switchyard with double busbars of tubular type, diagonal layout, busbars above: 1 Busbar system I, 2 Busbar system II, 3 Busbar disconnector, 4 Circuit-breaker, 5 Current transformer, 6 Feeder disconnector, 7 Line trap, 8 Capacitive voltage transformer. T Bay width, T_1 Width initial bay, T_2 Width final bay

"Busbars below"

With this arrangement, the busbars are mounted on the disconnectors with the outgoing lines strung at right angles to them. At their points of intersection, single-column disconnectors maintain the connection with their vertical isolating distance. This economical layout requires lightweight busbar strain portals only at the ends of the installation, and the bays are narrow. It can be of single or double-row form. The single-row arrangement (Fig. 11-20) is more space-saving. Compared with a two-row layout it requires about 20 % less area. The circuit-breakers for all outgoing lines are on the same side of the busbars so that only one path is needed for transport and operation. The lines to the transformers lie in a third plane.

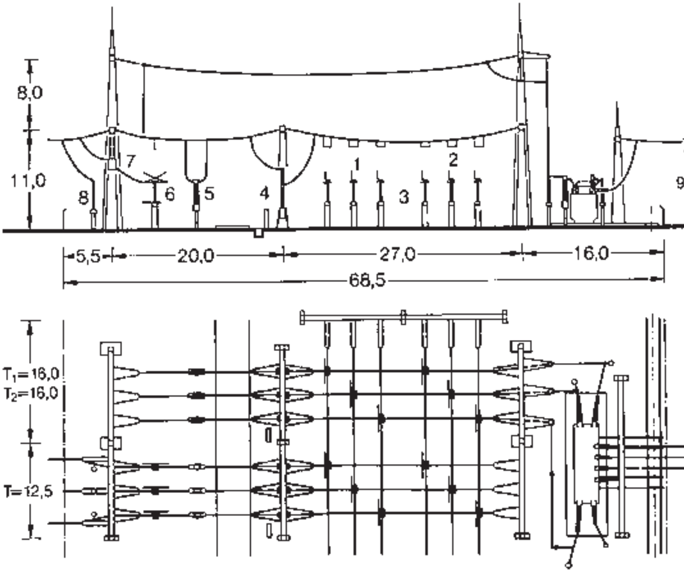


Fig. 11-20

245 kV outdoor switchyard with double busbars, diagonal layout, busbars below, single-row arrangement: 1 Busbar system I, 2 Busbar system II, 3 Busbar disconnector, 4 Circuit-breaker, 5 Current transformer, 6 Feeder disconnector, 7 Line trap, 8 Capacitive voltage transformer. T Bay width, T_1 Width initial bay, T_2 Width final bay with busbar dead-end.

The 420 kV switchyards of the German transmission grid are of the diagonal type. To meet the stringent demands of station operation and reliability, double or triple busbars with sectionalizing and an additional bypass bus are customary. Tube-type busbars are preferred. These can handle high current ratings and high short-circuit stresses.

The space-saving single-row layout with the circuit-breakers of all outgoing lines in one row is very effective here, too. Using two-column isolators on the feeders simplifies the layout. Single-column isolators are used for the busbars and the bypass bus (see Fig. 11-21).

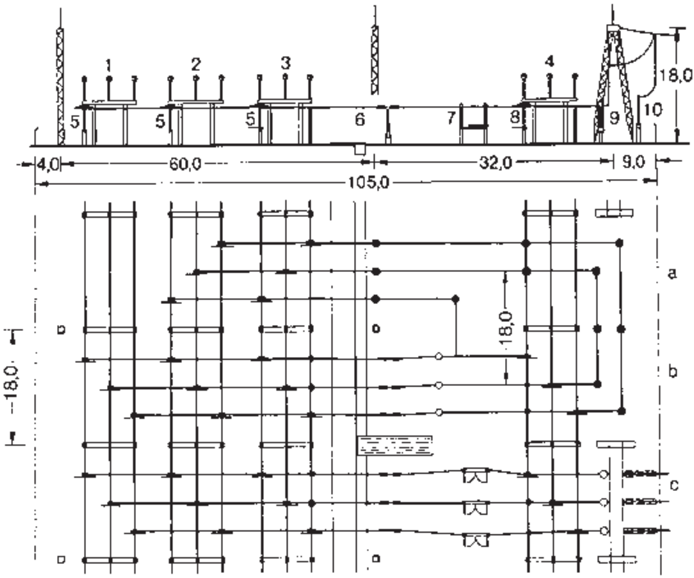


Fig. 11-21

420 kV outdoor switchyard with tubular conductors, triple busbars and bypass bus, diagonal layout, single-row arrangement:
1 Busbar system I, 2 Busbar system II, 3 Busbar system III, 4 Bypass bus, 5 Busbar disconnector, 6 Circuit-breaker, 7 Feeder disconnector, 8 Bypass disconnector, 9 Current transformer, 10 Voltage transformer; a and b Ties for busbars 1, 2 and 3 and bypass bus 4, c Outgoing line.

1 ½-breaker layout

The 1½-breaker configuration is used mainly in countries outside Europe. It is employed for all voltages above 110 kV, but predominantly in the very high voltage range.

The double busbars of these stations are arranged above, both outside or inside, and can be of tube or wire.

The more economical solution of stranded conductors is often used for the links to the apparatus, because with the relatively short distances between supports, even the highest short-circuit currents can exert only limited stresses on the equipment terminals.

The branches are always arranged in two rows. The disconnectors used are of the pantograph and two-column vertical-break types. Vertical-break disconnectors are employed in the outgoing line. Fig. 11-22 shows a section through one bay of a 525 kV station; the busbars are of wire. This arrangement allows the station to be operated on the ring bus principle while construction is still in progress, and before all the switchgear apparatus has been installed.

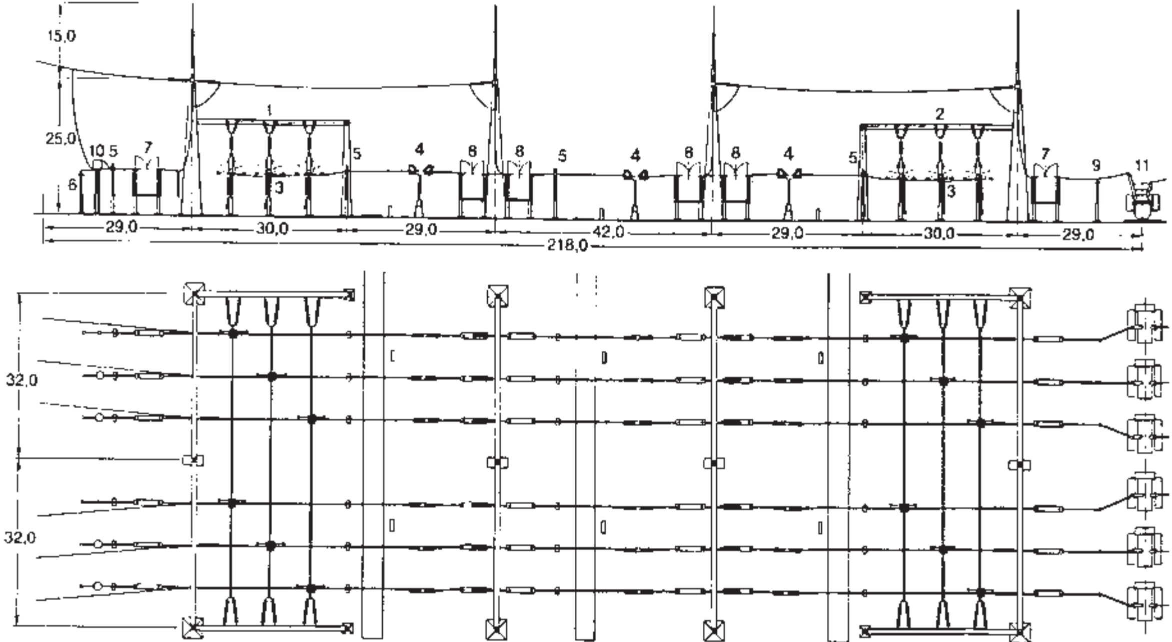


Fig. 11-22

525 kV outdoor switchyard, 1½-breaker layout: 1 Busbar system I, 2 Busbar system II, 3 Busbar disconnector, 4 Circuit-breaker, 5 Current transformer, 6 Voltage transformer, 7 Feeder disconnector, 8 Branch disconnector, 9 Surge arrester, 10 Line trap, 11 Transformer.

11.4 Innovative HV switchgear technology

11.4.1 Concepts for the future

With the use of modern, microprocessor controlled date processing techniques not only in substation and network automation systems, but also in the secondary equipment of switchgear installations, with fast communication buses and newly developed sensors for current and voltage, the availability of high and extra-high voltage switching devices and switchgear systems can be significantly increased and their maintenance-friendliness enhanced.

11.4.1.1 Sensors

New sensors permit the detection of all the relevant parameters of primary components in switchgear systems which indicate the current status of the equipment, such as switch position, gas density, energy storage behaviour of operating mechanism, and thus establish the necessary conditions for modern switchgear monitoring.

The devices used for these purpose are, for example, optical and therefore wearfree rotary encoders to detect the position of circuit-breakers, and gas density sensors for SF_6 gas-insulated switchgear. The sensor signals are processed by powerful microcomputers located either close to the process in the switchgear system, or at a remote control station depending on the requirements.

As these sensors are integrated as additional measuring instruments, the high availability of today's switchgear systems is not impaired. Retrofitting to existing systems is also possible.

11.4.1.2 Monitoring in switchgear systems

Monitoring is understood as the detection, recording and graphical presentation of measured variables with the aim of monitoring the condition of important equipment such as circuit-breakers, transformers and instrument transformers. Continuous detection of the actual stresses such as switching frequency, breaking operations on fault currents and arc duration can be used to determine the condition of primary components in operation and be drawn upon for condition-orientated maintenance. Furthermore, deviations from specified behaviour can be used for early detection of faults.

According to international surveys by CIGRE, the main causes of serious faults in circuit-breakers, i.e. failures with interruptions to service, are identified as the operating mechanism and leakage of the insulating medium SF_6. The influence of electronics on the overall failure behaviour of a system is taken into account in that self-monitoring processes implemented in hardware and software achieve an inherent increase in the system's reliability (see IEC TR 62063).

In the field of monitoring, special attention must be paid to the evaluation of the large quantity of measurment data obtained, as only the combination of condition monitoring with intelligent evaluation leads to the correct diagnosis and initiation of the necessary maintenance operations. Special algorithms for data reduction and trend calculation are the basic prerequisites of a monitoring system.

As an example, the P-F curve shown in figure 11-23 represents the qualitative relationship between the condition of a system and time. As a result of the operating stresses on the system under observation, the fault mechanism comes into action at a certain time t_1, i.e. condition worsens until a time t_2 at which the fault indicating parameter(s) has/have deteriorated to a measurable level. This point P is designated “potential fault”. As a rule, it can be assumed that the condition of the system will deteriorate further from this time onwards, generally even at increasing speed, until the fault actually occurs at time t_3 (point F).

Such behaviour is typical of the ageing mechanism of oil/paper or plastic insulation. Leakage in a gas-insulated switchgear system is a further example of the circumstances described.

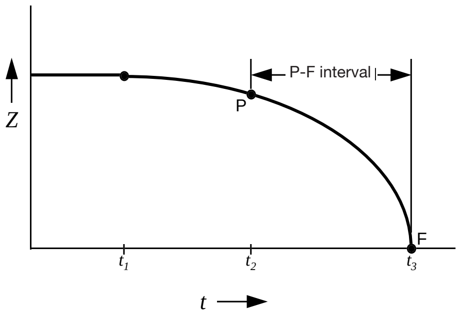


Fig. 11-23

P-F curve for the condition of an equipment parameters as a function of time
Z Condition of the equipment *P Potential fault*
t Time *F Fault*

The aim of a monitoring system, the, must be to detect point P with sufficient sensitivity that there is enough zime to initiate suitable actions, i.e. that the P_F interval is still large enough.

11.4.2 Innovative solutions

11.4.2.1 Compact outdoor switchgear installations

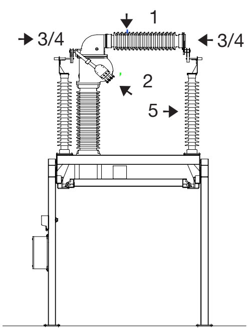
A significant step toward reducing the space requirements of switchgear installations has been made by combining primary devices into more and more compact multifunctional switchgear units. This concept is not new and has already been implemented many times in applications such as outdoor switchgear installations with draw-out circuit-breakers. The implementation of non-conventional current and voltage transformers now makes it possible to combine a large number of functions on one device bench. As a result, a range of combination switchgear has been developed in the last few years.

Another possibility for reducing the area required for outdoor installations significantly is to use hybrid installation designs. In this case, gas-insulated switchgear is used in which many primary components (circuit-breakers, transformers, disconnectors etc.) are installed in a common housing. Only the busbars and, depending on the basic design, the associated busbar disconnectors are installed outdoors

All new switchgear components are distinguished by consistent integration of non-conventional sensors (in this case primarily current and voltage sensors), processor-controlled mechanisms (see 11.4.1.1) and connection to the bay control with fibre optics. This yields the following:

– increased availability
– less space required
– shorter project runtimes and
– extended maintenance intervals with a significant increase in ease of maintenance.

Fig. 11-24 shows a design for compact outdoor switchgear installations for $U_n \leq$ 145 kv with transverse LTB circuit-breakers and integrated SF_6 current transformers. The illustrated compact and prefabricated switchgear with prefabricated busbar connections makes it easy to set up simple secondary substations and H-configurations economically and quickly. The circuit is disconnected on both sides of the circuit-breaker by the module moving to the side.



5 Functions in 1 module

1 Circuit-breaker

2 Current transformer

3/4 Disconnector and earthing switch, if required

5 Surge arrester can replace the post insulator

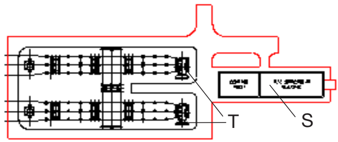
Fig. 11-24

Slide-in, compact switching module with LTB circuit-breaker and integrated SF_6 current transformer for $U_n \leq$ 145 kv

An example of the layout of a simple H-configuration with these modules is shown in comparison to a conventional H-configuration in Fig. 11-25. Dispensing with busbars and outgoing-feeder disconnectors allows smaller dimensions in comparison to conventional outdoor installations.

Conventional Design

total area: ***2600 m²***
switchgear installation: ***930 m²***
earthing system: ***3700 m²***



Compact Design

total area: ***1200 m²***
switchgear installation: ***300 m²***
earthing system: ***1000 m²***

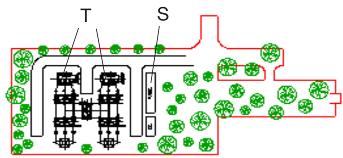


Fig. 11-25

View of two installation layouts in H-configuration for U_n ≤ 145 kv in conventional and compact design, T Transformers, S Secondary technology

Another variation of a compact switching module for use up to 170 kV is shown in Fig. 11-26. The disconnector functions are realized with a draw-out circuit-breaker. This means that the conventional disconnectors are replaced by maintenance-free fixed contacts and moving contacts on the circuit-breaker. An option is to install conventional or optical current and voltage transformers and earthing switches. The circuit-breaker can be simply withdrawn for maintenance, or if necessary, quickly replaced by a spare breaker. The main advantages here are also significant space savings, smaller bases, steel frames and reduced cabling requirements. This switching module is particularly suited for single busbars and H-configurations.

1 Draw-out circuit-breaker
2 Circuit-breaker rails
3 Disconnector isolating contact, fixed side (forms the isolating distance for circuit-breaker when withdrawn)
4 Current transformer

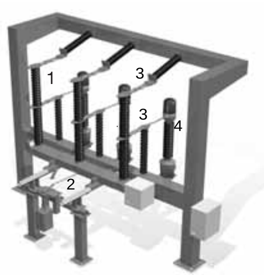


Fig. 11-26

Compact switching module for U_n ≤ 170 kv with draw-out circuit-breaker

Fig. 11-27 shows a compact switching module for applications of up to 550 kV. It is a combination of a circuit-breaker with one or two non-conventional current transformers installed on the interruptor chambers and two pantograph disconnectors. This compact design is only possible using very small non-conventional current transformers. The current transformer signals are conducted through the tension insulators via fibre-optic cables to the control cubicle. Such compact modules make it possible to reduce the surface area required for an outdoor installation by up to 55 %. This concept is particularly suitable for installations in 1$^1/_2$ circuit-breaker design.

1 Circuit-breakers of up to 550 kV

2 Disconnectors on both sides (earthing switch possible)

3 Optical current transformer

4 Tension insulator for fibre optics

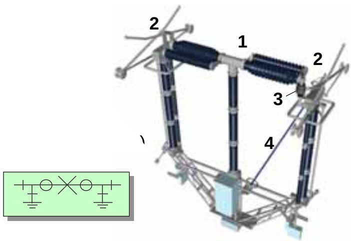


Fig. 11-27

Compact switching module for $U_n \leq 550$ kv with circuit-breaker, a built-in non-conventional current transformer and two pantograph disconnectors

Fig. 11-28 shows a comparison of a conventional 500 kV outdoor switchgear installation in $1^{1}/_{2}$ circuit-breaker design with an installation in compact design using the modules described above. This makes the saving in surface area with the same functionality particularly clear.

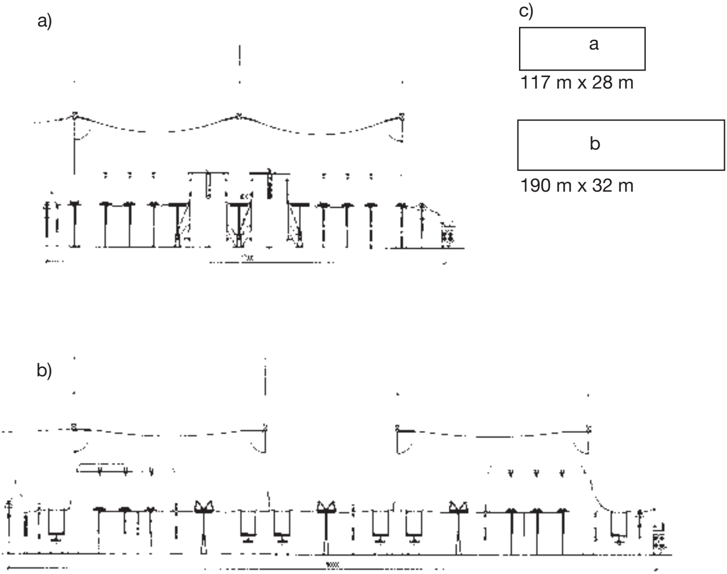


Fig. 11-28

Switchgear installation design of a 500 kV $1^{1}/_{2}$ circuit-breaker installation with compact switching modules a), compared to conventional design b), comparison of areas c)

11.4.2.2 Hybrid switchgear installations

Two insulation media, i.e. air and SF_6, can be combined in high-voltage installations with the modular principle of SF_6-isolated installations. This type of installation is referred to as a “hybrid installation”.

Fig. 11-29 shows a hybrid switching device for voltage levels of up to 550 kV. The name “Plug And Switch System” – PASS – indicates the philosophy of this concept. The highly integrated components allow that in new installations and in retrofit projects compact PASS units can be erected and comissioned quickly. These units are connected to the secondary equipment of the substation by prefabricated cable links, which include both the auxiliary voltage supply cables and the fibre-optic cables to connect to the station control system.

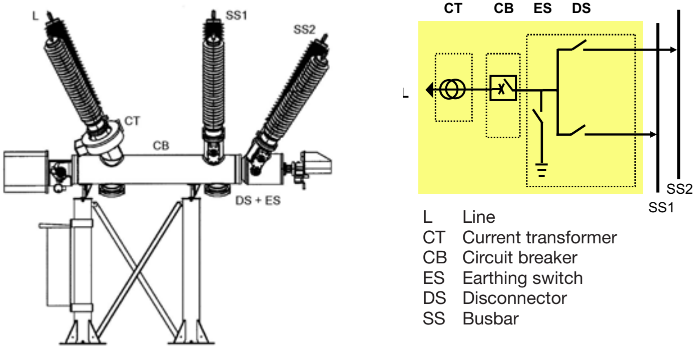


Fig. 11-29

Plug and Switch System, PASS, in single-phase design for U_n ≤ 170 kV

Fig. 11-30 shows the comparison of an AIS double bus configuration with a hybrid type using PASS-modules. The saving of space amounts to as much as 60% in new installations. For retrofit projects, the space required by the switchgear installations is generally dictated by the existing busbars and the gantries. In this case, the advantages of the PASS solutions are primarily in the savings in foundations, drastically reduced cabling requirements and fast installation and commissioning.

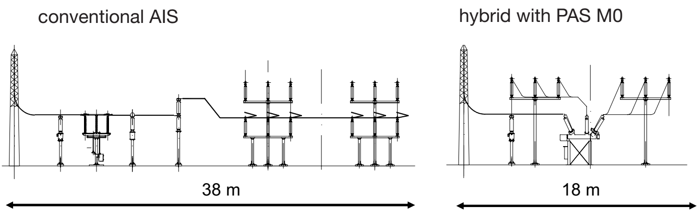
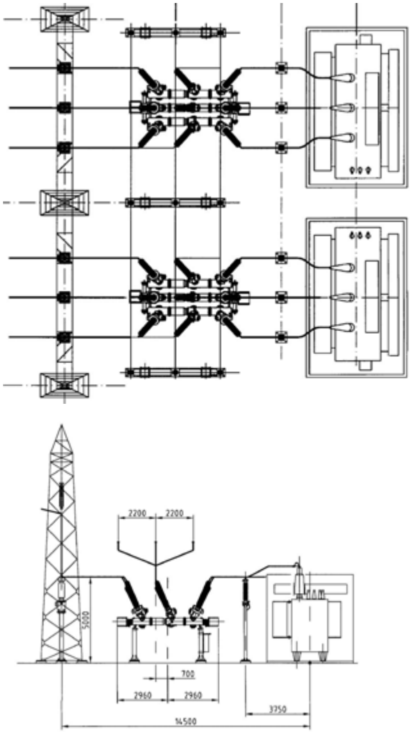
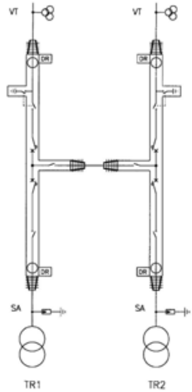


Fig. 11-30

Comparison of an double bus configuration U_n = 145 kV

Switchgear installations in H configuration can also be extremely advantageously constructed in hybrid design. A special version of the PASS M0 module contains two circuit-breakers, which makes the system even more compact. See Fig. 11-31





VT Voltage transformer

SA Surge arrester

TR Transformer

Fig 11-31

H-configuration as hybrid switchgear with PASS-modules for U_n =145 kV

The most important characteristic of PASS is the compact, modular design, which accommodates serveral functions in a single unit, e.g.:

- bushings for connection of one or two bushbars,
- one or more combined disconnector and earthing switches
- circuit-breaker
- current transformer

PASS is therefore equivalent to a complete high voltage panel.

With the exception of the bushbars, all the live components in PASS are located in earthed enclosures of cast or fabricated aluminium filled with SF_6 gas, and thus protected from environmental influences. The result is an extremely low maintenance requirement..

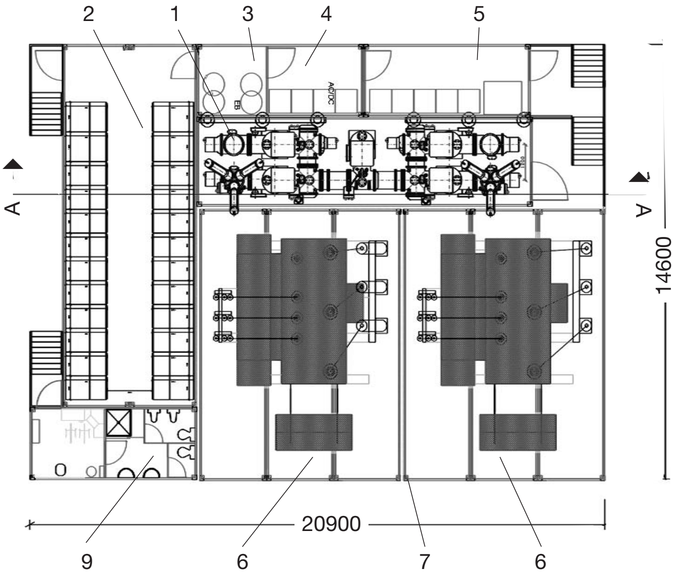


Fig. 11-32

Ground plan of a prefabricated, modular transformer substation, 1 High-voltage substation: H-configuration ELK-0 with 5 circuit-breakers, 2 Medium-voltage switchgear: 24 bays, 3 Neutral treatment (under module 1), 4 Auxiliary supply, 5 Control system/control room, 6 Modular transformer oil pit with 63 MVA transformer, 7 Modular fire protection wall, 9 Personnel module with small sewage system and oil separator

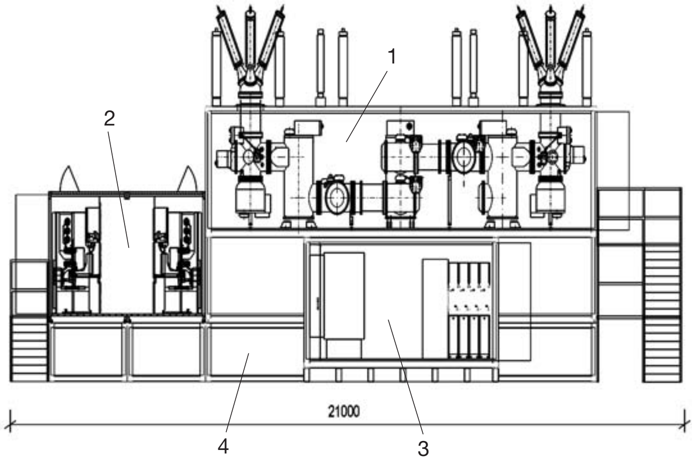


Fig. 11-33

Section through the installation, view A - A:
1 High voltage module, 2 Medium voltage module, 3 Neutral treatment, 4 Foundation modules as cable basement

11.5 Installations for high-voltage direct-current (HVDC) transmission

11.5.1 General

Transmitting energy in the form of high-voltage direct current is a technical and economic alternative to alternating-current transmission. It is used since more than 50 years for transferring bulk power over large distances by overhead lines or cables, for coupling asynchronous networks and for supplying densely populated areas, if there is a shortage of transmission routes. Typically, an HVDC transmission has a rated power of more than 100 MW and many are in the 1,000 - 3,000 MW range.

The basic principle of an HVDC link is shown in Fig. 11-34. The alternating voltage of a supply system, which may also be a single power station, is first transformed to a value suitable for transmission. It is then converted to d.c. in an arrangement with controlled valves. A second converter is required at the other end of the link. This one converts the direct current back into alternating current, which is then transformed to the voltage of the network being supplied.

The flow of power along the line is determined by the difference between the d.c. voltages at the ends of the line and by the ohmic resistance of the line, according to the formula

$P_d = U_d \cdot I_d = \dfrac{U_{d1} + U_{d2}}{2} \cdot \dfrac{U_{d1} - U_{d2}}{R} = \dfrac{U^2_{d1} - U^2_{d2}}{2R}$. Here, P_d is the power relating to the middle of the line, U_{d1} and U_{d2} are the d.c. voltages at the beginning and end of the line, respectively, and R is the ohmic line resistance.

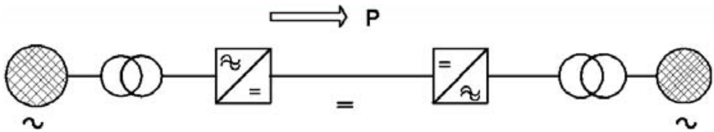


Fig. 11-34

Block diagram of a HVDC link

Common HVDC converter technology is based on line-commutated 12-pulse converters with thyristor valves. In such converters the polarity of the d.c. current is fixed. In the following this conventional HVDC is addressed as "HVDC". More recently voltage source converters based on IGBTs (switchable devices) have been introduced for d.c. cable transmission in the low power range up to 500 MW presently. Such voltage source converters developed by ABB for d.c. transmission are described in detail in chapter 11.5.5.

With the three-phase bridge circuit used in HVDC systems, the equation for the d.c. voltage of the converter is

$$U_d = k.U_V \left[\cos\alpha - + \frac{u_k}{2} \cdot \frac{I_d}{I_{dN}} \right]$$

where U_V is the valve-side voltage of the transformer, α the firing angle of the converter, u_k the transformer's relative impedance voltage, I_d the d.c. transmission current and I_{dN} the nominal d.c. transmission current. The factor k=1,35 for is due to the three-phase bridge arrangement (table 12.-11: no-load d.c. voltage U_{do}/U_2). The d.c. current is smoothed by d.c. reactors and distributed to the secondary transformer windings corresponding to the firing sequence of the thyristor valves and the commutation processes. Since the phase angle of the fundamental current and the d.c. voltage can be controlled almost instantly with the firing angle control system of the converter, the transmitted power can be varied very quickly and within wide limits.

The firing angle in the range between 0 and 90 ° determines the converter to operate as rectifier. By changing control from rectifier mode to inverter mode ($\alpha > 90$ °), it is possible to reverse the d.c. voltage and hence the energy flow direction in two-point connections. The speed of reversal can be adapted as necessary to the needs of the coupled networks. The quick response of the converter control can even be used to support stability by slightly modulating the transmitted power to attenuate power fluctuations in one of the networks.

In multiterminal systems the polarity of the transmission voltage must be constant. Hence for power reversal polarity reversal switches are needed. A power reversal in a terminal is, therefore, accomplished only within seconds.

Because of delayed ignition and commutation overlap, line-commutated converters require reactive power Q:

$$Q = P_d \tan \varphi \, ; \, \varphi = \text{arc} \cos (\cos \alpha - \frac{u_k}{2} \frac{I_d}{I_{dN}})$$

where φ is the displacement angle of the fundamental frequency current of the converter versus the grid voltage. The reactive power requirement of a conventional HVDC converter is typically about 50 to 60 % of the actual active power. By means of special control modes, it can be varied within certain limits, so an HVDC converter can assist to maintain voltage stability in the three-phase network.

11.5.2 Selection of main data for HVDC transmission

The described technical characteristics of HVDC transmission are completely independent of the transmission distance and the kind of DC connection used, overhead line or cable; they are also valid for back-to-back stations in which rectifier and inverter are assembled in one station.

On the other hand, the main data d.c. current and d.c. voltage of an HVDC link are very much influenced by the type of conductor and transmission distance. With an overhead line, minimization of the line costs and capitalized losses calls for the highest possible transmission voltage, a limit usually being set by the line's permissible surface voltage gradient. The station costs, which increase with DC voltage, become less significant as the length of line increases. DC lines with transmission voltages of up to + 600 kV already exist.

Submarine cables with a transmission voltage of 450 kV and a length of 250 km are already in use. Links more than twice as long and with transmission voltages of 500 kV are being planned.

For back-to-back stations, the main data are governed by optimization of the converter valves. One chooses the rated current attainable with the largest available thyristor without paralleling, at present about 4000 A; the d.c. voltage then follows accordingly.

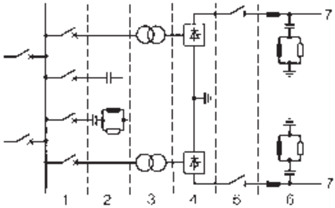
11.5.3 Components of a HVDC station

The basic circuit of an HVDC converter station is shown in Fig. 11-35. The a.c. switchgear comprises not only the feeders to the converters, but also various branches for filter circuits and capacitor banks. The circuit-breakers must be capable of frequently switching large capacitive powers.

Fig. 11-35

Basic circuit of an HVDC converter station:

1 A.C. switchgear
2 A.C. filter and reactive power compensation
3 Converter transformers
4 Converter bridges
5 D.C. switchgear
6 Smoothing reactor and d.c. filter
7 D.C. line poles 1 and 2

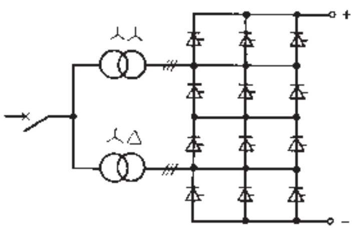


The a.c. filters are required to absorb current harmonics generated by the converter, and in this way, reduce distortion of the system voltage. With 12-pulse converter units, it is practice to use tuned series resonant circuits for the 11th and 13th harmonics together with broad-band high-pass filters for the higher harmonics. These a.c. filters also furnish some of the reactive power needed by the converters. The remainder has to be provided by capacitor banks. At low system short-circuit outputs (Sk less than 3 Pd) it may be necessary to provide synchronous compensators instead of the capacitor banks.

The converter transformers convert the network voltage into the three-phase voltage needed by the converter bridges. As Fig. 11-36 shows, a 12-pulse converter unit requires two transformers connected differently to produce the two three-phase systems with a phase offset of 30°. Converter transformers for HVDC are built with two or three windings in single-phase or three-phase units. When the converter valves operate, the windings on the valve side are galvanically connected to a high d.c. potential, and the dielectric strength of their main insulation therefore has to be designed for high d.c. voltage. Windings and iron parts have to be specially dimensioned owing to the high harmonic currents and the consequent leakage flux.

Fig. 11-36

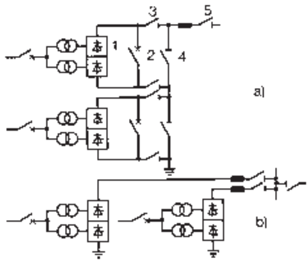
Twelve-pulse converter unit, comprising two three-phase bridges connected in series on the d.c. side.



The converter units each consist of two three-phase bridge arrangements with their respective transformers, one of which is in YyO connection, the other in Yd5 connection. On the d.c. side, they are connected in series and on the a.c. side are brought to a common circuit-breaker to form a twelve-pulse unit. If the station has to be divided into more than two sections which can be operated independently, because of the maximum permissible power in the event of a fault, twelve-pulse units are connected in series or parallel.

Fig. 11-37

One pole of an HVDC station with several converter units:
a) Series connection,
b) Parallel connection of twelve-pulse units
1 Twelve-pulse converter unit,
2 Bypass breaker,
3 Unit disconnector,
4 Shunt disconnector,
5 Line disconnector



A 12-pulse converter unit consists of twelve valves. HVDC converter valves are made up of thyristors. For high valve voltages, up to a hundred thyristors are connected in series. To obtain a uniform voltage distribution, the thyristors have additional circuitry consisting mainly of RC components. The heat sinks of the thyristors are cooled with forced-circulation air, oil or de-ionized water, the latter being the most common method. The valves are mostly ignited electronically by devices triggered by light pulses fed through fibre-optic cables. Converters with thyristors triggered directly by light are also used.

The d.c. switchgear has to perform a number of very different functions, depending on the converter station's design (cf. Fig. 11-37). The equipment used is mainly apparatus which has proved its performance in a.c. installations and been modified to meet the particular requirements. The purpose of the bypass switch parallel with the twelve-pulse unit is to commutate the station direct current when the unit is put into, or taken out of, operation. The shunt disconnector enables the direct current to be diverted from the disconnected unit.

Ground faults on a d.c. line are cleared by controlling the voltage to zero. D.C. circuit breakers are therefore not necessary with a two-terminal HVDC link. Multiterminal HVDC systems can, however, benefit from HVDC breakers (Fig. 11-38) as these improve the system's performance. A 500 kV HVDC circuit-breaker developed and tested by ABB has been put successfully in operation. The first multi-terminal HVDC transmission system entered service in North America in early 1992.

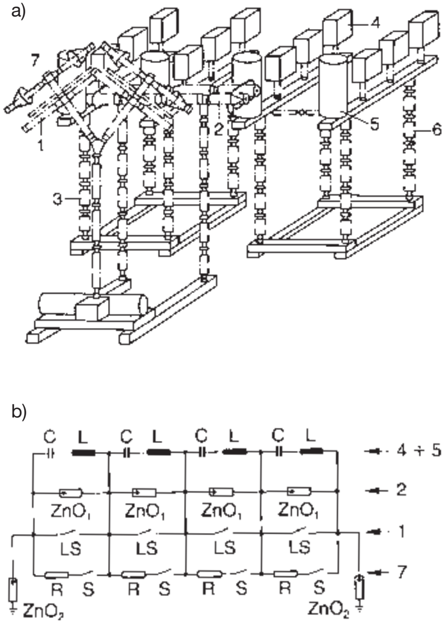


Fig. 11-38

500 kV HVDC circuit-breaker

a) Perspective arrangement
b) Equivalent circuit diagram

1 Air-blast breaker
2 Energy absorber (ZnO arrester)
3 Post insulators
4 Capacitor bank
5 Resonant-circuit reactor
6 Post insulators
7 Closing resistors (open during tripping), added as necessary

The smoothing reactors used on the d.c. side of HVDC stations smooth the direct current and limit the short-circuit current in the event of line faults. Their inductance is usually between 0.1 and 1 H. They are mostly built as air-insulated air-core reactors.

The d.c. voltage is filtered with DC filters. Their characteristics are matched to the data of the transmission line, it being particularly important to avoid resonance at the 1st and 2nd harmonics of the network frequency.

The lines for the two DC poles are usually carried on one tower. This is called a bipolar line. If there are special requirements for transmission reliability, two bipolar lines can be used on one or two towers. In the second case, the full power of the remaining healthy substation poles can be transmitted without earth return current even if a tower breaks with appropriate switchovers where two line poles fail. Both cases exploit the fact that the lines can take a high thermal overload under the standard economic design.

11.5.4 Station layout

In modern HVDC installations, the thyristor valves are air-insulated and placed in a valve hall. Generally, four valves are combined in a stack and connected to one AC phase. Three such assemblies constitute a twelve-pulse unit. Fig. 11-39 shows the layout of a station for bipolar transmission of 1000 MW at a d.c. voltage of ± 400 kV.

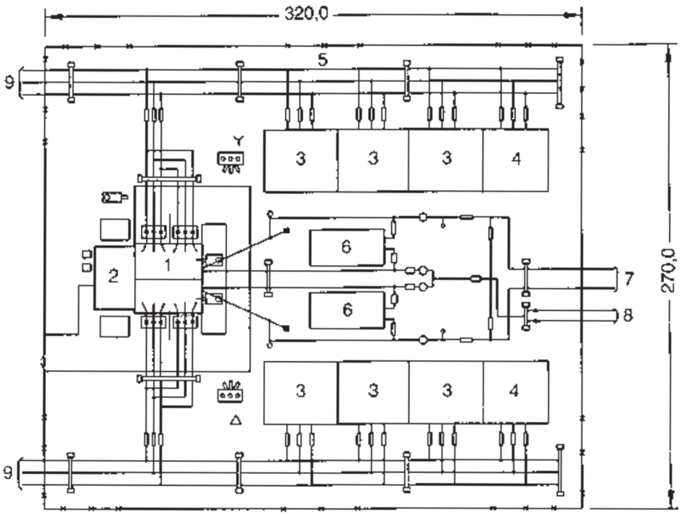


Fig. 11-39

Layout of an HVDC station for a rated voltage of ± 400 kV and rated power 1000 MW
1 Valve hall, 2 Control house, 3 A.C. filter circuits, 4 Capacitor bank, 5 A.C. switchgear, 6 D.C. filters, 7 D.C. line ± 400 kV, 8 Earth electrode line, 9 A.C. infeed 345 kV

11.5.5 HVDC Light converter stations

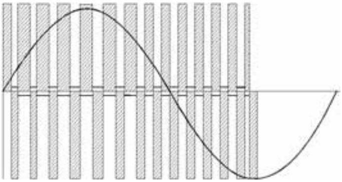
With the appearance of high switching frequency components, such as IGBTs (Insulated Gate Bipolar Transistor) it becomes advantageous to build high power VSCs (Voltage Source Converters) using PWM (Pulse Width Modulation) technology. ABB developed such VSC as "HVDC Light" for application in the transmission and distribution networks. From a system point of view a VSC acts as a motor or generator without mass that can control active and reactive power in all four quadrants almost instantaneously. HVDC Light unit sizes range from a few tens of MW to presently 500 MW and for DC voltages up to ±150 kV and units can be connected in parallel. Below these power levels a large number of converters of comparable construction principles are in operation for railway power supply or as traction converters on locomotives.

Technology

The IGBT-valves in the PWM bridge are used to create a three-phase voltage system by switching very fast between the positive and negative potential of a d.c. source and the a.c. side of the bridge. The width of the voltage pulses reaches a maximum at the peak of the desired fundamental frequency. At zero crossing of the fundamental voltage the voltage pulses of positive and negative polarity are of equal length. Fig. 11-40 presents schematically one phase of the pulsed a.c. converter voltage and the included fundamental a.c. voltage.

Fig. 11-40

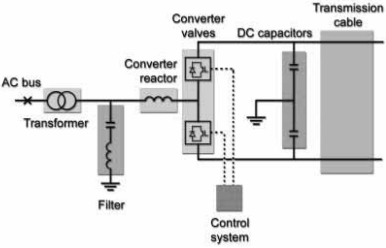
The PWM pattern and the corresponding power frequency voltage of a VSC converter



The basic circuit of an HVDC Light converter station is shown in Fig. 11-41. The key part of the HVDC Light converter consists of an IGBT valve bridge. Standard transformers can be applied to connect the valve bridge to the AC-grid. A converter reactor separates as a low pass filter the fundamental frequency from the raw PWM waveform. A shunt AC-filter is placed on the AC-side of the reactor to absorb the higher harmonic currents . On the d.c. side there is a d.c. capacitor that serves as a d.c. filter too.

Fig. 11-41

Basic circuit of an HVDC Light converter station



For a fast response of the converter control the pulse frequency is chosen high above the network frequency, typically at 2 kHz. The high pulse frequency of the converter allows not only to create the desired fundamental voltage but also a.c. voltages of higher frequency which can be used for eliminate disturbing harmonics in the a.c. system (active filtering).

To protect the converter valves the a.c. current of the converter is limited to the design current. Therefore, the converter does not increase to the short circuit power of the a.c. system. HVDC Light does not rely on the AC network's ability to keep the voltage and frequency stable. Unlike conventional HVDC, the short circuit capacity is not important. HVDC Light can feed load into a passive network (i.e. lacking synchronous machines). Even a black start of a network is possible with HVDC Light.

Active and reactive power control

With PWM it is possible to create any phase angle or amplitude (up to a certain limit) by changing the PWM pattern. Hereby PWM offers the possibility to control both active and reactive power independently. The difference between the pulsed converter voltage and the system voltage of the a.c. grid is acting upon converter reactors. The fundamental frequency voltage drop across the converter reactors defines the fundamental current of the converter. The magnitude of this voltage as the difference between the network voltage and the fundamental voltage of the converter can be deliberately controlled within limits depending on the capacity of the converter. The phase shift of this voltage can be controlled in all quadrants. Thus the active and reactive power between the converter and the network can be controlled independently from each other. Due to the high pulse frequency a change of the power is possible almost without delay. Active power is provided or absorbed on the d.c. side of the converter. Reactive power operation is defined by the difference of the magnitude of converter voltage and system voltage. At reduced converter voltage the converter operates as reactor, with increased converter voltage as capacitor.

The control is performed by a control software specifically developed by ABB. All functions for control, supervision and protection of the stations are implemented in a family of microprocessor circuit boards.

Station Layout

The majority of equipment in a HVDC Light is delivered in enclosures and tested at the factory before shipment. For example the IGBT valves, the d.c. capacitor, the control equipment, the valve cooling equipment and the station service are all deliv-ered in enclosures. This simplifies the civil works and also makes the installation and commissioning faster than for a traditional HVDC converter. The heaviest piece of equipment weighs about 20 tons and is transportable by truck direct to site. The equipment of a 330 MW converter is installed within an area of only about 92x45 m. For offshore application the converter equipment can be designed for installation in several stories thus reducing the required surface drastically.

The key to short delivery times is standardization. The Light concept lends itself to a modular standardized design with a high degree of factory testing. Different types of Light stations have many modules in common, which shortens the time for design and manufacturing. The absence of buildings and a minimum of civil works also contribute to short delivery times. A normal delivery time for a complete Light project today is about 12 month.

Table 11.6

Differences between HVDC and HVDC Light

Characteristic	LCC HVDC	HVDC Light
Power range	Above 250 MW up to 1500 MW per 12-pulse converter unit	A few 10 up to 500 MW per converter unit
Power reversal	Change of the polarity of the converter DC voltage. For multiterminal operation polarity reversal switches required.	Change of the polarity of the converter DC current. In multiterminal operation no switching required.
Reactive power demand	Typically 50-60% of the actual active power Considerable size and space of AC filters needed	No demand, instead able to deliver or absorb reactive power as required (works as SVC)
Short circuit power S_k at connecting point of the grid required?	Yes, minimum 3 times the rated power of the HVDC	No. Able to feed load into a passive network (i.e. lacking synchronous machines). Island operation possible. Black start capability.
Dimensions of the converter station	Considerable space needed for many components (the valve hall, AC- filters, DC-filters and reactive power compensation), see Fig. 11-39	Compact, since no reactive power compensation and DC-filters and negligible AC-filters, see Fig. 11-41

11.6 Static reactive power compensation and improvement of power quality

For the transmission of bulk power on long a.c. overhead lines it is important to balance the reactive power requirement of the transmission lines exactly. For this purpose in the past breaker-switched reactors and capacitor banks were used as compensation equipment in substations. To improve the reactive power balance also series capacitors were installed in series with transmission lines. By balancing the reactive power of the transmission lines their transmission capacity could be used better, transmission losses were reduced and the voltage profile along the lines could be maintained within permitted limits. Sometimes capacitor banks were designed also as filters for reducing disturbing harmonics in the network and deviations of the voltage from the normal sinus wave form of 50 or 60 Hz, respectively.

Contrary to the reactive power management of synchronous compensators or synchronous generators in power plants the above described compensation method is addressed as static compensation. With the development of power electronics quite a number of new static compensation equipment were introduced for AC power transmission. This new equipment partly improved the original solutions considerably or represented really new converter-based solutions.

Quite a number of different solutions are collectively known as Flexible AC Transmission Systems (FACTS), based on state of the art, high power electronics. Given the nature of power electronics equipment, FACTS solutions will be particularly justifiable in applications requiring one or more of the following qualities:

- Rapid dynamic response
- Ability for frequent variations in output
- Smoothly adjustable output
- Less use of breaker-switched equipment.

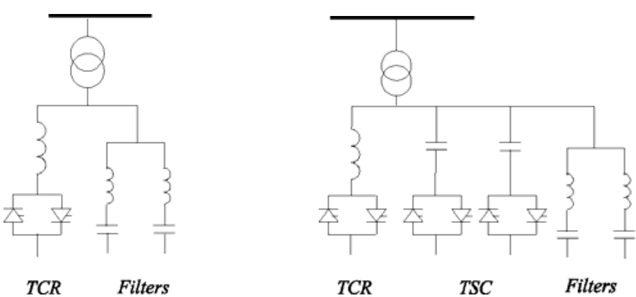
Important FACTS devices are SVC (Static Var Compensators), conventional Series Capacitors (SC) as well as Thyristor-Controlled Series Capacitors (TCSC) and STATCOM. Still others are PST (Phase-shifting Transformers) and UPFC (Universal Power Flow Controllers).

11.6.1 SVC Static Var Compensator

An SVC is based on thyristor controlled reactors (TCR), thyristor switched capacitors (TSC), and/or capacitor banks tuned to Filters (Fig. 11-42). A TCR consists of a fixed reactor in series with a bi-directional thyristor valve. TCR reactors are as a rule of air core type, glass fibre insulated, epoxy resin impregnated. The reactive power of a TCR is controlled continuously between zero and rated value by the phase angle controlled firing of the thyristor valves. The capacitor banks are designed to adjust the control range of an SVC, as filters they improve the harmonic performance of the system.

A TSC consists of a capacitor bank in series with a bi-directional thyristor valve and a small damping reactor (not shown in Fig. 11-42) which damps the turn-on process and also serves to de-tune the circuit to avoid parallel resonance with the network. The thyristor switch acts to connect or disconnect the capacitor bank for an integral number of half-cycles of the applied voltage.

Fig. 11-42 Several configurations of SVC



The fast VAR control of SVC make it highly suitable for fulfilling of the following functions:

- Steady-state as well as dynamic voltage stabilisation, meaning increased power transfer capability and reduced voltage variations.
- Synchronous stability improvements, meaning increased transient stability and improved power system damping.
- Dynamic balancing of unsymmetric loads.

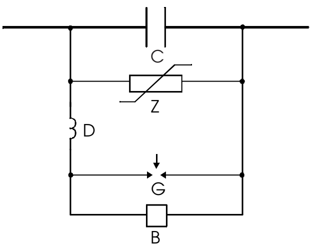
11.6.2 Thyristor-Controlled Series Capacitors (TCSC)

The circuit diagram of a conventional series capacitor (SC) is shown in Fig. 11-43. The main protective device is a varistor, usually of ZnO type, limiting the voltage across the capacitor to safe values in conjunction with system faults giving rise to large short circuit currents flowing through the line.

A spark gap is utilized in many cases additionally, to enable by-pass of the series capacitor in situations where the varistor is not able to absorb the excess energy during a fault sequence.

Finally, a circuit breaker is incorporated in the scheme to enable the switching in and out of the series capacitor as need may be. It is also needed for extinguishing of the spark gap, or, in the absence of a spark gap, for by-passing of the varistor in conjunction with faults close to the series capacitor.

Fig. 11-43 Main configuration of a Series Capacitor (SC).



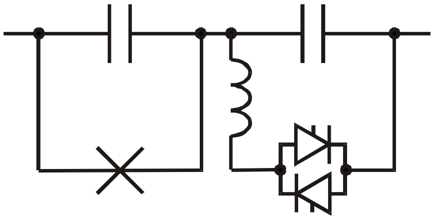
C Capacitor bank
Z Metal oxide varistor
D Discharge damping reactor
G Forced triggered spark gap
B By-pass breaker

Though very useful indeed, conventional series capacitors are limited in their flexibility due to their fixed ratings. By introducing control of the degree of compensation, additional benefits are gained.

In early types of controllable series capacitors, mechanical circuit breakers are used to switch segments of the capacitor in and out according to need. This is adequate in most situations for power flow control, but for applications requiring more dynamic response, its usefulness is reduced due to the switching limitations associated with using circuit breakers.

State of the art of controllable series compensation is TCSC, shown in Fig. 11-44. Here, the introduction of thyristor technology has enabled an improved concept of series compensation. Added benefits are dynamic power flow control, power oscillation damping, as well as mitigation of sub-synchronous resonance (SSR), should this be an issue. Today series compensation systems of long transmission lines include normally both controlled as well as fixed compensation.

Fig. 11-44 Thyristor-Controlled Series Capacitor (TCSC).



11.6.3 STATCOM Static Synchronous Compensator

A Static Compensator consists of a voltage source converter, a coupling transformer and controls. In Fig. 11-45 the configuration of a STATCOM and the vector diagram of its main electrical values are presented. I_q is the converter output current and is perpendicular to the system voltage V_{ac} on the a.c. side of the converter transformer. The converter voltage V_i has the same phase angle as the transformer voltage V_t. The magnitude of the converter voltage and thus the reactive output of the converter is controllable. If $V_i > V_t$, the STATCOM supplies reactive power to the ac system. If $V_i < V_t$, the STATCOM absorbs reactive power.

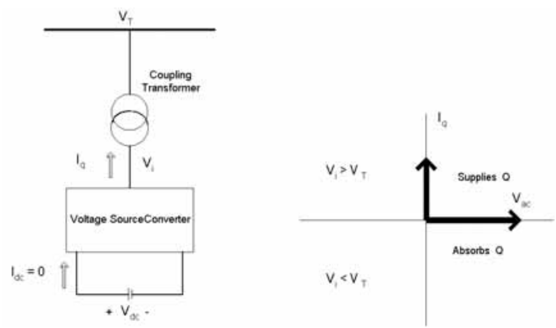
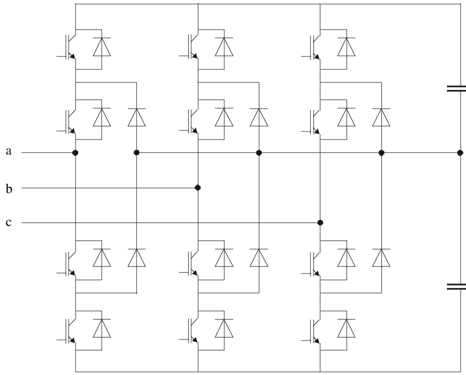


Fig. 11-45 Schematic circuit and vector diagram of a STATCOM.

For extended range of VAR operation, additional fixed capacitors, thyristor switched capacitors or an assembly of more than one converter may be used. A Voltage Source Converter (VSC) of three-level configuration is built up as in Fig. 11-46. One side of the VSC is connected to a capacitor bank, which acts as a DC voltage source. The converter produces a variable AC voltage at its output by switching via the semiconductor valves the positive pole, the neutral, or the negative pole of the capacitor bank directly to any of the converter a.c. outputs. State of the art for STATCOM valves is the use of IGBT (Insulated Gate Bipolar Transistors). The semiconductor valves in a STATCOM respond almost instantaneously to a switching order. A response time shorter than a quarter of a cycle is obtained.

Fig. 11-46: 3-level VSC configuration.

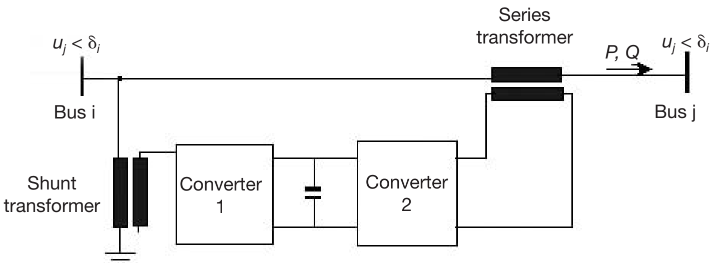


The high switching frequency used in the IGBT based STATCOM concept results in an inherent capability to produce voltages at frequencies well above the fundamental one. This property can be used for active filtering of harmonics already present in the network.

11.6.4 Unified Power Flow Controller (UPFC)

The Unified Power Flow Controller consists of two VSC converters operated from a common DC link, as shown in Fig. 11-47. On the a.c. side Converter 1 is shunt-connected. Converter 2 is arranged in series with the transmission line. Power flow control is performed by Converter 2 by injecting an AC voltage with controllable magnitude and phase angle in series with the transmission line. Since the phase angle of the line current is given and can assume any value in the four quadrants, Converter 2 has to be able to deliver power in all quadrants. With respect to the reactive power Converter 2 is able to perform this function on its own. The basic function of Converter 1 is to supply or absorb the active power demanded by Converter 2 at the common DC link. It can also generate or absorb controllable reactive power and provide independent shunt reactive power for compensation of the line or for voltage control.

Fig. 11-47 Unified Power Flow Controller (UPFC).



A UPFC can regulate active and reactive power independently from each other. With its ability of fast controllability the UPFC can improve the dynamic stability in the a.c. system. In principle, a UPFC can perform voltage support, power flow control and dynamic stability improvement with one and the same device.

11.6.5 Applications of FACTS in interconnected networks

Urgent need of the application of FACTS in interconnected networks results from the deregulation of the energy market causing a considerable increase of power exchange in the transmission lines coupling different grids. Another challenge for power transmission arises from the introduction of new energy sources or the industrial development of large countries. Also, in some cases, environmental considerations might render the building of new lines as well as uprating to ultrahigh system voltages very difficult. This is where the application of FACTS could contribute to provide more transmission power by a better use of the existing system.

Power quality is another target in power transmission and distribution. Since transmission services are now provided under contract, well defined restrictions on voltage and current distortion, sags and fluctuations are coming into force. Light flicker in work places as well as domestic dwellings, and energy and production outages due to poor quality of electrical grids have to be kept within accepted limits. Some examples of FACTS are given below to demonstrate possible applications.

There are three principally different locations for the application of SVCs:

- close to major load centers such as large urban areas
- at critical substations, normally at remote places out in the grids
- at infeeds to large industries such as steel plants

One example of the installation of an SVC for voltage support in a meshed network is found close to the city of Oslo in the southern parts of Norway. This plant is rated at +/- 160 Mvar and it is connected to the 420 kV system at a substation southwest of the city. At distant short circuits in the network the SVC ensures that the loads in the city area can notice virtually no voltage change. One can say that the SVC has isolated the city from the effect of the remote system fault.

Typical applications for series compensation are long transmission lines from large hydro power stations to remote load centres. The earliest series compensation schemes (SC) were installed already 50 years ago in Sweden. Later striking installations were built in Latin America. In Argentina, there are 10 series capacitors altogether rated at close to 2.400 Mvar at 500 kV in operation in a long power corridor (length over 1.000 km), bringing vast amounts of power from the south-west of the country up to the power-hungry Buenos Aires area. In Brazil has been operating a Thyristor-controlled Series Capacitor (TCSC) and five fixed Series Capacitors (SC) in a 500 kV interconnector between its northern and southern power systems. All in all, there are installed about 1100 Mvar of series capacitors of which about 10% are thyristor-controlled. The series capacitors installed in the 1000 km North-South Interconnection have the task of raising the steady-state and dynamic stability of the intertie.

A typical application of a STATCOM (trade name: “SVC Light“) is operated in a residential area in Texas for dynamic voltage support and improving dynamic stability of a 138 kV grid. The STATCOM rated at –100/+100 Mvar is very compact, and replaces an old power plant. A number of 138 kV Mechanically-Switched Capacitor Banks (MSC) are controlled and operated from the SVC Light, as well.

12 Transformers and other Equipment for Switchgear Installations

12.1 Transformers

12.1.1 Design, types and dimensions

The purpose of transformers is to transfer electrical energy from systems of one voltage U_1 to systems of another voltage U_2.

Transformers can be differentiated according to their manner of operation (Fig. 12-1):

1. *Power transformers,* the windings of which are in parallel with the associated systems. The systems are electrically independent. The transfer of power is solely by induction.
2. *Autotransformers,* the windings of which are connected in line (series winding RW and parallel winding PW). The throughput power S_D is transferred partly by conduction and partly by induction.
3. *Booster transformers;* their windings are electrically independent, one winding being connected in series with one system in order to alter its voltage. The other winding is connected in parallel with its associated system (excitation winding EW). The additional power S_Z is transferred purely inductively.

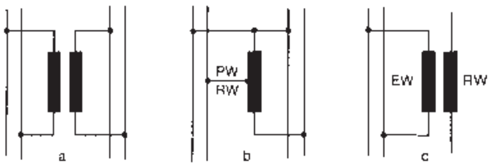


Fig. 12-1

Different types of transformers according to their manner of operation: a) Power transformer, b) Autotransformer, RW Series winding, PW Parallel winding, c) Booster transformer, EW Excitation winding, RW Series winding.

The following distinctions are made according to applications:

1. Transformers for the supply of power IEC 60076-1 (VDE 0532 Part 101), such as distribution or main transformers, machine transformers and system-tie transformers,
2. Industrial transformers, such as welding transformers, furnace transformers, starting transformers and converter transformers,
3. Transformers for traction systems,
4. Special transformers, e.g. for testing, protection and control purposes.

Three-phase distribution transformers are covered by standards DIN 42500 (≙ HD 428.151) and DIN 42523 (≙ HD 538.151).

Transformers are divided into the following categories:

1. *Class A:* dry-type transformers (e.g. cast-resin transformers)
   Core and windings are not contained in an insulating liquid. Heat losses are dissipated direct to the ambient air, hence large surface area and low current density.
   Up to approximately 20000 kVA and a maximum of 36 kV.
   ABB resin-encapsulated transformers of the RESIBLOC type are characterized by extremely high mechanical resistance of the windings because of fibre-glass-reinforced resin insulation and a very high resistance to fluctuations in temperature.

2. *Class 0:* oil-immersed transformers
   Core and windings are contained in mineral oil or similarly flammable synthetic liquid with a fire point ≤ 300 °C which is simultaneously a coolant and insulating medium.

3. *Class K*
   Core and windings are contained in a synthetic liquid having a fire point > 300 °C which is also a coolant and insulating medium. In construction, they are much like oil-immersed transformers.

   ABB uses silicone liquid for transformers with ratings of up to 10 000 kVA and service voltages of up to 36 kV.
   Silicone liquid is flame-retardant and non-polluting. Other synthetic liquids (ester) with a fire point > 300 °C may be encountered, besides silicone liquid.

   Askarel is no longer used as a coolant (environmental hazard).

Ratio variability

Ability to vary the ratio is important particularly with main transformers; it is used for matching the service voltage in the event of load fluctuations, for load distribution or for adjusting active and reactive current in interconnected networks, and for voltage correction with electric furnaces, rectifier stations, etc. In the simplest case, this is done with the transformer dead, by altering the connection between winding sections with the aid of extra winding terminals, so-called tappings (normally ± 4 % or ± 5 %).

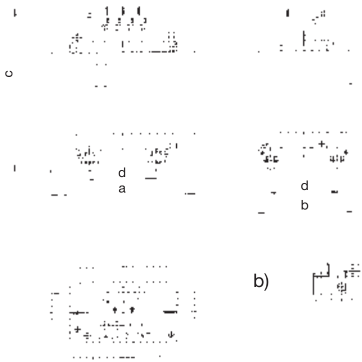
For *stepwise variation under load,* the tap changer (available in oil-insulated and dry design) is preferably installed at the neutral end of the HV winding with power transformers, and at the series winding with series transformers and autotransformers.

The tap changer, which connects the respective tappings while under load, consists basically of a load switch and a selector (or alternatively just a selector switch) with or without preselection.

Continuous variation under load can be done with moving windings in the form of a special design as a rotary transformer or moving-coil regulator.

Fig. 12-2 shows an oil-insulated transformer (a) which has the currently preferred hermetically encapsulated design without expansion tank and a resin-encapsulated transformer (b) without enclosure. There are no standards for the dimensions of distribution transformers. Table 12-1 lists the main dimensions of a number of distribution transformers as examples of practical transformer designs with varying technical data from the ABB production range.

a)



b)

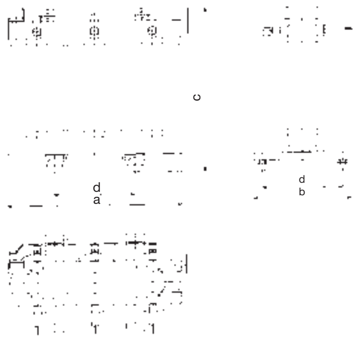


Fig. 12-2

Structural types of distribution transformers

a) hermetically encapsulated oil-insulated transformers

b) RESIBLOC resin-encapsulated transformers without enclosure

Table 12-1

Main dimensions of ABB distribution transformers, as shown in Fig. 12-2
a) Oil-insulated transformers, hermetically encapsulated
b) RESIBLOC resin-encapsulated transformers without enclosure

	Tech. data	Main dimensions in mm			
		a	b	c	d
a)	10 kV, 250 kVA, 4%	1170	740	1440	520
	20 kV, 250 kVA, 4%	1170	770	1510	520
	10 kV, 630 kVA, 6%	1420	870	1440	670
	20 kV, 630 kVA, 6%	1460	930	1525	670
b)	10 kV, 250 kVA, 4%	1110	660	1250	520
	20 kV, 250 kVA, 4%	1350	660	1560	520
	10 kV, 630 kVA, 6%	1500	810	1360	670
	20 kV, 630 kVA, 6%	1560	810	1820	670

12.1.2 Vector groups and connections

Vector groups

The vector group denotes the way in which the windings are connected and the phase position of their respective voltage vectors. It consists of letters identifying the configuration of the phase windings and a number indicating the phase angle between the voltages of the windings.

With three-phase a.c. the winding connections are categorized as follows:

a) Delta (D, d)
b) Star (Y, y)
c) Interconnected star (Z, z)
d) Open (III, iii)

Capital letters relate to the high-voltage windings, lower-case letters to the medium and low-voltage windings. The vector group begins with the capital letter. In the case of more than one winding with the same rated voltage, the capital letter is assigned to the winding with the highest rated power; if the power ratings are the same, to the winding which comes first in the order of connections listed above. If the neutral of a winding in star or interconnected star is brought out, the letter symbols are YN or ZN, or yn or zn, respectively.

To identify the phase angle, the vector of the high-voltage winding is taken as a reference. The number, multiplied by 30° denotes the angle by which the vector of the LV winding lags that of the HV winding. With multi-winding transformers, the vector of the HV winding remains the reference; the symbol for this winding comes first, the other symbols follow in descending order according to the winding's rated voltages.

Example:

For a transformer with three power windings (HV windings 220 kV in neutral connection with brought-out neutral, MV winding 110 kV in neutral connection with brought-out neutral, and LV winding 10 kV in delta connection), if the vectors of the neutral voltage of HV and MV winding are in phase and the vector of the neutral voltage of the LVwinding lags behind them by $5 \cdot 30 = 150°$, the identifying symbols are:

YN, yn 0, d 5.

Preferred connections

Yyn 0 — for *distribution transformers.* The neutral point can be loaded continuously with up to 10 % of the rated current, or with up to 25 % of the rated current for a maximum of 1.5 hours. Example: for connecting arc suppression coils.

YNyn 0 — with *compensating winding,* used for large system-tie transformers. The neutral point can be loaded continuously with the rated current.

YNd 5 — intended for *machine and main transformers* in large power stations and transformer stations. The neutral point can be loaded with the rated current. Arc suppression coils can be connected (delta winding dimensioned for the machine voltage).

Yzn 5 — for *distribution transformers,* used up to approx. 250 kVA for local distribution systems. The neutral point can be loaded with the rated current.

Dyn 5 for *distribution transformers* above approx. 315 kVA, for local and industrial distribution systems. The neutral point can be loaded with the rated current.

Ii 0 for *single-phase transformers,* intended for traction power supply or for three-phase banks with very high voltages and powers.

If single-phase transformers are combined to form three-phase banks, the switchgear, instrument transformers and conductor cross-sections must be designed for the voltage and current ratings given in Table 12-2.

Table 12-2

Values of U_r and I_r for transformers of connection III iii

Connection of windings	Rated voltage U_r	Rated current I_r
Star	$\sqrt{3}\ U_{ph}$	I_{ph}
Delta	U_{ph}	$\sqrt{3}\ I_{ph}$

U_{ph} phase (conductor/earth) voltage, I_{ph} phase (winding) current.

Identification and arrangement of terminals

Terminations of the windings (coils) brought out in the same winding sense are denoted 1U1,1V1,1W1 for the primary windings and 2U1, 2V1, 2W1 for the secondary windings. The terminations at the other ends of the windings, brought out in the inverse winding sense, are designated 1U2, 1V2, 1W2 for the primary windings and 2U2, 2V2, 2W2 for the secondary windings.

As a rule, the terminals of a transformer (1U,1V,1W for the primary side and 2U, 2V, 2W for the secondary side) are arranged from right to left as viewed from the low-voltage side, with their inscriptions visible from the low-voltage side, Fig. 12-3.

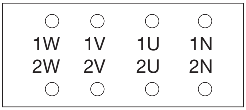


Fig. 12-3

Identification and arrangement of the terminals of a transformer (in accordance with DIN 42402)

12.1.3 Impedance voltage, voltage variation and short-circuit current withstand

Voltage drops

The *impedance voltage* U_{kr} *is* defined as that voltage having the rated frequency which must be applied to the primary side of a transformer so that the rated current I_r flows when the secondary terminals are short-circuited. Since only the short-circuit impedance is present in the circuit,

$$U_{kr} = \sqrt{3} \cdot I_r \cdot Z_k.$$

The rated impedance voltage is usually stated as a percentage of the voltage rating U_r of the winding to which the voltage is applied:

$$u_{kr} = \frac{U_{kr}}{U_r} \cdot 100\ \%.$$

The impedance voltage is composed of the ohmic voltage drop (U_R, u_R) which is in phase with the current, and the reactive voltage (U_x, u_x), which leads the current in time by 90°.

Ohmic voltage drop:

$$u_{Rr} = \frac{P_{kr}}{S_r} \cdot 100\ \% = \frac{\text{Impedance losses at rated power}}{\text{rated power}}\ 100\ \%.$$

Reactive voltage:

$$u_{Xr} = \sqrt{u_{kr}^2 - u_{Rr}^2}.$$

In the case of a partial load, the short-circuit voltage U_k is proportional to the load on the transformer:

$$u_k = u_{kr} \frac{I}{I_r} = u_{kr} \frac{S}{S_r}$$

For distribution transformers, according to DIN 42500 a rated impedance voltage u_{kr} is allocated to each power rating S_r, Table 12-3.

Table 12-3

Rated impedance voltage u_{kr}

Rated output S_r in kVA[1]										u_{kr}
50	(63)	100	160	(200)	250	(315)	400	(500)	630	4 %
630	(800)	1000	(1250)	1600	(2000)	2500				6 %

[1] Rated outputs not in brackets are preferred.

Transformers with a rated impedance voltage u_{kr} = 4 % are used mainly in distribution networks in order to keep the voltage drop small.

Transformers with a rated impedance voltage u_{kr} = 6 % are preferably to be used in industrial networks and in high-power distribution networks in order to limit the short-circuit stress. The rated impedance voltages of medium-size and large transformers are even higher so as to achieve sufficient short-circuit strength.

Voltage variation

The voltage variation between no-load and a symmetrical load of any magnitude for any cos φ can be calculated from the rated impedance voltage and the impedance losses at rated load. It is denoted u_φ, and referred to the rated voltage.
For a given part load $a = S/S_r$ and a given power factor cos φ,

$$u_\varphi = a \cdot u'_\varphi + \frac{1}{2} \cdot \frac{(a \cdot u''_\varphi)^2}{10^2} + \frac{1}{8} \cdot \frac{(a \cdot u''_\varphi)^4}{10^6} + \ldots^{1)}$$

where

$$u'_\varphi = u_{Rr} \cdot \cos\varphi + u_{Xr} \cdot \sin\varphi$$

and

$$u''_\varphi = u_{Rr} \cdot \sin\varphi - u_{Xr} \cdot \cos\varphi$$

The actual voltage at the terminals on the output side of the loaded transformer will then be

$$U_a = U_r \left(1 - \frac{u_\varphi}{100\ \%}\right)$$

Example:

Find the full-load voltage U_a for a transformer with rated load on the output side at cos φ = 0.8 (sin φ = 0.6).

Rated output: S_r = 2500 kVA,
Impedance losses: P_{kr} = 24 kW,
Impedance voltage: u_{kr} = 6 %.

$$u_{Rr} = \frac{P_{kr}}{S_r} \cdot 100\ \% = \frac{24\ \text{kW}}{2500\ \text{kVA}}\ 100\ \% = 0.96\ \%$$

$$u_{xr} = \sqrt{u_{kr}^2 - u_{Rr}^2} = \sqrt{6^2 - 0.96^2\ \%} = 5.923\ \%$$

$$u'_\varphi = u_{Rr} \cos\varphi + u_{xr} \sin\varphi = 0.96 \cdot 0.8 + 5.923 \cdot 0.6 = 4.32\ \%$$

$$u''_\varphi = u_{Rr} \sin\varphi - u_{xr} \cos\varphi = 0.96 \cdot 0.6 - 5.923 \cdot 0.8 = -4.16\ \%$$

$$u_\varphi = u'_\varphi + \frac{1}{2}\frac{(u''_\varphi)^2}{10^2} = 4.32 + \frac{1}{2} \cdot \frac{(-4.16)^2}{10^2} = 4.4\ \%.$$

$$U_a = U_r \left(1 - \frac{u_\varphi}{100\ \%}\right) = 0.965 \cdot U_r.$$

1) If u_{kr} < 20 % the third summand can be disregarded. The second summand may also be disregarded if u_{kr} < 4 %.

12

Short-circuit current and its limitation

The criterion for the short-circuit is a reference impedance composed of the impedances of the network (Z_Q) and transformer (Z_k). This is

$$I_{k3p} = \frac{U_r}{\sqrt{3}\,|Z_Q + Z_k|} \approx \frac{I_k}{u_{kr}\ \%} \cdot 100\ \%.$$

With distribution transformers of ratings up to 3150 kVA and $Z_Q \leq 0.05 \cdot Z_k$, the network impedance Z_Q can usually be disregarded.

The short-circuit impedance limits the short-circuit current. Thermal stress is governed by the sustained short-circuit current I_k. The maximum permissible short-circuit duration is 2 s as per IEC 60076-5, unless otherwise specified by the customer.

With transformers of vector groups Dy and Yd, the single-phase sustained short-circuit current is about the same as the three-phase value. At windings in interconnected star connection, the single-phase sustained short-circuit current can reach roughly 1.4 times the three-phase value, as its zero-sequence impedance is usually very small.

Table 12-4

Reference impedances for two-winding transformers (IEC 60076-5)

Rated power kVA	Typical values of z_k (or u_{kr}) %	Maximum system voltage kV	Typical values of reference system fault level S_{kQ}[1)] MVA
to 630	4.0	7.2 12 17.5 and 24	500
from 630 to 1 250	5.0	36	1 000
from 1 250 to 3 150	6.25	52 and 72.5	3 000
from 3 150 to 6 300	7.15	100 and 123	6 000
from 6 300 to 12 500	8.35	145 and 170	10 000
from 12 500 to 25 000	10.0	245	20 000
from 25 000 to 200 000	12.5	300	30 000
		420	40 000

1) If not specified

12.1.4 Losses, cooling and overload capacity

Transformer losses

Fig. 12-4 shows the usual values of no-load losses P_0 and impedance loss P_k for two-winding transformers. The total losses P_v of a transformer at any loading a = S/S_r can be calculated from the relationship:

$$P_v = P_0 + a^2 P_k.$$

The no-load losses P_0 are composed of the hysteresis losses and eddy-current losses in the iron, and leakage losses in the dielectric. These losses are not affected by the load.

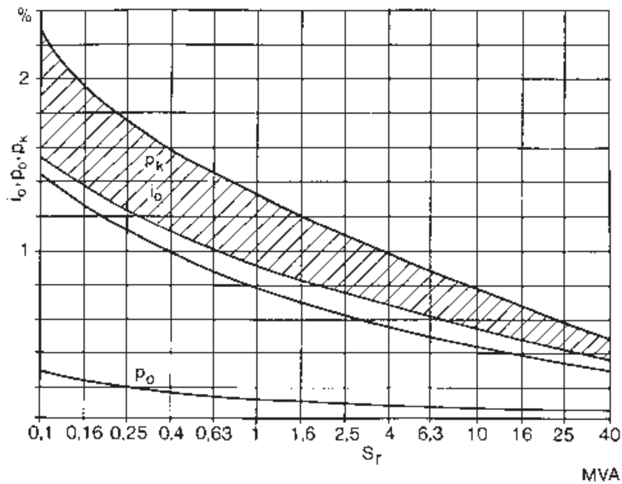


Fig. 12-4

Typical values for two-winding transformers. i_0 (percentage no-load current), p_0 (percentage no-load losses) and p_k (percentage impedance losses) as a function of rated power S_r.

Power range 2.5 MVA to DIN 42500

Power range 2 to 10 MVA to DIN 42504 and 12.5 to 80 MVA to DIN 42508
Upper limit of p_k for rated high voltage 123 kV,
Lower limit of p_k for rated high voltage 36 kV.

12

The *impedance losses* P_k comprise the copper losses in the windings and the additional losses. Impedance losses, which are caused by eddy currents inside and outside the windings, vary as the square of the load. The efficiency η of a transformer at any load is determined sufficiently accurately from

$$\eta = 100\ \% - \frac{P_0 + a^2 P_k}{a \cdot S_r \cdot \cos\varphi + P_0} \cdot 100\ \%$$

Example

Find the efficiency of a 250 kVA transformer for 20/0.4 kV with P_0 = 610 W and P_k = 4450 W at half-load (a = 0.5) and cos φ = 0.8.

$$\eta = 100\ \% - \frac{0.61 + 0.5^2 \cdot 4\ 45}{0.5 \cdot 250 \cdot 0.8 + 0.61} \cdot 100\ \% = 98.29\ \%.$$

In order to assess a transformer, however, it is more informative to evaluate the losses and their distribution, rather than the efficiency.

Cooling

The method of cooling is stated by the manufacturer in the form of four capital letters, the first two letters denoting the coolant and the manner of circulation for the winding, and the last two letters indicating the coolant and manner of circulation for cooling the outside of the transformer. These code letters are explained in Table 12-5.

Table 12-5

Key to cooling systems

Coolant	Symbols
Mineral oil or equiv. synth. liquid with fire point ≤ 300 °c	O
Other synth. liquids	K
Gas with fire point > 300 °C	G
Air (dry-type transformers)	A
Water	W

Coolant circulation	Symbols
Natural circulation	N
Forced circulation (non-directed)	F
Forced circulation (directed)	D

Examples

AN = Dry-type transformer with natural air circulation,
ONAN = Oil-immersed self-cooled transformer.

Overload capacity to DIN 57536 (VDE 0536)

The maximum time for which transformers can be overloaded at a given bias load and coolant temperature is shown in Fig. 12-5 for air-cooled oil-immersed transformers in the case of two different loads recurring regularly in a 24-hour cycle.

In the diagram:

K_1 Initial load as a proportion of rated power,
K_2 Permitted overload as a proportion of rated power (normally > 1),
t Duration of K_2 in h,
Θ_a Coolant temperature in °C.

Hence

$$K_1 = \frac{S_1}{S_r};\ K_2 = \frac{S_2}{S_r};\ \frac{K_2}{K_1} = \frac{S_2}{S_1}$$

Here, S_1 is the initial load, S_2 the maximum permitted load and S_r the rated power. Under normal circumstances, K_2 should not exceed 1.5.

Example:

Transformer 1250 kVA with ONAN cooling. Bias load 750 kVA. What is the maximum permitted load over 4 hours at 20 °C?

$K_1 = 0.6$; t = 4 h. Fig. 12-5a yields $K_2 = 1.29$.

$S_2 = K_2 \cdot S_r = 1.29 \cdot 1250$ kVA = 1612 kVA.

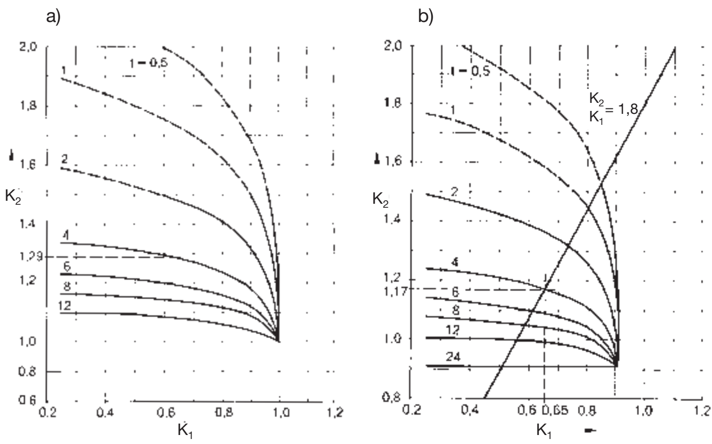


Fig. 12-5

Transformer with ONAN and ONAF cooling. Values of K_2 for given values of K_1 and t (in hours), a) Θ_a = 20 °C, b) Θ_a = 30 °C

For a given case of transformer loading, the power rating S_r can be calculated from:

$$S_r = \frac{S_1}{K_1} = \frac{S_2}{K_2}$$

Example:

At Θ_a = 30 °C, a transformer with ONAN cooling is to run for 4 hours at 450 kVA and otherwise at 250 kVA. What power rating is required?

S_1 = 250 kVA, t_1 = 20 h; S_2 = 450 kVA, t_2 = 4 h.

$$\frac{S_2}{S_1} = \frac{450}{250} = 1.8 = \frac{K_2}{K_1}$$

From Fig. 12-5 b for K_2/K_1 = 1.8 when t = 4 h: K_1 = 0.65; K_2 = 1.17.

$$S_r = \frac{450}{1.17} = \frac{250}{0.65} = 385 \text{ kVA} \rightarrow 400 \text{ kVA}.$$

12.1.5 Parallel operation

Transformers are in parallel operation if they are connected in parallel on at least two sides. A distinction is made between busbar interconnection and network interconnection. The following conditions must be satisfied in order to avoid dangerous transient currents:

1. vector groups should have the same phase angle number; terminals of the same designation must be connected together on the HV and LV sides; Exception: Phase angle numbers 5 and 11 (Table 12-6);
2. the ratios should be as similar as possible, i.e. the same rated voltages on the HV and LV sides;
3. approximately the same impedance voltages u_k maximum permissible discrepancies ± 10 %. In the event of larger differences, an inductance (reactor) can be connected ahead of the transformer with the lower impedance voltage.
4. rated output ratio smaller than 3:1.

Table 12-6 Parallel operation of transformers with phase angle numbers 5 and 11

Phase angle number required	Phase angle number available		Connection to conductors HV side L1	L2	L3	Connection to conductors LV side L1	L2	L3
5	5		1U	1V	1W	2U2	2V2	2W2
5	11		1U	1W	1V	2W1	2V1	2U1
		or	1W	1V	1U	2V1	2U1	2W1
		or	1V	1U	1W	2U1	2W1	2V1
11	11		1U	1V	1W	2U1	2V1	2W1
11	5		1U	1W	1V	2W2	2V2	2U2
		or	1W	1V	1U	2V2	2U2	2W2
		or	1V	1U	1W	2U2	2W2	2V2

Load distribution of parallel transformers with different rated impedance voltages

Transformers connected in parallel assume a partial load such that all the transformers have the same average impedance voltage. If the impedance voltage of a transformer is referred to an output other than its rated output, its magnitude varies in accordance with the output. A 100 kVA transformer with u_{kr} = 4 % has at 60 kVA an impedance voltage u_k of 0.6 · 4 = 2.4%.

Example:

transformer 1:	S_{r1} = 100 kVA,	u_{kr1} = 4.0 %
transformer 2:	S_{r2} = 250 kVA,	u_{kr2} = 6.0 %
transformer 3:	S_{r3} = 500 kVA,	u_{kr3} = 4.5 %
total	S = 850 kVA	

We have:

$$\frac{S}{u_k} = \frac{S_{r1}}{u_{k1}} + \frac{S_{r2}}{u_{k2}} + \ldots$$

The resultant impedance voltage is then:

$$u_k = \frac{S}{\frac{S_{r1}}{u_{kr1}} + \frac{S_{r2}}{u_{kr2}} + \frac{S_{r3}}{u_{kr3}}} = \frac{850}{\frac{100}{4} + \frac{250}{6} + \frac{500}{4.5}} = 4.78\ \%$$

The power assumed by the individual transformers is:

$$S_1 = S_{r1} \frac{u_k}{u_{kr1}} = 100 \cdot \frac{4.78}{4} = 120\ \text{kVA}$$

$$S_2 = S_{r2} \frac{u_k}{u_{kr2}} = 250 \cdot \frac{4.78}{6} = 199\ \text{kVA}$$

$$S_3 = S_{r3} \frac{u_k}{u_{kr3}} = 500 \cdot \frac{4.78}{4.5} = 531\ \text{kVA}$$

$$S_{tot} = S_1 + S_2 + S_3 = 120\ \text{kVA}$$

Transformer 1 is thus overloaded by 20 % and transformer 3 by 6 %. Since the individual transformers should not be subjected to overload, the transformers may only assume a partial load such that the impedance voltage of each is u_k = 4 %, as in the case with transformer 1. Therefore,

$$S_1 = 100 \cdot \frac{4}{4} = 100\ \text{kVA}$$

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$$S_2 = 250 \cdot \frac{4}{6} = 167 \text{ kVA}$$

$$S_3 = 500 \cdot \frac{4}{4.5} = 444 \text{ kVA}$$

$$S_{tot} = S_1 + S_2 + S_3 = 711 \text{ kVA}$$

If this output is not sufficient, another 160 kVA transformer with u_{kr} = 4 % will have to be installed.

Effect of dissimilar transformation ratios of transformers connected in parallel

Dangerous transient currents can occur if transformers with different voltages between taps are operated in parallel. Disregarding any dissimilarity in impedance phase angle φ_k, the voltage difference Δu proportional to the difference in ratio drives through both sides a circulating current of

$$I_a = \frac{\Delta u}{u_{k1}/I_{r1} + u_{k2}/I_{r2}}$$

If, for example, $u_{k1} = u_{k2}$ = 6 %, I_{r1} = 910 A, I_{r2} = 1445 A und Δu = 4 %, then

$$I_a = \frac{4\ \%}{6\ \% / 910\ A + 6\ \% / 1445\ A} = 377.34 \text{ A.}$$

This balancing current is superimposed on the transformer load currents that are supplied to the network. It is added to the current of that transformer which has the greater secondary no-load voltage.

12.1.6 Protective devices for transformers

Overcurrent time relays respond to short circuits; they trip the circuit-breakers.

Thermal relays respond to unacceptable temperature rises in the transformer, and signal overloads.

Make-proof percentage differential relays detect internal short circuits and faults, including those on lines between the current transformers; they trip the appropriate transformer breakers, but do not respond to the inrush current of a sound transformer.

Buchholz relays detect internal damage due to gassing or oil flow; they signal minor disturbances and trip the breaker if the trouble is serious.

Temperature monitors signal when a set temperature is reached, or trip circuit-breakers.

Dial-type telethermometers indicate the temperature in the transformer's topmost oil layer with maximum and minimum signal contacts.

Oil level alarms respond if the oil level is too low.

Oil flow indicators detect any disruption in the circulation in closed-circuit cooling and trigger an alarm.

Airflow indicators detect any break in the flow of forced-circulation air, and trigger an alarm.

12.1.7 Noise levels and means of noise abatement

Since transformers are located in or near residential areas, the noise they produce must be determined so as to assess the need for any countermeasures.

The noise of transformers is defined as the A-weighted sound pressure level measured in dB (A) at a specified measuring surface with a sound level meter, and then converted to a sound power level with the following formula:

$L_{WA} = L_{PA} + L_S$

In which:

L_{WA} A-weighted sound power level in dB
L_{PA} A-weighted sound pressure level in dB
L_S Measuring-surface level in dB

The measurements must be performed according to IEC 60551 (VDE 0532 Part 7). For transformers with water cooling or fan-less air cooling, at least 6 measurements must be taken at a distance of 0.3 m from the surface of the transformer. For transformers with other cooling systems, the relevant measurement regulations as per IEC 60551 (VDE 0532 Part 7) apply.

Table 12-7

A-weighted sound power level in dB (A) for transformers up to a rated power of 2.5 MVA

Rated power	Oil-insulated transformers as per DIN 42500			Resin-encapsulated transformers
kVA	List A'	B'	C'	as per DIN 42523[1)]
50	55	50	47	–
100	59	54	49	59 (51)
160	62	57	52	62 (54)
250	65	60	55	65 (57)
400	68	63	58	68 (60)
630	70	65	60	70 (62)
1 000	73	68	63	73 (65)
1 600	76	71	66	76 (68)
2 500	81	76	71	81 (71)

[1)] Values in parentheses for the reduced series

The causes and effects of the noise produced by transformers and their cooling systems are so diverse that it is not possible to recommend generally applicable noise

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Possible measures include:

Actions by the transformer manufacturer to reduce airborne and structure-borne noise.

Structural measures against airborne noise, e.g. sound-absorbent walls or enclosures.

Anti-vibration treatment of the foundations to reduce transmission of structure-borne noise, e.g. spring-mounted supporting structure.

12.2 Current-limiting reactors IEC 60289

12.2.1 Dimensioning

Current-limiting reactors (series reactors) are reactances employed to limit short-circuit currents. They are used when one wishes to reduce the short-circuit power of networks or installations to a value which is acceptable with regard to the short-circuit strength of the equipment or the breaking capacity of the circuit-breaker.

Since the reactance of a series reactor must remain constant when short-circuit currents occur, only the air-core type of construction is suitable[1)]. If iron cores were used, saturation of the iron brought about by the short-circuit currents would cause a drop in the inductance of the coil, thus seriously reducing the protection against short circuits.

Voltage drop and voltage variation

The rated impedance is the impedance per phase at rated frequency. The resistance of a current-limiting reactor is negligible and in general, amounts to not more than some 3 % of the reactance X_L.

The rated voltage drop ΔU_r is the voltage induced in the reactor when operating with rated current and rated reactance:

$$\Delta U_r = I_r \cdot X_L$$

When referred to the nominal voltage of the system, the rated voltage drop is denoted Δu_r and usually stated in %:

$$\Delta u_r = \frac{\Delta U_r \cdot \sqrt{3}}{U_n} 100\ \%.$$

Example:

A reactor in a three-phase system with a rated voltage of 10 kV has a reactance of 5 %. Its rated current is 400 A. This statement indicates that the voltage drop at the reactor is 5 % of the system phase-to-earth voltage. The absolute value in volts is

$$\Delta U_r = \frac{\Delta U_r \cdot U_n}{\sqrt{3} \cdot 100\ \%} = \frac{5\ \% \cdot 10\ 000\ \text{V}}{\sqrt{3} \cdot 100\ \%} = 289\ \text{V}.$$

1) Air-core reactors can cause the frequency of the recovery voltage to assume extremely high values (150 to 250 kHz). Reduction of these natural frequencies to the values for circuit-breakers defined by VDE 0670 Part 104 can be achieved by fitting capacitors.

For given values of reactance and current, the voltage variation U_φ in the network, i.e. the difference between the network voltage before and after the reactor, is also dependent on cos φ, Fig. 12-6. Thus, whereas the voltage difference U_φ across the reactor is small under normal operating conditions, it increases in the event of a short circuit

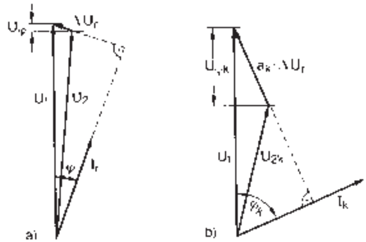
1. in proportion to the short-circuit current and

2. with the increase in phase displacement angle under fault conditions.

Fig. 12-6

Vector diagram of a reactor:

a) Normal operation
b) Short-circuit operation
U_1 System voltage before reactor
U_2 System voltage after reactor
U_φ Voltage variation in system



According to Fig. 12-6, for a given load a= I/I_r and a given power factor cos φ

$$U_\varphi = a \cdot \Delta\, U_r \cdot \cos(90\,° - \varphi)$$

or $$u_\varphi = a \cdot \Delta\, u_r \cdot \sin \varphi.$$

Example:

At a power factor of cos φ = 0.8 and rated current, a reactor with $\Delta\, u_r$ = 6 % causes a voltage variation in the network of u_φ = 6 % • 0.6 = 3.6 %.

If large motors are connected after reactors and the current ratings of the motor and the reactor are of the same order of magnitude, account must be taken of the voltage drop due to the large starting current of the motor. The drop must not be so large as to endanger the safe run-up of the motor.

Inherent power and throughput power

The inherent power of a reactor is the product of the voltage drop $\Delta\, U_r$ and the rated current I_r.

$$S_E = 3 \cdot \Delta\, U_r \cdot I_r \text{ (three-phase).}$$

The throughput of a reactor is the product of the line-to-earth voltage $U_n/\sqrt{3}$ and the rated current I_r.

$$S_D = \sqrt{3} \cdot U_n \cdot I_r \text{ (three-phase).}$$

Selection of a current-limiting reactor

If the given short-circuit power S''_{k1} of a grid system is to be reduced to a value of S''_k by fitting a reactor, its required percentage rated voltage drop is

$$\Delta\, u_r = 1.1 \cdot 100\,\% \cdot S_D \cdot \frac{S''_{k1} - S''_{k2}}{S''_{k1} \cdot S''_{k2}}.$$

Example:

$$U_n = 6\text{ kV},\quad I_r = 600\text{ A};$$
$$S''_{k1} = 600\text{ MVA},\quad S''_{k2} = 100\text{ MVA};$$

$$\Delta u_r = 1.1 \cdot 100\,\% \cdot \sqrt{3} \cdot 6\text{ kV} \cdot 0.6\text{ kA}\,\frac{600\text{ MVA} - 100\text{ MVA}}{600\text{ MVA} \cdot 100\text{ MVA}} = 5.72\,\%.$$

In practice, one will select the next-highest standardized value, 6 % in this instance.

If the short-circuit power S''_{k1} before a reactor is given, and its percentage rated voltage drop is Δu_r, the short-circuit power S''_{k2} after the reactor is:

$$S''_{k2} = \frac{1.1 \cdot 100\,\% \cdot S_D \cdot S''_{k1}}{1.1 \cdot 100\,\% \cdot S_D + \Delta u_r \cdot S''_{k1}}.$$

Taking the values of the example above, this yields:

$$S''_{k2} = \frac{1.1 \cdot 100\,\% \cdot \sqrt{3} \cdot 6\text{ kV} \cdot 0.6\text{ kA} \cdot 600\text{ MVA}}{1.1 \cdot 100\,\% \cdot \sqrt{3} \cdot 6\text{ kV} \cdot 0.6\text{ kA} + 6\,\% \cdot 600\text{ MVA}} = 96\text{ MVA}.$$

12.2.2 Reactor connection

The scheme shown in Fig. 12-7 under a), with the reactors in the tee-offs, is the one most commonly used. The circuit shown in b), with the reactors in the feeder, is often chosen for reasons of saving space. For the same degree of protection, the costs of purchase and operation are higher than with reactors in the branches.

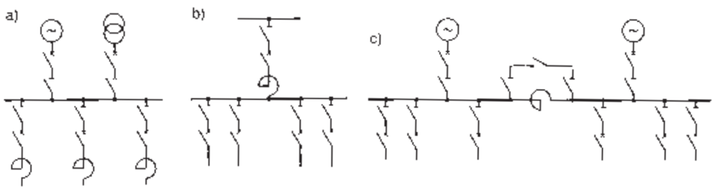


Fig. 12-7

The most common reactor connections:
a) Feeder connection, b) Tee-off connection, c) Busbar sectionalizer connection.

In power stations with a high short-circuit power, it is usual to fit busbar sectionalizing reactors together with bypass circuit-breakers, as shown in c). In this way, a permanent connection is established between the busbars, although in the event of a fault, when the circuit-breaker opens, the short-circuit power is limited approximately to that of the individual systems.

It is even better to use I_s-limiters (Section 8.1.6) instead of circuit-breakers for bypassing reactors, because these devices interrupt the bypass without any delay and therefore prevent hazardous peak current values from occurring.

12.2.3 Installation of reactors

When installing reactors, care must be taken to ensure that the heat losses occurring during operation are dissipated by adequate ventilation. As a rough estimate, one can assume a fresh air requirement of 4 to 5 m^3/min per kilowatt of heat loss. The air flow cross-sections necessary in the rooms can be calculated more accurately using the method described in Section 4.4.2 for transformers.

Care must also be taken that reactors are situated sufficiently far away from neighbouring metal parts to ensure that these are not heated excessively by eddy currents.

Reactors should not be situated at distances of less than 500 mm from constructional items of steel, and steel reinforcement in ceilings, floors and walls. If the floor is steel-reinforced, the reactor must be placed on a concrete pedestal, Fig. 12-8.

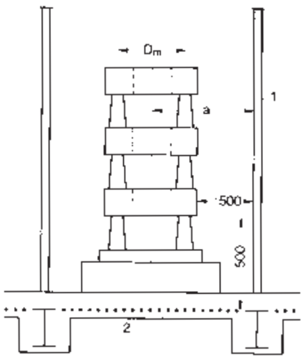


Fig. 12-8

Installation of a current-limiting reactor: D_m mean diameter of reactor, a distance between centre line of reactor and metal item
1 Steel-reinforced wall
2 Reinforcing bars
(dimensions in mm)

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With cell enclosures of non-magnetic materials (aluminium alloys), the minimum clearance for the highest equipment voltage in question (DIN VDE 0101) is sufficient. Closed structures (short-circuit loops) with a good electrical conductivity must be avoided in the vicinity of strong magnetic fields. If necessary, the short-circuit loop should be split and the junction joined by means of non-conducting material to prevent excessive heating by circulating currents.

If one is forced to use magnetic materials, the distance between reactor and metal structure should be selected so that under rated conditions, the root-mean-square value of the magnetic field strength does not exceed 20 A/cm. The field strength is calculated as

$$H = 0.1 \cdot \frac{I_r \cdot w \cdot D_m}{a^2}$$

Here, I_r rated current in A, w number of turns in reactor, for D_m and a, see Fig. 12-8.

12.3 Capacitors[1)]

12.3.1 Power capacitors

The term power capacitor is chiefly applied to capacitors having a rated frequency of 50 or 60 Hz which compensate the lagging reactive power at points of heavy demand in public and industrial networks. This general designation also includes ”furnace capacitors” and ”medium-frequency capacitors”, which cover the high reactive power requirement of melting furnaces and inductive heating coils, and also ”welding machine capacitors” and ”fluorescent lamp capacitors” used for compensating welding transformers and the ballasts of fluorescent lamps. The design of power capacitors is regulated by the following standards: DIN VDE 0560-1 (VDE 0560 Part 1), and IEC 60831-1 (VDE 0560 Part 46) – self-restoring up to 1000 V –, IEC 60931-3 (VDE 0560 Part 45) – non-self-restoring up to 1000 V – and IEC 60871-1 (VDE 0560 Part 410) – over 1000 V –.

The reactive power Q_C of a capacitor is determined by its capacitance C, the rms value of the operating voltage U and the system frequency f:

$$Q_C = 2 \cdot p \ \cdot f \cdot C \cdot U^2$$

The rated power of a capacitor Qr as stated on its nameplate is always in relation to its rated voltage U_r and rated frequency f_r.

In three-phase networks, three-phase capacitors are as a rule to be used. These consist of two-phase capacitors, connected together in either star or delta. For the same reactive power,

$$C_Y = 3 \cdot C_\Delta$$

Here:
C_Y: The capacitance in one phase with star connection, and
C_Δ: The capacitance in one phase with delta connection.

The temperature range for power capacitors is specified by the temperature classes (IEC 60831-1, Table 1). The following temperature values are applicable for the permissible ambient temperatures, e.g. for the -25°C class (preferred temperature class):

maximum:	50 °C,
max. average over 24 h:	40 °C,
max. average over 1 year:	30 °C,
minimum:	-25 °C.

Voltage and frequency increases and total harmonic distortion of the voltage or the current place additional stress on capacitors.

Capacitors must be able to carry continuously 1.3 times the current flowing with sinusoidal rated voltage and frequency at an ambient air temperature corresponding to their temperature class. With this loading, the voltage must not be higher than 1.1 U_r, no account being taken of transient overvoltages.

If the limiting conditions stated above are exceeded, the chosen capacitor must be replaced by one with a higher voltage rating and a rated power according to the equation

$$Q_{r2} = Q_{r1} \, (U_{r2}/U_{r1})^2.$$

1) We are thankful for contibutions provided by Condensator Dominit GmbH.

Where such a capacitor is directly connected to the system, the connection lines and the switching and protection devices must also be rated correspondingly higher. However, this does not ensure that the system conditions are compatible for other loads. For this reason, in most cases it is better to include inductor-capacitor units (see 12.3.3).

When selecting the switchgear apparatus, protective devices and conductors, attention must be paid to the possibility of overloading mentioned above. Taking account of the permissible difference in capacitance (+10%), this is (1.1 · 1.3) = 1.43 times the capacitor current rating.

HRC fuses serve only as short-circuit protection and do not provide adequate protection against overcurrents. It is therefore recommended that capacitors be protected against overcurrent by suitable overcurrent relays which should trip when the permissible overload is exceeded. Protection by means of overcurrent relays does not at the same time provide protection against overvoltages.

All capacitor installations must be connected direct to a means of discharge, without intervening isolators or fuses. Low-voltage capacitors must discharge in this way to a residual voltage of max. 75 V within 3 minutes. A maximum discharge time of 10 minutes is stipulated for high-voltage capacitors.

The residual voltage at the capacitor must not exceed 10 % of the rated voltage before reconnection.

When capacitors are connected in star, the neutral point must not be directly earthed. Indirect earthing via surge arresters (overvoltage protectors) is permissible.

For installation, connection and special protective measures, note must be taken of DIN VDE 0100, DIN VDE 0101, DIN VDE 0105 standards and the ”Technical connection requirements for power installations” of the responsible energy utility.

12.3.2 Compensation of reactive power

Many electrical loads draw not only active power, which, apart from the internal losses (expressed in the efficiency η), is made usable, but also require reactive power for their function. This reactive power is not measured by the active energy meter, but for customers with special rates it is recorded by corresponding reactive volt-ampere-hour meters and is subject to charges of a greater or lesser amount. Furthermore, the reactive power always has an unfavourable effect on the electrical equipment in that it constitutes an additional load on generators, transformers and conductors. It gives rise to additional voltage drops and heat losses.

Static reactive power compensation (SVC) is dealt with in section 11.6.

It is economically sound to draw the reactive power from capacitors, (figure 12-9). These are preferably to be located in the vicinity of the largest reactive loads (motors and transformers) in order to relieve the transmission networks, including transformers and generators, of the corresponding share of the reactive current and thus also avoid the costs of reactive energy. If the capacitors are properly positioned, by reducing the reactive current in this way, it is possible in many instances to connect additional loads to existing supply systems without having to increase the power or extent of the network.

Figure 12-10 shows the reactive power before correction as $Q_1 = P \cdot \tan \varphi_1$ and after correction as $Q_2 = P \cdot \tan \varphi_2$, where φ_2 is the phase displacement angle of the desired $\cos \varphi_2$. The required compensation power is calculated according to the following formula:

$$Q_c = P \cdot (\tan \varphi_1 - \tan \varphi_2)$$

Table 12-8 provides an aid to calculation.

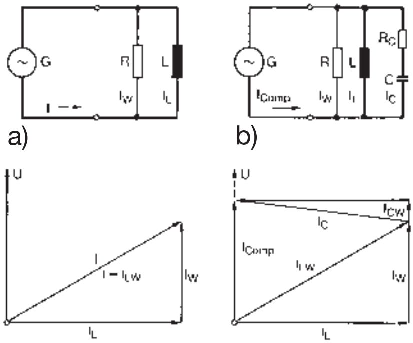

Fig. 12-9
Active and reactive currents in an electrical system:
a) uncompensated
b) compensated by capacitors
With full power factor correction, the generator G only has to supply the current I_w for the active load R and the active current Icw for the capacitor loss resistance R_c.

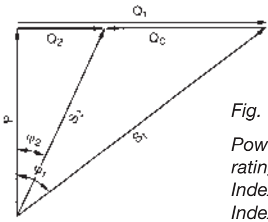

Fig. 12-10

Power vector diagram for determination of the capacitor rating QC for power factor correction;
Index 1: Values without correction,
Index 2: Values with correction.

Example:

A motor with a $\cos \varphi = 0.6$ draws an active power P = 60 kW from the network. The reactive power drawn by the motor, where $\tan \varphi = 1.333$, is Q = 60 kW · 1.333 = 80 kvar. If this reactive power is to be corrected by a capacitor to $\cos \varphi = 1$, the capacitor must correspondingly have a rating of 80 kvar.

In most cases, such extensive correction to cos j = 1 is not necessary. If, in the present case, a $\cos \varphi = 0.8$ would be sufficient (a frequent demand of power supply utilities), the capacitor rating can be calculated as follows:

$\cos \varphi_1 = 0.6$; $\tan \varphi_1 = 1.333$; desired $\cos \varphi_2 = 0.9$; $\tan \varphi_2 = 0.750$:

$Q_C = P \cdot (\tan \varphi_1 - \tan \varphi_2)$

Q_C = 60 kW · (1.333 – 0.750) = 60 kW · 0.583 = 35 kvar.

A calculation factor of 0.85 can be read off from table 12-8 for an improvement in the $\cos \varphi$ from 0.6 to 0.9. Therefore, to simplify:

Q_C = P · 0.85 = 60 kW · 0.58 = 34.8 kvar.

The capacitor is therefore only to be dimensioned for approximately this reactive power.

Table 12-8

Determination of the factor (tan φ_1 – tan φ_2) calculation of the reactive power at various power factors cos φ_1

Existing power factor cos φ_1	Desired power factor cos φ_2 0.70	0.75	0.80	0.85	0.90	0.92	0.94	0.96	0.98	1.00
0.30	2.16	2.30	2.43	2.56	2.70	2.75	2.82	2.89	2.98	3.18
0.35	1.66	1.79	1.93	2.06	2.19	2.25	2.31	2.38	2.47	2.68
0.40	1.27	1.41	1.54	1.67	1.81	1.87	1.93	2.00	2.09	2.29
0.45	0.96	1.10	1.23	1.36	1.50	1.56	1.62	1.69	1.78	1.98
0.50	0.71	0.85	0.98	1.11	1.25	1.31	1.37	1.44	1.53	1.73
0.52	0.62	0.76	0.89	1.02	1.16	1.22	1.28	1.35	1.44	1.64
0.54	0.54	0.68	0.81	0.94	1.07	1.13	1.20	1.27	1.36	1.56
0.56	0.46	0.60	0.73	0.86	1.00	1.05	1.12	1.19	1.28	1.48
0.58	0.38	0.52	0.65	0.78	0.92	0.98	1.04	1.11	1.20	1.40
0.60	0.31	0.45	0.58	0.71	0.85	0.91	0.97	1.04	1.13	1.33
0.62	0.25	0.38	0.52	0.65	0.78	0.84	0.90	0.97	1.06	1.27
0.64	0.18	0.32	0.45	0.58	0.72	0.77	0.84	0.91	1.00	1.20
0.66	0.12	0.26	0.39	0.52	0.65	0.71	0.78	0.85	0.94	1.14
0.68	0.06	0.20	0.33	0.46	0.59	0.65	0.72	0.79	0.88	1.08
0.70		0.14	0.27	0.40	0.54	0.59	0.66	0.73	0.82	1.02
0.72		0.08	0.21	0.34	0.48	0.54	0.60	0.67	0.76	0.96
0.74		0.03	0.16	0.29	0.42	0.48	0.55	0.62	0.71	0.91
0.76			0.11	0.24	0.37	0.43	0.49	0.56	0.65	0.86
0.78			0.05	0.18	0.32	0.38	0.44	0.51	0.60	0.80
0.80				0.13	0.27	0.32	0.39	0.46	0.55	0.75
0.82				0.08	0.21	0.27	0.34	0.41	0.49	0.70
0.84				0.03	0.16	0.22	0.28	0.35	0.44	0.65
0.86					0.11	0.17	0.23	0.30	0.39	0.59
0.88					0.06	0.11	0.18	0.25	0.34	0.54
0.90						0.06	0.12	0.19	0.28	0.48
0.92							0.06	0.13	0.22	0.43
0.94								0.07	0.16	0.36

The value read from the table is to be multiplied by the active power P in kW to obtain the required capacitor rating Q_C in kvar.

The electricity supply utilities generally specify a cos φ of approx. 0.9. Compensation beyond cos φ = 1.0 (overcompensation) is to be avoided as this gives rise to capacitive (leading) reactive power which stresses the conductors in the same way as inductive (lagging) reactive power, and unwelcome voltage increases ΔU can occur.

$$\Delta U \approx \frac{Q}{S} \cdot U$$

Where:

U: Voltage without capacitor
Q: Reactive power of the capacitor
S: Network short-circuit power

Power factor correction with non-choked capacitors is not directly permissible in networks to which sources of harmonics such as converters are connected.

The network impedance and capacitor bank form a parallel resonant circuit, the resonant frequency of which is:

$$f_R = \frac{f_N}{2 \cdot \pi \cdot \sqrt{L_N} \cdot \sqrt{C}}$$

f_N: Rated network frequency (e.g. 50 Hz)
L_N: Phase value of the network/load inductance
C: Capacitor capacitance

In a first approximation, this resonant frequency can also be calculated from the network short-circuit power S and the compensating power Q_{C1} at rated network frequency f_N.

$$f_R = \frac{\sqrt{S}}{\sqrt{Q_{C1}}} \cdot f_N$$

At this resonant frequency, the source of harmonics (e.g. rectifier) encounters a higher network impedance. In consequence, the harmonic current causes a larger harmonic voltage than in an uncompensated network, which can result in unacceptably severe distortion of the voltage. Transient currents whose values can be a multiple of the exciting current harmonic flow between the network and capacitor. Transformers and particularly capacitors are thus subjected to additional stresses and can become overloaded.

It should be noted that impermissible levels of harmonics can be caused in the network by non-choked capacitors, even without separate sources of harmonics. From the point of view of the superimposed network, namely, the transformer impedance and capacitor bank form a series resonant circuit. Only a relatively low harmonic voltage in the superimposed network can cause a high current if the frequency of the harmonic voltage is close to the resonant frequency. Here too, then, there is a risk of overloading.

12.3.3 Inductor-capacitor units (detuned filters)

Since the resonant frequencies of parallel and serial resonant circuits can be calculated from the network inductance and the capacitor rating, it appears possible to position the resonant point so that it creates little disturbance. As, however, the network short-circuit power can change in response to switching conditions, and furthermore loads are constantly being connected and disconnected in the network and power factor correction systems are designed to be switched in stages, the resonant frequency will shift according to the network constellation and pass through critical zones of resonance.

In order to avoid resonance problems, inductor-capacitor units (detuned filters) should be used. In these, a reactor coil is connected in series with each capacitor, and the resonant frequency f_{LC} of this configuration set to a level which is below the lowest typical harmonic frequency. The impedance of the inductor-capacitor unit is capacitive below f_{LC} and inductive above f_{LC}, i.e. the resonant circuit formed by the network inductance and inductor-capacitor unit cannot find any resonant point with frequencies above f_{LC}. Neither a critical parallel resonance nor a critical serial resonance arises with the harmonics in the network.

The reactor coil is determined by its relative impedance at the fundamental wave (choking factor p):

$$p = \frac{X_L}{X_c}$$

Where:
X_L : Reactance of the reactor coil
X_C : Reactance of the capacitor

$$f_{LC} = \frac{f_1}{\sqrt{p}}$$

In general, the 5th harmonic is the lowest frequency with a non-negligible disturbance level. In this case, f_{LC} must be $< 5 \cdot f1$, i.e. a choking factor of $p > 4\%$ is to be selected. In practice, it is then appropriate to perform correction with p = 7% so that a sufficient difference is achieved between the natural frequency of the correction stage and the 5th harmonic.

A network can also be burdened with the 3rd harmonic between phases, for instance from single-phase rectifiers and overexcited transformers. In these cases, $f_{LC} < 3 \cdot f_1$ must apply, i.e. a choking factor of $p > 11.1\%$ is to be selected. In practice, it is appropriate to perform correction with a choking factor p = 12.5%.

12.3.4 Filter circuit systems (tuned filters)

If the power of the harmonic source in a network is relatively high in relation to the network short-circuit power, and this causes impermissibly high harmonic voltages at the busbars or impermissibly high harmonic currents to be fed back to the superimposed network, the use of filter circuit systems (tuned filters) can be necessary. These filter circuit systems absorb harmonic currents, preventing them from being fed back into the superimposed network and significantly reducing the harmonic voltage level. It is important to consider the entire network if filter circuit systems are to be correctly dimensioned.

The function of a filter circuit system is therefore not only that of improving the displacement factor (fundamental power factor cos φ), but also of improving the power factor λ in total ($\lambda = P/S$; $\cos \varphi = P_1/S_1$; Index 1: Fundamental wave). It should be noted that not only a displacement factor cos φ which is too low, but also a power factor λ which is too low can give rise to extra charges in some countries.

A filter circuit system contains one or more tuned filter units, which as a rule consist of a reactor and capacitor in series. They are tuned in such a way that comparatively low impedances in relation to the network impedance result from the harmonic frequencies to be filtered. At network frequency a filter circuit system functions like a capacitor bank to improve the power factor cos φ. If this should be undesirable, counter-compensation can be integrated. In general, the filter units in a filter circuit system only have to be rated for the typical 6-pulse harmonics, i.e. the 5th, 7th, 11th, 13th etc. Where a strong 3rd harmonic is generated (e.g. by induction furnaces, heating systems with generalized phase control, etc.) this frequency may also have to be taken into account.

Normally, all the tuned filter units in a filter circuit system are switched together. If it is necessary to switch the filter units independently, they must be switched on in the sequence of ascending ordinals, i.e. 5^{th}, 7^{th}, 11^{th}, etc., and switched off in the reverse order. Filter units connected in parallel with the same centred frequency require automatic tolerance trimming to ensure even distribution of the current.

12.3.5 Ripple control compatibility of PF correction systems

In networks with audio frequency ripple control systems, it must be ensured that the signals transmitted are not impermissibly reduced nor impermissibly increased. The existing signal frequencies must be known, and compatibility ensured with the type of correction applied (non-choked capacitors, inductor-capacitor units, filter circuit systems, etc.) and its ratings.

12.3.6 Methods of power factor correction

Individual correction

The phase-shifting capacitor is coupled direct to the terminals of the load and switched in common with it. The advantages are reduced load on distribution lines and switchgear, no capacitor switches or quick-discharge resistors are required, and installation is simple and inexpensive. This technique is preferably used for relatively large individual loads.

Individual correction of three-phase motors

For fixed motor correction, the motor and capacitor are switched on and off by the same switching device and are monitored by the same protection system. The capacitor discharges through the motor windings. Nevertheless, regulations require the capacitor to be fitted with a safety discharge system.

To avoid over-compensation at partial load and self-excitation of the motor as it runs down after disconnection, correction may amount to only 90 % of the open-circuit reactive power.

The permissible capacitor rating for correction Q_C is:

$$Q_c = 0.9 \cdot \sqrt{3} \cdot U \cdot I_0$$

I_0 No-load current of the motor

At full load, a cos φ of over 0.95 is normally achieved in this way, and at no-load it is close to 1. For a correction requirement above this, the capacitor needs its own switching device and may then also require an additional quick-discharge system.

For star-delta starting of motors equipped with capacitors, see figure 12-11. On the topic of motor starting, see also section 12.3.7, ”Motor start-up correction”.

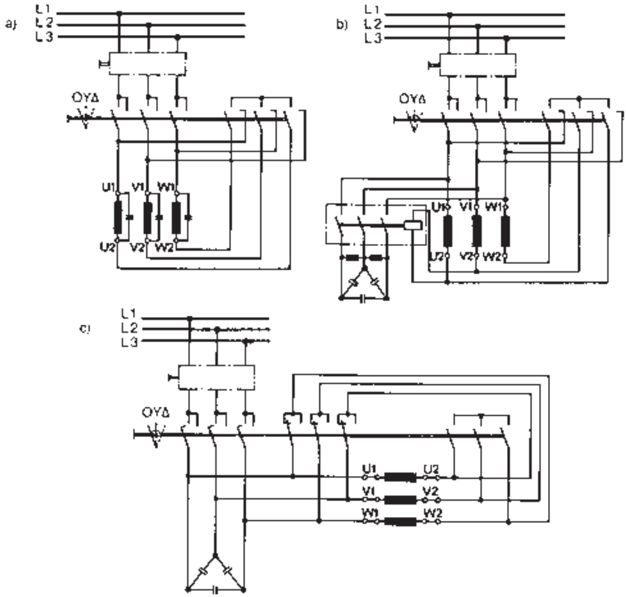

Fig. 12-11

PF correction of a three-phase motor:
a) When using a normal star-delta switch
b) Connection of capacitor in the delta position of the star-delta switch
c) With a special star-delta switch

Operating sequence of switching elements on starting: Change from "off" to "star": 1. Delta connections open, 2. Network connection closes, 3. Neutral point connections close;

Change from "star" to "delta": 1. Neutral point connections open, 2. Delta connections close. The sequence is reversed when stopping.

Individual correction of transformers

Direct connection of a capacitor to a transformer, together with which it is switched on and off, is possible and permissible on both the HV and LV sides.

According to VDEW specifications, when connecting capacitors on the low-voltage side, the capacitor ratings must be as stated in table 12-9. It must however be noted that permanent transformer correction of this kind is no longer desired by several power supply utilities.

Table 12-9

Connection of capacitors to the low voltage side of transformers

Transformer rating kVA	Transformer voltage, HV side 5 . . . 10 kV Capacitor rating kvar	15 . . . 20 kV Capacitor rating kvar	25 . . . 30 kV Capacitor rating kvar
25	2	2,5	3
50	3,5	5,0	6
75	5	6	7
100	6	8	10
160	10	12,5	15
250	15	18,0	22
315	18	20,0	24
400	20	22,5	28
630	28	32,5	40

If capacitors in a network have to be choked on account of excessive harmonics, this is also to be taken into account in the permanent transformer correction.

Individual correction of welding equipment

The capacitor rating for welding transformers and resistance welding machines can be between 30 and 50 % of the transformer rating. In the case of welding rectifiers, a capacitor rating of approximately 10% of the nominal rating is sufficient.

Welding equipment with large, variable power consumption, which generally also have a welding duration of only a few line periods, should preferably have dynamic PF correction. On the subject of dynamic loads, see also section 12.3.7, "Dynamic correction".

Group correction

The capacitors are connected to the distribution bus feeding, for example, a large number of small motors running continuously or intermittently, figure 12-12.

The motors and capacitors are switched by separate switches and monitored by separate protection systems. The capacitors can be switched on and off individually or in groups, as required.

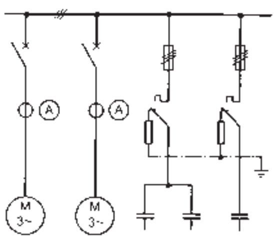

Fig. 12-12

Group correction.

Centralized correction

In comparatively large installations with many small and medium-size loads (motors, etc.) which are not usually in operation at the same time, the phase-shifting capacitors are connected centrally to the main busbar. The capacitors are switched either manually (figure 12-13a) or automatically via reactive power controllers (figure 12-13b), as required.

Advantage: Automatic control allows the capacitor rating to be closely matched to the reactive power required at any time, thus keeping cos j closer to the specified value in a cost-effective manner. The required correction rating is generally significantly lower than with individual correction, as it is rare for all the electrical loads to be in operation at the same time.

Disadvantage: Distribution lines between the busbar and points of consumption still carry the same reactive current.

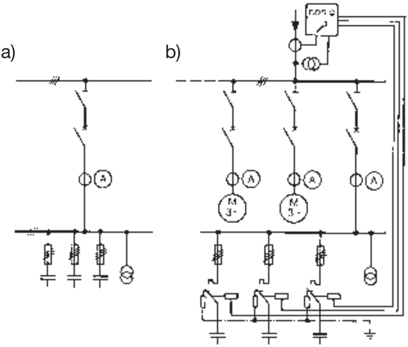

Fig. 12-13

Centralized correction:
a) Total correction
b) Correction with automatic control

HRC fuses, preferably for each capacitor, are to be provided for short-circuit protection. The reconnection time is to be taken into account when specifying the discharge system. The capacitor must be discharged to max. 10% of its rated voltage before connection.

Reactive power controllers function with single phase current measurement. With uneven load distribution, i.e. significantly different drawing of reactive power through the individual external conductors, no clear correction to the desired cos j is therefore ensured. In such cases, the use of an additional measuring system which supplies the controller with a measuring current corresponding to an equivalent symmetrical load distribution in terms of level and phase angle is recommended. On the topic of asymmetrical load distribution, see also section 12.3.7, ”Load balancing”.

12.3.7 Special correction systems

Capacitor banks serve to improve network quality. This is not always purely a matter of reducing load and avoiding reactive energy costs, but frequently also of improving voltage quality to avoid network problems. The following examples represent only a selection from the variety of applications.

Load balancing

Two-phase system frequency furnaces (e.g. quartz smelters) not only draw a large amount of reactive power; they also cause voltage unbalance, which, for example, leads to high losses in three-phase motors and therefore is only marginally permissible. For that reason, apart from the power factor correction system proper in parallel with the furnace, a load balancing system with capacitors and inductors following the principle of the Steinmetz circuit is required (see figure 12-14).

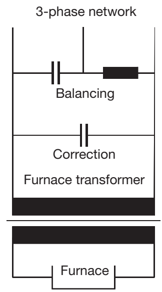

Fig. 12-14

Furnace correction with load balancing (Steinmetz circuit)

In most cases, correction and balancing are controlled manually, but fully automatic control is also possible. With full correction and balancing, the furnace then functions as a symmetrical three-phase purely resistive load.

An excessive voltage unbalance caused by uneven load distribution can be compensated for by the same principle, preferably with automatic control.

Motor start-up correction

On start-up, a motor draws a multiple of its rated current. This can cause various problems:

- Impermissibly great voltage dips, and disruption of the function of other loads

- Excitation and tripping of protection systems

- Motor fails to start as short-circuit power is too low

As this start-up current is predominantly reactive current, the required relief of load on the network and thus also maintenance of the voltage can be achieved by a reactive current compensation system with appropriately rapid reaction and a special motor starting controller. In the case of frequent motor starts (e.g. lifts or cranes) a system with a thyristor switch (see section on "Dynamic correction”) is preferably to be used.

Dynamic correction

Even with frequent, major load fluctuations, a conventional correction system whose stages are switched by power contactors can ensure that the power supply utility's requirement regarding the average power factor cos j is maintained. The necessary voltage stability and an effective reduction in transmission losses cannot however be achieved with such a system.

In such cases, dynamic power factor correction should preferably be used. As the correction stages are switched by thyristors which are triggered at equal voltage, the capacitor discharge can be disregarded. As a result, a reaction time of only one to two line periods can be achieved. A further advantage is that capacitors are switched by thyristors free of transients, and therefore even large correction ratings can be connected to the network without problems.

Flicker correction

Load changes cause voltage fluctuations. Even minor voltage fluctuations can, if they occur very frequently, lead to flickering (disturbing light fluctuations in lighting systems). One typical problem area here is that of spot welding machines, and in particular powerful grid welding systems, with

- large welding power,
- high cycle rates,
- asymmetrical network loads, and
- low power factors.

This problem can also be countered by dynamic power factor correction. Here, however, the requirements are significantly higher with a reaction time of below 5 milliseconds. It is also insufficient merely to compensate for the reactive current, as also the active power and load unbalance cause voltage changes which require correction.

12.4 Resistor devices

Resistor devices for low and high voltage are used in switchgear installations as

- Damping resistors for high-pass filters, in conjunction with arc suppression coils and for limiting capacitive and inductive overvoltages,
- Earthing resistors for earthing the neutrals of transformers and generators and also for earth fault protection,
- Loading resistors,
- Voltage dividers,
- Discharge resistors for capacitors,
- Transition and series resistors for tap changers,
- Starting and braking resistors and rheostats for electric motors.

The live parts are in the form of wire or cast elements or corrugated sheet-steel lattices. These components are made up into assemblies with ceramic insulators and can take the form of banks mounted on a frame.

Insulators are used for medium and high voltages.

In a resistor unit, electrical energy is converted into heat which the body of the resistor can absorb only partly and only for a very short time. It must always be dissipated to the ambient air. Resistor units are therefore usually air-cooled. Natural ventilation is generally sufficient. Separate ventilation or oil cooling is advisable in special cases.

The resistor elements normally have a tolerance of $\pm$ 10 %. Smaller tolerances are possible in special cases.

The rise in temperature, which can be up to about 400 K, increases the resistance. With cast iron resistors, for example, the resistance increase is 7.5 %/100 K (Table 12-10). When the maximum temperature of about 400 °C is reached, a nominal initial current of 600 A has fallen to 460 A.

Resistors are often not designed for a 100 % load factor, but only to operate for a limited time. If during this short period the load duration $t_B < T_\vartheta$, a higher loading is permissible. The maximum load duration t_{Bmax} during which the resistor element heats up to the permitted temperature limit with an overload of $I_a = a \cdot I_r$, is

$$t_{Bmax} = T_\vartheta \cdot \ln\left(\frac{a^2}{a^2 - 1}\right).$$

A sufficiently long interval must then follow to allow complete cooling.

Example:

Earthing resistors in medium and high-voltage installations for impedance earthing of generator and transformer neutrals must limit the earth fault current to values of 0.5 to 0.75 I''_{k3}. The resulting values are no danger, particularly with regard to electrical machines, and voltage rises due to any capacitive effects of network asymmetry are avoided. Also, in branched networks, a defined active current can be produced which makes it easier to measure and localize an earth fault. The load factor for these earthing resistors is governed by the protective devices in question and their speed of response.

For example, an earth resistor of this kind must limit the earth fault current to 400 A. The fault is cleared quickly. Cast iron resistors are chosen with a continuous load capacity of I_r = 60 A. Their thermal time constant is T_ϑ = 450 s. The maximum load duration is thus

$$t_{Bmax} = T_\vartheta \cdot \ln\left(\frac{a^2}{a^2-1}\right) = 450\ \text{s} \cdot \ln\left(\frac{(400/60)^2}{(400/60)^2-1}\right) = 10.25\ \text{s}.$$

Such earthing resistors are usually sized to operate for 10 s.

Table 12-10

Characteristics of commercially available resistor elements

Characteristics	Form of resistor elements Wire elements	Cast iron elements	Sheet steel grid
Material	CuNi44 (Constantan) NiCr8020 NiCr 6015 NiCr 3020[1)] CrNi 2520[1)]	Surface-treated cast iron	Corrosion-resistant steel sheet CrNi alloy steel sheet
Resistance of individual elements at 20 °C	150–0.5 Ω	02–0.01 Ω	0.75–0.04 Ω
Continuous load capacity of elements	0.5–20 A max. working temperature ϑ_{max} = 200 °C[1)] (CuNi44) ϑ_{max} = 1200 – 1300 °C[1)] NiCr (heating conductor)	25–125 A	25–250 A
Therm. time constant T_ϑ	20-90 s	240-600 s	120 s
Resistance increase with temperature	0.4%/100 K	7.5%/100 K	5%/100 K
Insulation level to housing to earth across insulators	 600 V/1 kV 3.6-52 kV	 1 kV 3.6-52 kV	 1 kV 3.6-52 kV

1) Ellen Ivers-Tiffée, Waldemar von Münch, Werkstoffe der Elektronik, 9. Auflage, Teuber Verlag 2004

12

12.5 Converter (rectifiers)

Semiconductor rectifiers are used exclusively today for rectifying alternating currents.

Rectifier assemblies are identified according to IEC 60146.

Table 12-11 shows a summary of calculation data for common rectifier circuits. The symbols denote the following:

u_2 = Instantaneous value of applied AC voltage

U_2 = Root-mean-square value of applied AC voltage

u_g = Instantaneous value of rectified voltage

U_g = Arithmetic mean of rectified voltage

U_{go} = Open-circuit DC voltage

i_g = Instantaneous value of rectified current

I_g = Arithmetic mean of rectified current

Tabelle 12- 11

Basic calculation data for common rectifier connections

Connection to	Alternating current			3-phase AC
Connection	Half-wave	Centre-tap	Bridge	3-phase bridge
Circuit diagram	Fig. 12-14	Fig. 12-15	Fig. 12-16	Fig. 12-17
No. of pulses p	1	2	2	6
Fundamental frequency of superimposed AC voltage (Hz)	50	100	100	300
Open-circuit DC voltage U_{do}/U_2	$\frac{\sqrt{2}}{\pi} = 0,45$	$\frac{\sqrt{2}}{\pi} = 0,45$	$\frac{2\sqrt{2}}{\pi} = 0,9$	$\frac{3\sqrt{2}}{\pi} = 1,35$
Rating of each valve as regards voltage for as regards current for	 U_2 I_g	 U_2 $\frac{1}{2} I_g$	 U_2 $\frac{1}{2} I_g$	 U_2 $\frac{1}{3} I_g$
Connected network power $P_1 / (U_{do} \cdot I_d)$	2,69	1,23 1,11[1)]	1,23 1,11[1)]	1,05
Mean transformer rating	3,09	1,49 1,34[1)]	1,23 1,11[1)]	1,05
Voltage ripple (in % von U_{do})	121,1	48,3	48,3	4,2

1) For operation with inductive load (e.g. large smoothing reactor)
All other figures apply to purely resistive load.

Common rectifier connections

1. *Half-wave connection, see Fig. 12-15*

   The simplest of all rectifier connections. It consists of a branch which blocks one half-wave of the applied AC voltage. The result is a pulsating DC voltage with gaps while the voltage is negative. This arrangement is normally used only for small currents (often in conjunction with capacitors) and up to very high voltages with a suitable number of plates or stacks connected in series. The rectifier assembly must block the full transformer voltage and when capacitors are used, their charging voltage as well.

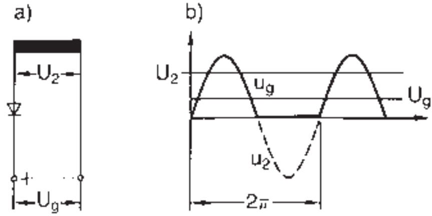

Fig. 12-15

Half-wave connection
a) Circuit diagram
b) Voltage curve

2. *Centre-tap connection, see Fig. 12-16*

   This arrangement requires a transformer which has a centre tap on its secondary winding. In the blocking direction, each branch carries the full transformer voltage. The connection is economical only for low voltages using the basic unit. For higher voltages requiring semiconductor devices to be connected in series, it is inferior to the following bridge connection because of the special transformer construction for the same number of plates. It is then appropriate only if suitable transformers are already available, i.e. when hot cathode or mercury vapour rectifiers are to be replaced by semiconductor units.

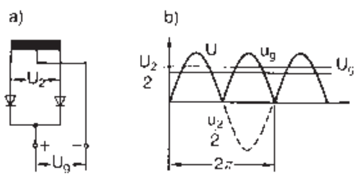

Fig. 12-16

Centre-tap connection
a) Circuit diagram
b) Voltage curve

3. Bridge connection, see Fig. 12-17.

Provided the voltages involved are not very low, in which case the centre-tap connection may be preferable, the bridge connection is the most practical and economical over a wide range of currents and voltages, and therefore the most commonly used of all single-phase arrangements. In the blocking direction, each of the 4 branches is subjected to the full transformer voltage.

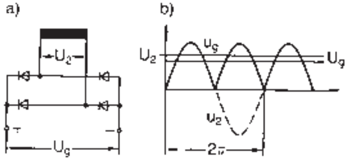

Fig. 12-17

Bridge connection
a) Circuit diagram
b) Voltage curve

4. 6-pulse Three-phase bridge connection, B6, see Fig. 12-18

This is the most convenient and economical connection for all relatively high powers at voltages exceeding those of the basic star or double-star connections. Here again, each of the 6 branches carries the phase-to-phase voltage in the blocking direction.

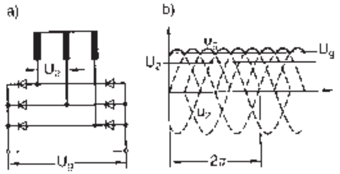

Fig. 12-18

Three-phase bridge connection
a) Circuit diagram
b) Voltage curve

5. Twelve pulse circuit, see figure 12-19

The twelve pulse circuits in power converter technology are an extension of the B6 bridge circuit. These circuits are obtained by connecting two six pulse bridge circuits in series or in parallel. The output voltages of the two converters are then at 30° to each other.

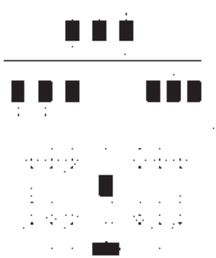

Fig. 12-19

6. Controllable IGBT (Insulated Gate Bipolar Transistor) converter (see figure 12-20)

Instead of a diode bridge, the rectifier can consist of a three-phase IGBT converter. As a result of the sine wave input current, the IGBT rectifier functions practically without feedback effects on the network. In consequence, no fault-susceptible and power-reducing filters to counter harmonics and compensate for reactive power are necessary.

Designed for uninterruptible power supply to critical systems such as computing centres, and also used in HVDC transmission systems, see section 11.5.

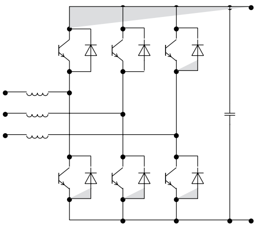

Fig. 12-20

13 Conductor Materials and Accessories for Switchgear Installations

13.1 Conductor bars, stranded conductors and insulators

13.1.1 Properties of conductor materials

Conductor bars for switchgear installations are made either of copper (Cu-ETP) or of aluminium (ENAW). Aluminium alloys with good electrical and mechanical properties are also used.

An advantage of aluminium is that a short-circuit arc gives rise mainly to non-conducting, dust-like residues of aluminium oxide. No metal is deposited on the neighbouring insulators or other components of the installation, thus limiting the extent of the damage. Open switchgear installations with aluminium busbars can therefore be reconnected much more quickly after a short-circuit arc.

The values given in Table 13-1 are typical values to be used in calculations concerning the construction of switchgear installations; the most important physical properties of commonly used conductor materials are compared in Table 13-2.

Table 13-1

Typical values for the properties of conductor materials

Designation Material	State	tensile - strenght R_m MPa min.	0,2%-yield-point R_{p02}, R'_{p02} [3] MPa	elongation at break A, A_{50}, A_{100} [1] % min.	hardness HV min.	hardness HV max.	Conductivity κ bei 20 °C MS/m min.
Copper							
Cu-ETP	D	—	—	—			58
Cu-ETP	H040	—	—	—	40	65	57
Cu-ETP	R200	200	max. 120	25…35			57
Cu-ETP	H090	—	—		90	110	55
Cu-ETP	R280	280	min. 240	8…10			56
Aluminium							
ENAW-1350A	- F	—			—		34,5
ENAW-1350A	- O	65	min. 20	20…26	20[2]		35,4
ENAW-1350A	- H 24	105	min. 75	3…8	33[2]		34,5
Malleable aluminium alloy							
ENAW-6101B	- T 6	215	min. 160	6…8	—	—	30
ENAW-6101B	- T 7	170	min. 120	10…12	—	—	32

[1] depends on material thickness
[2] only for information
[3] R_{p02} = min value R'_{p02} = max value

Table 13-2

Comparison of the most important properties of common conductor materials

Property		Copper Cu-ETP	Pure aluminium 99.5(A)	Pantal EAl MgSi(B)	Brass CuENBT	Steel (galvanized)
Density	kg/dm^3	8.9	2.7	2.7	8.5	7.85
El. conductivity at 20 °C	MS/m	58	35	30	≈ 18	≈ 7
El. conductivity at 60 °C	MS/m	48	30	26	≈ 16	≈ 6
Conductivity.../density...		6.3	13	11	≈ 2	≈ 1
Spec. resistance at 20 °C	$\Omega \cdot mm^2/m$	0.0178	0.0286	0.0333	≈ 0.0555	≈ 0.143
Temperature coeff. of el. resistance between 1 °C and 100 °C	K^{-1}	0.0038	0.0040	0.0036	0.0024	0.005
Melting point	° C	1083	658	630	≈ 912	1400
Heat of fusion	J/g	181.28	386.86	376.81	167.47	293.07
	J/cm^3	1612	1047	1017	1444	2 302
Mean spec. heat between 1 °C and 100 °C	$J/g \cdot K$	0.393	0.92	0.92	0.377	0.485
	$J/cm^3 \cdot K$	3.475	2.386	2.386	3.205	3.558
Thermal conductivity between 1 °C and 100 °C	$W/c \cdot K$	394	220	190	120	46
Mean coeff. of expansion between 1 °C and 100 °C	$mm/m \cdot K$	0.017	0.024	0.023	0.018	0.012
Young's modulus	GPa	110 000	65 000	70 000	≈ 90 000	210 000
Thermal limit current density[1)]	A/mm^2	154	102	89	91	
Melting current density[1)]	A/mm^2	3 060	1910	1 690	1900	

[1)] Thermal limit current density is the current density at which the conductor temperature rises from 35 °C to 200 °C when loaded for 1 s. Conductive heat removal disregarded.

Melting current density is the current density at which the conductor temperature rises to the melting temperature when loaded for 1⁄100 s. Values according to Müller-Hillebrand.

13.1.2 Conductor bars for switchgear installations

Maximum continuous temperatures to DIN 43 670 and DIN 43 671

for bar conductor screw connections to DIN 43 673,	
non-oxidized and greased	approx. 120 °C,
silvered, or equivalent treatment,	approx. 160 °C,
for post insulators and bushings to DIN VDE 0674 Part 1	approx. 85 °C,
for equipment terminals IEC 60694	bare approx 90 °C,
(VDE 0670 Part 1000)	tinned, silvered approx. 105 °C.

A convenient method of monitoring for thermal overload temperatures is to use temperature-sensitive paints. These change their original colour when certain temperatures are exceeded. The change persists after the painted item has cooled. The original colour is regained only gradually, under the influence of moisture in the air. The colour can be restored immediately by wetting. Temperature-sensitive paints can be applied to any surface. Oil or grease should first be removed with petrol or white spirit.

Influence of bar temperature on strength of conductor material

The strength of the conductor material decreases with rising temperature, and much more rapidly with aluminium than with copper. The values in Table 13-3 are valid for aluminium. For temperatures above 160 °C, they also depend on the duration of heating.

Table 13-3

Influence of temperature on the strength of aluminium

Temperature	20	100	160	250	°C
Tensile strength σ_B	90…130	90…120	80…110	70…30	N/mm²
Yield point $R_{p0.2}$	80…120	80…110	70…100	60…30	N/mm²
Elongation at fracture	10…5	10…5	11…7	to 60	%

Under short-circuit conditions, therefore, conductor temperatures of 200 °C for aluminium and for copper must not be exceeded, see VDE 0103.

If items of equipment are influenced only very slightly, or not at all, by the thermal behaviour of the busbars, the maximum permissible conductor temperature is governed only by the long-term thermal strength of the conductors and their insulation.

This is the case, for example, with busbars which owing to sufficiently long connections are not thermally coupled to their associated equipment.

Profile selection and arrangement for alternating current

The cross-sectional shape of busbar conductors has a considerable influence not only on their bending strength, but also on their electrical load capacity.

With direct current, there is no skin effect, so in this case the shape of the conductor is important only with regard to the heat-emitting surface area. For direct current, therefore, it is preferable to use flat bars or continuously cast conductors of large cross section.

With alternating current, on the other hand, skin effect and other factors cause an increase in the conductor resistance, and this must be kept small by selecting an appropriate section profile. The effect the shape and arrangement of component conductors of the same total cross-section area can have on the current-carrying capacity of busbars for AC is illustrated in Fig. 13-1.

If the current permits, one or two flat conductors per phase are provided, thus simplifying installation. Two conductors is the most favorable number from the standpoint of losses, and is therefore to be preferred.

For higher currents, four flat conductors have proved to be an effective arrangement. The distance between the second and third conductor has to be increased in order to achieve a better current distribution. Increasing the distance from 10 to 30 mm produces no significant improvement. It has been shown that with a distance of 70 mm, the relative currents in the individual conductors differ by only $\pm$ 7%.

The loading on the four conductors is then:

Conductor	1	2	3	4
Current carried as % of total current	26.7	23.3	23.3	26.7

If four flat conductors per phase are not sufficient, then channel sections are considered. These have favorable skin effect properties. If even more flat conductors were to be used, the result would be a comparatively large cross-section which, in addition, is very uneconomical. For example, an arrangement with seven conductors would give the following current distribution among the conductors:

Conductor	1	2	3	4	5	6	7
Relative current %	25.6	14.2	7.5	5.4	7.5	14.2	25.6

For high currents in low-voltage installations, when using flat conductors, the simplest solution is to split up large composite conductors by dividing the three phases among smaller cross sections, Fig. 13-2. These then have a significantly lower eddy-current factor and also a smaller inductive voltage drop.

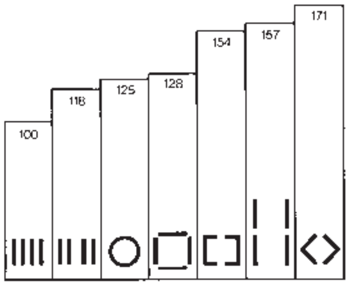

Fig. 13-1

Current-carrying capacity per cent of some busbar conductor arrangements of the same total cross-section area

Fig. 13-2

Arrangement of a three-phase bus with four parallel conductors per phase:
a) Usual arrangement with the three phases L_1, L_2, L_3 next to each other
b) Conductors in split phase arrangement L_1, L_2, L_3, L_1, L_2, L_3 …

Continuous current-carrying capacity

The Tables 13-4 to 13-12 below give values for the continuous current-carrying capacity of different cross-sections of *copper* (see DIN 43671) and *aluminium* (see DIN 43670).

For *indoor installations*[1)], the tables are based on the following assumptions:

1. ambient air still,
2. bare conductors partly oxidized, giving a radiation coefficient of 0.40 (Cu) and 0.35 (Al), or
3. conductors painted (only the outside surfaces in the case of composite busbars), giving a radiation coefficient of approx. 0.90.

For *outdoor installations,* the tables are based on the following assumptions:

1. slight air movement, e.g. due to ground thermals, of 0.6 m/s,
2. bare conductors normally oxidized, giving a radiation coefficient of 0.60 (Cu) and 0.50 (Al), possible solar irradiation 0.45 (Cu) and 0.35 (Al) kW/m^2, or
3. conductors painted, giving a radiation coefficient of approx. 0.90 and solar irradiation of 0.7 kW/m^2.
   The values for outdoor installations thus correspond to central European conditions.

[1)] For open-type indoor installations, the values stated in the tables can be multiplied by between 1.05 and 1.1 since it is found that slight air movements independent of the busbars occur in such cases.

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Continuous current-carrying capacity of copper conductors (DIN 43 671)

Table 13-4

Copper conductors of rectangular cross-section in indoor installations. Ambient temperature 35 °C. Conductor temperature 65 °C. Conductor width vertical: clearance between conductors equal to conductor thickness; with alternating current, clearance between phases > 0.8 × phase centre-line distance.

Width × thickness	Cross-section	Weight[1]	Material[3]	Continuous current in A AC up to 60 Hz painted no. of conductors 1	2	3	4	bare no. of conductors 1	2	3	4	Continuous current in A DC and AC 16⅔ Hz painted no. of conductors 1	2	3	4	bare no. of conductors 1	2	3	4
mm	mm²	kg/m	Cu-ETP																
12 × 5	59.5	0.529	R 350	203	345	411		177	312	398		203	345	411		177	312	398	
12 × 10	119.5	1.063	R 350	326	605	879		285	553	811		326	605	879		285	553	811	
20 × 5	99.1	0.882	R 350	319	560	728		274	500	690		320	562	729		274	502	687	
20 × 10	199	1.77	R 350	497	924	1 320		427	825	1 180		499	932	1 300		428	832	1 210	
30 × 5	149	1.33	R 350	447	760	944		379	672	896		448	766	950		380	676	897	
30 × 10	299	2.66	R 350	676	1 200	1 670		573	1 060	1 480		683	1 230	1 630		579	1 080	1 520	
40 × 5	199	1.77	R 350	573	952	1 140		482	836	1 090		576	966	1 160		484	848	1 100	
40 × 10	399	3 55	R 350	850	1 470	2 000	2 580	715	1 290	1 770	2 280	865	1 530	2 000		728	1 350	1 880	

[1] Calculated for a density of 8.9 kg/dm³.

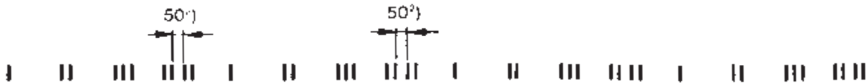
[2] Minimum clearance given in mm.

[3] Material: actual designation acc EN 13601.

Continued on next page

Table 13-4 (continued)

Copper conductors of rectangular cross-section in indoor installations. Ambient temperature 35 °C. Conductor temperature 65 °C. Conductor width vertical: clearance between conductors equal to conductor thickness; with alternating current, clearance between phases > 0.8 × phase centre-line distance.



Width × thickness	Cross-section	Weight[1]	Material[3]	Continuous current in A AC up to 60 Hz painted no. of conductors 1	2	3	4	bare no. of conductors 1	2	3	4	Continuous current in A DC and AC 16⅔ Hz painted no. of conductors 1	2	3	4	bare no. of conductors 1	2	3	4
mm	mm²	kg/m	Cu-ETP																
50 × 5	249	2.22	R 350	679	1 140	1 330	2 010	583	994	1 240	1 920	703	1 170	1370		588	1 020	1 300	
50 × 10	499	4.44	R 300	1 020	1 720	2 320	2 950	852	1510	2 040	2 600	1 050	1 830	2 360		875	1 610	2 220	
60 × 5	299	2.66	R 300	826	1 330	1 510	2 310	688	1 150	1 440	2 210	836	1 370	1 580	2 060	696	1 190	1 500	1 970
60 × 10	599	5.33	R 300	1 180	1 960	2 610	3 290	985	1 720	2 300	2 900	1 230	2 130	2 720	3 580	1 020	1 870	2 570	3 390
80 × 5	399	3.55	R 300	1 070	1 680	1 830	2 830	885	1 450	1 750	2 720	1 090	1 770	1 990	2 570	902	1 530	1 890	2 460
80 × 10	799	7.11	R 300	1 500	2 410	3 170	3 930	1 240	2 110	2 790	3 450	1 590	2 730	3 420	4 490	1 310	2 380	3 240	4 280
100 × 5	499	4.44	R 300	1 300	2 010	2 150	3 300	1 080	1 730	2 050	3 190	1 340	2 160	2 380	3 080	1 110	1 810	2 270	2 960
100 × 10	988	8.89	R 300	1 810	2 850	3 720	4 530	1 490	2 480	3 260	3 980	1 940	3 310	4100	5 310	1 600	2 890	3 900	5 150
120 × 10	1 200	10.7	R 300	2 110	3 280	4 270	5 130	1 740	2 860	3 740	4 500	2 300	3 900	4 780	6 260	1 890	3 390	4 560	6 010
160 × 10	1 600	14.2	R 300	2 700	4 130	5 360	6 320	2 220	3 590	4 680	5 530	3 010	5 060	6 130	8 010	2 470	4 400	5 860	7 710
200 × 10	2 000	17.8	R 300	3 290	4 970	6 430	7 490	2 690	4 310	5 610	6 540	3 720	6 220	7 460	9 730	3 040	5 390	7 150	9 390

[1] Calculated for a density of 8.9 kg/dm³.

[2] Minimum clearance given in mm.

[3] Material designation acc EN 13601.

Table 13-5

Copper conductors of annular cross-section, ambient temperature 35 °C, conductor temperature 65 °C, with alternating current, phase centre-line distance ≧ 2.5 × outside diameter

Outside diameter D mm	Wall-thickness a mm	Cross-section mm²	Weight[1)] kg/m	Material[2)] Cu-ETP	Continuous in A DC and AC up to 60 Hz indoor painted	bare	outdoor painted	bare
20	2	113	1.01	R 360	384	329	460	449
	3	160	1.43	R 360	457	392	548	535
	4	201	1.79	R 290	512	438	613	599
	5	236	2.10	R 290	554	475	664	648
	6	264	2.35	R 250	591	506	708	691
32	2	188	1.68	R 360	602	508	679	660
	3	273	2.44	R 360	725	611	818	794
	4	352	3.14	R 290	821	693	927	900
	5	424	3.78	R 290	900	760	1 020	987
	6	490	4.37	R 250	973	821	1 100	1 070
40	2	239	2.13	R 360	744	624	816	790
	3	349	3.11	R 360	899	753	986	955
	4	452	4.04	R 290	1 020	857	1 120	1 090
	5	550	4.90	R 290	1 130	944	1 240	1 200
	6	641	5.72	R 250	1 220	1 020	1 340	1 300
50	3	443	3.95	R 360	1 120	928	1 190	1 150
	4	578	5.16	R 290	1 270	1 060	1 360	1 310
	5	707	6.31	R 290	1 410	1 170	1 500	1 450
	6	829	7.40	R 250	1 530	1 270	1 630	1 570
	8	1 060	9.42	R 250	1 700	1 420	1 820	1 750
63	3	565	5.04	R 290	1 390	1 150	1 440	1 390
	4	741	6.61	R 290	1 590	1 320	1 650	1 590
	5	911	8.13	R 290	1 760	1 460	1 820	1 750
	6	1 070	9.58	R 250	1 920	1 590	1 990	1 910
	8	1 380	12.3	R 250	2 150	1 780	2 230	2 140
80	3	726	6.47	R 290	1 750	1 440	1 760	1 690
	4	955	8.52	R 290	2 010	1 650	2 020	1 930
	5	1 180	10.5	R 290	2 230	1 820	2 230	2 140
	6	1 400	12.4	R 250	2 430	1 990	2 440	2 340
	8	1 810	16.1	R 250	2 730	2 240	2 740	2 630
100	3	914	8.15	R 290	2 170	1 770	2 120	2 020
	4	1 210	10.8	R 290	2 490	2 030	2 430	2 320
	5	1 490	13.3	R 290	2 760	2 250	2 700	2 580
	6	1 770	15.8	R 250	3 020	2 460	2 950	2 820
	8	2 310	20.6	R 250	3 410	2 780	3 330	3 180

1) Calculated for a density of 8.9 kg/dm³. Preferred outside diameters in heavy type.

2) Material designation acc EN 13600.

Table 13-6

Copper conductors of round cross-section (round copper bar), ambient temperature 35 °C, conductor temperature 65 °C; with alternating current, phase centre-line distance ≧ 2 × diameter.

Diameter D mm	Cross-section a mm²	Weight[1)] kg/m	Material[2)] Cu-ETP	Continuous current in A DC and AC up to 60 Hz painted	 bare
5	19,6	0,175	R 350	95	85
8	50,3	0,447	R 350	179	159
10	78,5	0,699	R 350	243	213
16	210	1,79	R 300	464	401
20	314	2,80	R 300	629	539
32	804	7,16	R 300	1 160	976
50	1960	17,50	R 300	1 930	1 610

1) Calculated for a density of 8.9 kg/dm³.
2) Material designation acc EN 13600.

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Continuous current-carrying capacity of aluminium conductors (DIN 43670)

Table 13-7

Aluminium conductors of rectangular cross-section in indoor installations. Ambient temperature 35 °C. Conductor temperature 65 °C. Conductor width vertical: clearance between conductors equal to conductor thickness; with alternating current, clearance between phases > 0.8 × phase centre-line distance.

Width × thickness	Cross-section	Weight[1]	Material[3]	Continuous current in A AC up to 60 Hz painted no. of conductors 1	2	3	4	bare no. of conductors 1	2	3	4	Continuous current in A DC and AC 16⅔ Hz painted no. of conductors 1	2	3	4	bare no. of conductors 1	2	3	4
mm	mm²	kg/m	ENAW-1350 A-1350				50[2])				50[2])								
12 × 5	59.5	0.160	H 14	160	292	398		139	263	375		160	292	398		139	263	375	
12 × 10	119.5	0.322	H 14	257	490	720		224	440	652		257	490	720		224	440	652	
20 × 5	99.1	0.268	H 14	254	446	570		214	392	537		254	446	576		214	392	539	
20 × 10	199	0.538	H 14	393	730	1 060		331	643	942		393	733	1 020		331	646	943	
30 × 5	149	0.403	H 14	356	606	739		295	526	699		356	608	749		296	528	703	
30 × 10	299	0.808	H 14	536	956	1340		445	832	1 200		538	964	1 280		447	839	1 180	
40 × 5	199	0.538	H 14	456	762	898		376	658	851		457	766	915		376	662	862	
40 × 10	399	1.08	H 14	677	1 180	1 650	2 190	557	1 030	1 460	1 900	682	1200	1 570		561	1 040	1 460	
50 × 5	249	0.673	H 14	556	916	1 050	1 580	455	786	995	1 520	558	924	1 080		456	794	1 020	
50 × 10	499	1.35	H 14	815	1 400	1 940	2 540	667	1 210	1 710	2 210	824	1 140	1 850		674	1 250	1 730	
60 × 5	299	0.808	H 14	655	1 070	1 190	1 820	533	910	1 130	1 750	658	1 080	1 240	1 610	536	924	1 170	1 530
60 × 10	599	1.62	H 14	951	1 610	2 200	2 870	774	1 390	1 940	2 480	966	1 680	2 130	2 810	787	1 450	2 000	2 650

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Table 13-7 (continued)

Width × thickness	Cross-section	Weight[1]	Material[3]	Continuous current in A AC up to 60 Hz painted no. of conductors				bare no. of conductors				Continuous current in A DC and AC 16⅔ Hz painted no. of conductors				bare no. of conductors			
				1	2	3	4	1	2	3	4	1	2	3	4	1	2	3	4
m			ENAW- 1350 A - 1350 -				50[2]				50[2]								
mm	mm²	kg/m																	
80 × 5	399	1.08	H 112[4]	851	1 360	1 460	2 250	688	1 150	1 400	2 180	858	1 390	1 550	2 010	694	1 180	1 470	1 920
80 × 10	799	2.16	H 112[4]	1 220	2 000	2 660	3 460	983	1 720	2 380	2 990	1 250	2 150	2 670	3 520	1 010	1 840	2 520	3 340
100 × 5	499	1.35	H 14	1 050	1 650	1 730	2 660	846	1 390	1 660	2 580	1 060	1 710	1 870	2 420	858	1 450	1 780	2 320
100 × 10	999	2.70	H 14	1 480	2 390	3 110	4 020	1 190	2 050	2 790	3 470	1 540	2 630	3 230	4 250	1 240	2 250	3 060	4 050
100 × 15	1 500	4.04	H 14	1 800	2 910	3 730	4 490	1 450	2 500	3 220	3 380	1 930	3 380	4 330	5 710	1 560	2 900	4 070	5 400
120 × 10	1 200	3.24	H 14	1 730	2 750	3 540	4 560	1 390	2 360	3 200	3 930	1 830	3 090	3 770	4 940	1 460	2 650	3 580	4 730
120 × 15	1 800	4.86	H 14	2 090	3 320	4 240	5 040	1 680	2 850	3 650	4 350	2 280	3 950	5 020	6 610	1 830	3 390	4 740	6 280
160 × 10	1 600	4.32	H 14	2 220	3 470	4 390	5 610	1 780	2 960	4 000	4 820	2 380	4 010	4 820	6 300	1 900	3 420	4 590	6 060
160 × 15	2 400	6.47	H 14	2 670	4 140	5 230	6 120	2 130	3 540	4 510	5 270	2 960	5 090	6 370	8 380	2 370	4 360	6 040	8 000
200 × 10	2 000	5.40	H 14	2 710	4 180	5 230	6 660	2 160	3 560	4 790	5 710	2 960	4 940	5 880	7 680	2 350	4 210	5 620	7 400
200 × 15	3 000	8.09	H 14	3 230	4 950	6 240	7 190	2 580	4 230	5 370	6 190	3 660	6 250	7 740	10 160	2 920	5 350	7 370	9 750

1) Calculated for a density of 2.7 kg/dm³.

2) Minimum clearance given in mm.

3) Material: material designation acc to DIN 40501-2 (see also section 16.2.2)

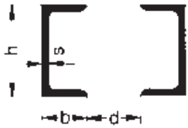
4) Alternative H 111 and 0 possible.

Table 13-8

Aluminium conductors of U-section in indoor installations, ambient temperature 35 °C, conductor temperature 65 °C.

When facing [ ], gap vertical; with alternating current, phase centre-line distance ≧ 2*h*

Material: E-Al or other material to DIN 40501 Part 3; semi-finished product to be used; channel sections to DIN 46424.

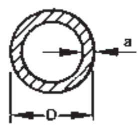


Dimensions				Cross-section		Weight[1)]		Material[2)]	Continuous current in A DC and AC up to 60 Hz			
									painted		bare	
h	*b*	*s*	*d*	[	[ ]	[	[ ]	1350 A-	[	[ ]	[	[ ]
mm	mm	mm	mm	mm²	mm²	kg/m	kg/m	1350 -				
60	30	4	25	448	896	1.22	2.44	H 112[3)]	880	1 800	685	1 370
80	37.5	6	25	858	1 720	2.32	4.64	H 12	1 460	2 540	1 140	2 000
100	37.5	8	25	1 270	2 540	3.47	6.94	H 12	2 000	3 450	1 550	2 700
120	45	10	30	1 900	3 800	5.17	10.3	H 12	2 720	4 700	2 100	3 750
140	52.5	11	35	2 450	4 900	6.66	13.3	H 12	3 350	5 800	2 600	4 600
160	60	12	40	3 070	6 140	8.34	16.7	H 12	4 000	7 000	3 100	5 400
180	67.5	13	45	3 760	7 520	10.2	20.4	H 12	4 750	8 200	3 800	6 400
200	75	14	50	4 510	9 020	12.2	24.4	H 12	5 500	9 500	4 300	7 400

1) Calculated for a density of 2.7 kg/dm³.
2) Material: ENAW-1350 A and ENAW-1350 acc DIN 40501-2, U-Profile acc DIN 46424
3) Alternative H 111 and 0 possible.

Table 13-9

Aluminium conductors of annular cross-section, ambient temperature 35 °C, conductor temperature 65 °C; with alternating current, phase centre-line distance ≧ 2.0 × outside diameter.



Outside diameter	Wall-thickness	Cross-section	Weight[1)]	Material[2)]	Continuous current in A DC and AC up to 60 Hz		Continuous current in A	
D	a			1350 A	indoor		outdoor	
mm	mm	mm²	kg/m	1350 -	painted	bare	painted	bare
20	2	113	0.305	H 14	305	257	365	354
	3	160	0.433	H 14	363	305	435	421
	4	201	0.544	H 14	407	342	487	472
	5	236	0.636	H 14	440	370	527	511
	6	264	0.713	H 14	465	392	558	540

1) Calculated for a density of 2.7 kg/dm³. Preferred outside diameters in heavy type.
2) Minimum clearance given in mm.
3) Material: material designation acc to DIN 40501-2 (see also section 16.2.2)
Continued on next page

Outside diameter D mm	Wall-thickness a mm	Cross-section mm²	Weight[1)] kg/m	Material[2)] 1350 A 1350 -	Continuous current in A DC and AC up to 60 Hz indoor painted	indoor bare	outdoor painted	outdoor bare
32	2	188	0.509	H 14	478	395	539	519
	3	273	0.739	H 14	575	476	649	624
	4	352	0.950	H 14	653	539	737	708
	5	424	1.15	H 14	716	592	808	777
	6	490	1.32	H 14	769	636	868	835
40	2	239	0.645	H 14	591	485	648	621
	3	349	0.942	H 14	714	595	783	750
	4	452	1.22	H 14	813	667	892	854
	5	550	1.48	H 14	896	734	982	941
	6	641	1.73	H 14	966	792	1 060	1020
50	4	578	1.56	H 14	1 010	822	1 080	1030
	5	707	1.91	H 14	1 120	909	1 190	1 140
	6	829	2.24	H 14	1 210	983	1 290	1 230
	8	1 060	2.85	H 112[3)]	1 370	1 110	1 460	1390
	10	1 260	3.39	H 112[3)]	1 490	1 210	1 580	1 510
63	4	741	2.00	H 14	1 270	1 020	1 310	1 240
	5	911	2.46	H 14	1 400	1 130	1 450	1 380
	6	1 070	2.89	H 14	1 520	1 230	1 570	1 490
	8	1 380	3.73	H 112[3)]	1 730	1 390	1 790	1 700
80	4	955	2.58	H 14	1 600	1 280	1 600	1 510
	5	1 180	3.18	H 14	1 770	1 420	1 780	1 680
	6	1 400	3.77	H 14	1 920	1 540	1 930	1 820
	8	1 810	4.89	H 112[3)]	2 200	1 760	2 200	2 080
	10	2 200	5.94	H 112[3)]	2 410	1 920	2 420	2 280
100	4	1 210	3.26	H 14	1 980	1 570	1 930	1 820
	5	1 490	4.03	H 14	2 200	1 750	2 150	2 020
	6	1 770	4.78	H 14	2 390	1 900	2 340	2 200
	8	2 310	6.24	H 112[3)]	2 740	2 170	2 670	2 510
120	4	1 460	3.94	H 14	2 360	1 860	2 250	2 100
	5	1 810	4.88	H 14	2 620	2 070	2 500	2 340
	6	2 150	5.80	H 14	2 860	2 250	2 730	2 550
	8	2 820	7.60	H 112[3)]	3 270	2 580	3 120	2 920
	10	3 460	9.33	H 112[3)]	3 590	2 830	3 420	3 200
160	4	1 960	5.29	H 14	3 110	2 430	2 910	2 710
	5	2 440	6.57	H 14	3 460	2 710	3 240	3 010
	6	2 900	7.84	H 14	3 780	2 950	3 530	3 290
	8	3 820	10.3	H 112[3)]	4 340	3 390	4 060	3 780
	10	4 710	12.7	H 112[3)]	4 760	3 720	4 460	4 140

Continued on next page

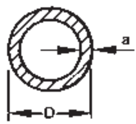
Table 13-9 (continued)

Outside diameter D mm	Wall-thickness a mm	Cross-section mm²	Weight[1)] kg/m	Material[2)] 1350 A - 1350 -	Continuous current in A DC and AC up to 60 Hz indoor painted	bare	Continuous current in A outdoor painted	bare
200	5	3 060	8.27	H 14	4 290	3 330	3 960	3 670
	6	3 660	9.87	H 14	4 690	3 640	4 320	4 000
	8	4 830	13.0	H 112[3)]	5 390	4 180	4 970	4 600
	10	5 970	16.1	H 112[3)]	5 920	4 600	5 460	5 060
	12	7 090	19.1	H 112[3)]	6 330	4 910	5 830	5 400
250	5	3 850	10.4	H 14	5 330	4 100	4 840	4 460
	6	4 600	12.4	H 14	5 810	4 480	5 280	4 870
	8	6 080	16.4	H 112[3)]	6 690	5 160	6 080	5 610
	10	7 540	20.4	H 112[3)]	7 360	5 680	6 690	6 170
	12	8 970	24.2	H 112[3)]	7 870	6 070	7 150	6 600

Continuous current-carrying capacity of Al Mg Si conductors

Table 13-10

Conductors of E-AlMgSi 0.5 F 22, annular cross-section, κ = 30 m/Ωmm² at ambient temperature 35 °C and conductor temperature 85 °C with AC, phase centre-line distance ≧ 2 × outside diameter



Outside diameter D mm	Wall-thickness a mm	Cross-section mm²	Weight kg/m	Continuous current in A[1)] DC and AC up to 60 Hz indoor painted	bare	outdoor painted	bare
20	2	113	0.305	372	314	446	432
	3	160	0.433	443	372	531	514
	4	201	0.544	497	418	595	576
	5	236	0.636	537	452	643	624
	6	264	0.713	568	479	681	659
32	2	188	0.509	584	482	658	634
	3	273	0.739	702	581	792	762
	4[2)]	352	0.950	797	658	900	864
	5	424	1.15	874	723	987	949
	6	490	1.32	939	777	1 060	1 020
40	2	239	0.645	721	592	791	758
	3	349	0.942	872	714	958	916
	4	452	1.22	993	814	1 089	1 042
	5[2)]	550	1.48	1 094	896	1 199	1 149
	6	641	1.73	1 179	967	1 294	1 245

Continued on next page

Table 13-10 (continued)

Outside diameter D mm	Wall-thickness a mm	Cross-section mm²	Weight kg/m	Continuous current in A[1] DC and AC up to 60 Hz indoor painted	bare	outdoor painted	bare
50	4[2]	578	1.56	1 233	1 004	1 319	1 258
	5	707	1.91	1 368	1 110	1 453	1 392
	6	829	2.24	1 477	1 200	1 575	1 502
	8[2]	1 060	2.85	1 673	1 355	1 783	1 697
	10	1 260	3.39	1 819	1 477	1929	1844
63	4	741	2.00	1 551	1 245	1 600	1 514
	5[2]	911	2.46	1 709	1 380	1 770	1 685
	6	1 070	2.90	1 856	1 502	1 917	1 819
	8[2]	1 380	3.73	2 112	1 697	2 186	2 076
80	4	955	2.58	1 954	1 563	1 954	1 844
	5[2]	1 180	3.18	2 161	1 734	2 173	2 051
	6[2]	1 400	3.77	2 344	1 880	2 357	2 222
	8[2]	1 810	4.89	2 686	2 149	2 686	2 540
	10	2 200	5.94	2 943	2 344	2 955	2 784
100	4	1 210	3.26	2 420	1 915	2 355	2 220
	5	1 490	4.03	2 685	2 135	2 625	2 466
	6	1 770	4.78	2 920	2 320	2 855	2 685
	8	2 310	6.24	3 345	2 650	3 260	3 065
120	4	1 460	3.94	2 880	2 270	2 745	2 565
	5	1 810	4.88	3 200	2 525	3 055	2 855
	6	2 150	5.80	3 490	2 745	3 335	3 115
	8	2 820	7.60	3 995	3 150	3 810	3 565
	10	3 460	9.33	4 385	3 455	4 175	3 905
160	4	1 960	5.29	3 795	2 965	3 555	3 310
	5	2 440	6.57	4 225	3 310	3 955	3 675
	6	2 900	7.84	4 615	3 600	4 310	4 015
	8	3 820	10.3	5 300	4 140	4 955	4 615
	10	4 710	12.7	5 810	4 540	5 445	5 055
200	5	3 060	8.27	5 240	4 065	4 835	4 480
	6	3 660	9.87	5 725	4 445	5 275	4 885
	8	4 830	13.0	6 580	5 105	6 070	5 615
	10	5 970	16.1	7 230	5 615	6 665	6 180
	12	7 090	19.1	7 730	5 995	7 120	6 595
250	5	3 850	10.4	6 510	5 005	5 910	5 445
	6	4 600	12.4	7 095	5 470	6 445	5 945
	8	6 080	16.4	8 170	6 300	7 425	6 850
	10	7 540	20.4	8 985	6 945	8 170	7 535
	12	8 970	24.2	9 610	7 410	8 730	8 060

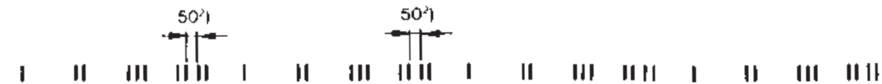
[1] The currents have been calculated from Table 13-9 with account taken of the correction factors k_1 = 0.925 as in Fig. 13-3 and k_2 = 1.32 as in Fig. 13-4. With an ambient temperature of 50 °C and a conductor temperature of 85 °C, the currents must be multiplied by the correction factor 0.82.

[2] Preferred wall thickness

Continuous current-carrying capacity of copper-clad aluminium conductors (DIN 43 670, Part 2)

Table 13-11

Copper-clad aluminium conductors of rectangular cross-section in indoor installations, ambient temperature 35 °C, conductor temperature 65 °C. Conductor width vertical: clearance between conductors equal to conductor thickness; with alternating current, clearance between phases > 0.8 × phase centre-line distance.



Width × thickness	Cross-section	Weight[1)]	Continuous current in A AC up to 60 Hz painted no. of conductors				bare no. of conductors				Continuous current in A DC and AC 16⅔ Hz painted no. of conductors				bare no. of conductors			
			1	2	3	4	1	2	3	4	1	2	3	4	1	2	3	4
mm	mm^2	kg/m																
12 × 5	59.8	0.217	177	324	440		154	292	416		177	324	442		154	292	416	
12 × 10	120	0.434	284	542	796		248	488	722		285	544	778		248	488	722	
20 × 5	98.7	0.358	265	464	594		225	415	562		265	464	600		225	415	565	
20 × 10	192	0.698	408	760	1 100		350	680	985		408	763	1 060		350	632	985	
30 × 5	148	0.538	370	630	772		313	555	733		370	632	780		313	556	736	
30 × 10	292	1.06	555	993	1 390		472	870	1 260		558	1 000	1 330		475	876	1 240	
40 × 5	198	0.719	474	794	937		400	700	895		475	798	953		400	702	905	
40 × 10	392	1.42	705	1 230	1 720	2 280	595	1 090	1 540	2 000	710	1 250	1 640		600	1 100	1 540	

Material: ENAW-1350A to DIN 40 501-2 and Cu-ETP to EN 13600 copper cladding comprises 15 % of cross-section area.

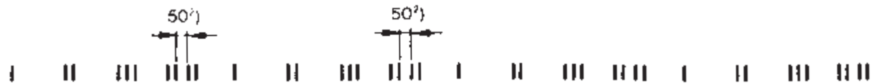
1) Calculated for a density of 3.63 kg/dm^3

2) Minimum clearance given in mm.

(continued)

Table 13-11 (continued)

Copper-clad aluminium conductors of rectangular cross-section in indoor installations. Ambient temperature 35 °C. Conductor temperature 65 °C. Conductor width vertical: clearance between conductors equal to conductor thickness; with alternating current, clearance between phases > 0.8 × phase centre-line distance.

Width × thickness	Cross-section	Weight[1]	Continuous current in A AC up to 60 Hz painted no. of conductors				bare no. of conductors				Continuous current in A DC and AC 16⅔ Hz painted no. of conductors				bare no. of conductors			
			1	2	3	4	1	2	3	4	1	2	3	4	1	2	3	4
mm	mm²	kg/m																
50 × 5	248	0.901	577	953	1 100	1 650	485	830	1 040	1 580	580	962	1 130		485	840	1 070	
50 × 10	492	1.79	850	1 460	2 020	2 650	705	1 280	1 890	2 340	860	1 500	1 930		713	1 320	1 810	
60 × 5	298	1.08	680	1 120	1 250	1 900	566	965	1 190	1 840	685	1 130	1 300	1 690	570	980	1 230	1 620
60 × 10	592	2.15	990	1 680	2 290	2 990	820	1 470	2 030	2 590	1 010	1 750	2 220	2 930	836	1 530	2 100	2 770
80 × 5	398	1.45	890	1 420	1 540	2 340	733	1 230	1 480	2 260	900	1 450	1 630	2 110	740	1 260	1 550	2 020
80 × 10	792	2.88	1 270	2 070	2 780	3 600	1 030	1 820	2 500	3150	1 310	2 240	2 800	3 670	1 070	1 950	2 650	3 500
100 × 10	992	3.60	1 540	2 500	3 230	4 180	1 270	2 170	2 940	3 670	1 600	2 740	3 360	4 420	1 320	2 390	3 200	4 200
120 × 10	1 192	4.32	1 870	2 850	3 640	4 540	1 540	2 480	3 250	3 980	1 980	3 320	4 330	5 620	1 630	2 880	4 130	5 360

Material: ENAW-1350A to DIN 40 501-2 and Cu-ETP to EN 13600 copper cladding comprises 15 % of cross-section area.

[1] Calculated for a density of 3.63 kg/dm^3
[2] Minimum clearance given in mm

Table 13-12

Copper-clad aluminium conductors of round cross-section in indoor installations, ambient temperature 35 °C, conductor temperature 65 °C; with alternating current, phase centre-line distance ≥ 1.25 × diameter.

Diameter mm	Cross section mm²	Weight[1)] kg/m	Continuous current in A DC and AC up to 60 Hz painted	bare
5	19.6	0.0713	78	70
8	50.3	0.182	148	132
10	78.5	0.285	201	177
16	201	0.730	386	335
20	314	1.14	525	452
32	804	2.92	1 000	850
50	1 960	7.13	1 750	1 500

Material: ENAW-1350A to DIN 40 501-2 and Cu-ETP to EN 13600 copper cladding comprises 15 % of cross-section area.

1) Calculated for a density of 3.63 kg/dm³

Correction factors for deviations from the assumptions

If there are differences between the actual conditions and the assumed conditions, the value of the continuous current taken from Tables 13-4 to 13-9, 13-11 and 13-12 must be multiplied by the following correction factors (DIN 43670, DIN 43670 Part 2 and DIN 43671):

k_1 correction factor for load capacity variations relating to conductivity,

k_2 correction factor for other air and/or busbar temperatures,

k_3 correction factor for thermal load capacity variations due to differences in layout,

k_4 correction factor for electrical load capacity variations (with alternating current) due to differences in layout,

k_5 correction factor for influences specific to location.

The current-carrying capacity is then

$$I_{cont} = I_{table} \cdot k_1 \cdot k_2 \cdot k_3 \cdot k_4 \cdot k_5.$$

The load capacity values for three-phase current with a frequency of 16⅔ Hz are the same as for direct current.

For frequencies $f_x > 50$ Hz, the load capacity value are calculated with the formula

$$I_x = I_{50} \sqrt{\frac{50}{f_x}}$$

Correction factor k_1

for load capacity variations relating to conductivity, see Fig. 13-3.

For example, in the case of the aluminium alloy E-AlMgSi 0.5 (κ = 30 m/Ωmm^2), the factor k_1 = 0.925.

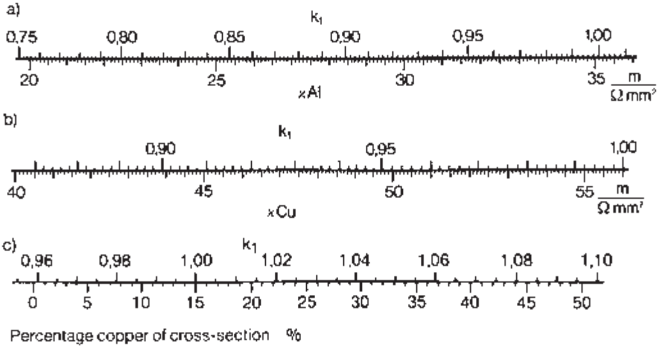


Fig. 13-3

Correction factor k_1 for variation of load capacity when conductivity differs a) from 35.1 m/ Ωmm^2 for aluminium materials and b) from 56 m/ Ωmm^2 for copper materials and c) factor k_1 for load capacity variation with copper-clad aluminium conductors having other than 15 % copper.

Correction factor k_2

for deviations in ambient and/or busbar temperature, see Fig. 13-4.

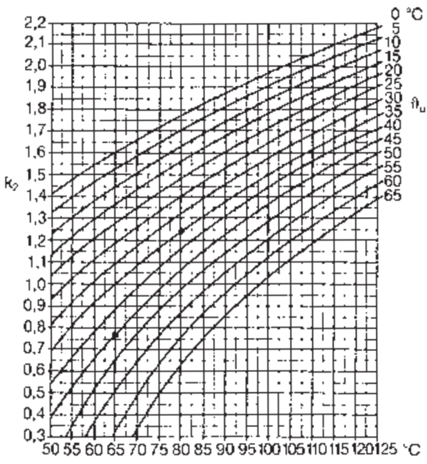


Fig. 13-4

Correction factor k_2 for load capacity variation at ambient temperatures other than 35 °C and/or busbar temperatures other than 65 °C;
ϑ_s busbar temperature,
ϑ_u mean ambient temperature over 24 hours, short-time maximum value 5 K above mean value.

When selecting the busbar cross-sections, attention must be paid to the maximum permissible operating temperature of the equipment and its connections, and also to heat-sensitive insulating materials. This applies in particular to metal-clad installations.

For example, at an ambient temperature of ϑ_u = 35 °C and an ultimate busbar temperature of ϑ_s = 80 °C (temperature rise 45 K), the factor k_2 = 1.24. With an ambient temperature of ϑ_u = 45 °C and an ultimate busbar temperature of ϑ_s = 65 °C (temperature rise 20 K), factor k_2 = 0.77.

Correction factor k_3

for thermal capacity load variations due to differences in layout, see Table 13-13.

Table 13-13

Correction factor k_3 for load capacity reduction with long side (width) of bus conductors in horizontal position or with busbars vertical for more than 2 m for Al = aluminium conductors DIN 43670, Al/Cu = copper-clad aluminium conductors DIN 43670 Part 2, Cu = copper conductors DIN 43671

Number of conductors		Width of busbar clearance mm	Thickness of conductor and painted mm	Factor k_3 when conductors bare Al	Al/Cu	Cu	Al	Al/Cu	Cu
		50…100	5…10	—	0.85	—	—	0.8	—
2		50…200		0.85	—	0.85	0.8	—	0.8
		50…80		0.85	0.85	0.85	0.8	0.8	0.8
3		100	5…10	—	0.8	—	—	0.75	—
		100…200		0.8	—	0.8	0.75	—	0.75
		up to 100		—	0.8	—	—	0.75	—
4	 	160		0.75	—	0.75	0.7	—	0.7
		200		0.7	—	0.7	0.65	—	0.65
2		up to 200		0.95	—	—	0.9	—	—

Correction factor k_4

for electrical load capacity variations (with alternating current) due to different layout, Fig. 13-5 for copper conductors, Fig. 13-6 for aluminium conductors and 13-7 for copper-clad aluminium conductors. Factor k_4 need be considered only if there is no branching within a distance of at least 2 m.

Correction factor k_5

Influences specific to the location (altitude, exposure to sun, etc.) can be allowed for with factor k_5 as given in Table 13-14.

Table 13-14

Correction factor k_5 for reduction in load capacity at altitudes above 1000 m.

Height above sea-level m	Factor k_5 indoors	Factor k_5 outdoors[1)]
1 000	1.00	0.98
2 000	0.99	0.94
3 000	0.96	0.89
4 000	0.90	0.83

[1)] Reduction smaller at geogr. amplitude above 60 ° and/or with heavily dust-laden air.

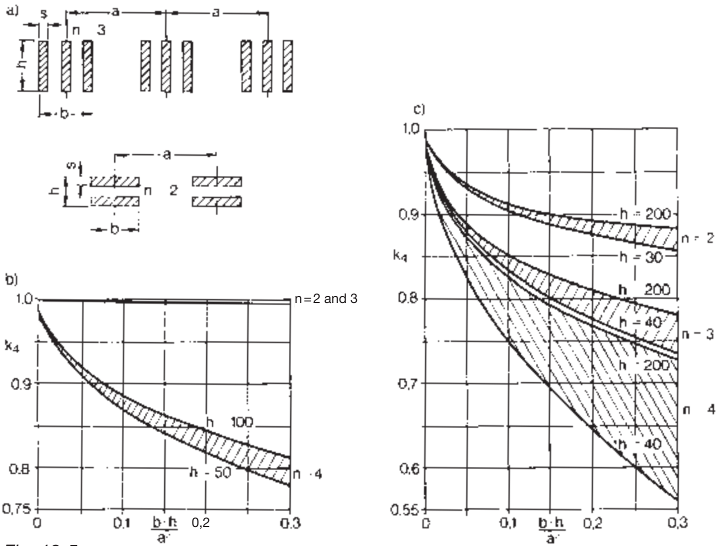
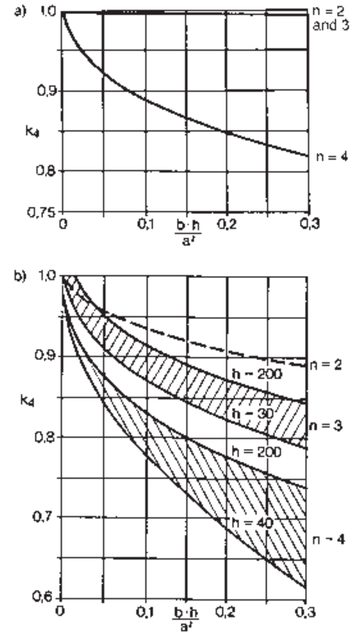


Fig. 13-5

Correction factor k_4 for reduction in load with alternating current up to 60 Hz due to additional skin effect in Cu conductors with small phase centre-line distance a:

a) Examples: Three-phase busbar with n = 3 conductors per phase and conductor thickness s in direction of phase centre-line distance a (above); AC single-phase busbar with n = 2 conductors per phase and conductor thickness s at right angles to phase centre-line distance a (below), b) Factor k_4 for conductors of s = 5 mm, and c) Factor k_4 for conductors of s = 10 mm as a function of $b \cdot h/a^2$; a, b and h in mm; parameter n = number of conductors per phase.



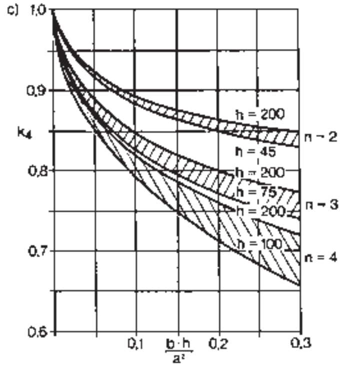


Fig. 13-6

Correction factor k_4 for reduction in load capacity with alternating current up to 60 Hz due to additional skin effect in Al conductors with small phase centre-line distance a; symbols as Fig. 13-5

a) Factor k_4 for conductor thickness s = 5 mm
b) Factor k_4 for conductor thickness s = 10 mm
c) Factor k_4 for conductor thickness s = 15 mm

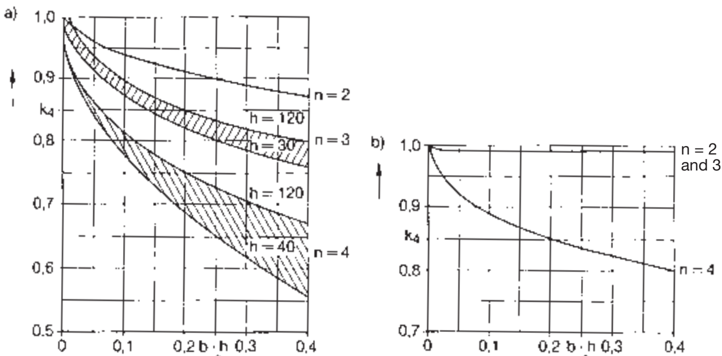


Fig. 13-7

Correction factor k_4 for reduction in load capacity with alternating current up to 60 Hz due to additional skin effect in copper-clad aluminium conductors with small phase centre-line distance a; symbols as Fig. 13-5

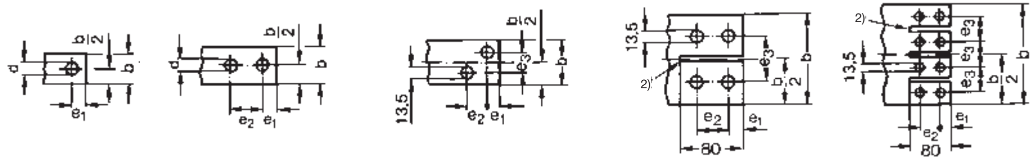
a) Factor k_4 for conductor thickness s = 10 mm
b) Factor k_4 for conductor thickness s = 5 mm

13.1.3 Drilled holes and bolted joints for busbar conductors[3)]

Table 13-15

Drilled holes for busbar conductors of rectangular cross-section (dimensions in mm)

	Conductor widths 12 to 50		25 to 60			60			80 to 120			160 to 200		
Shape[1)]	1		2			3			4			6		
Holes for conductor ends (drilling pattern)														
Drilling dimensions: Nominal width b	d	e_1	d	e_1	e_2	e_1	e_2	e_3	e_1	e_2	e_3	e_1	e_2	e_3
12	5.5	6	—	—	—	—	—	—	—	—	—	—	—	—
15	6.6	7.5	—	—	—	—	—	—	—	—	—	—	—	—
20	9.0	10	—	—	—	—	—	—	—	—	—	—	—	—
25	11	12.5	11	12.5	30	—	—	—	—	—	—	—	—	—
30	11	15	11	15	30	—	—	—	—	—	—	—	—	—



[1)] The shape coding 1 to 4 and 6 conforms to DIN 46206 Part 2 Flat connections.
[2)] With conductor widths of 120 mm and above, slots are to be provided in the end of one conductor or composite conductor. Permitted tolerance for hole-centre distance is ± 0.3 mm.
[3)] to DIN 43673 Parts 1 and 2

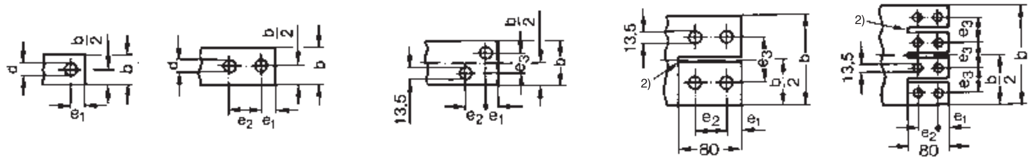
(continued)

Table 13-15 (continued)

Drilled holes for busbar conductors of rectangular cross-section (dimensions in mm)

Conductor widths	12 to 50		25 to 60			60			80 to 120			160 to 200		
Shape[1)]	1		2			3			4			6		

Holes for conductor ends (drilling pattern)



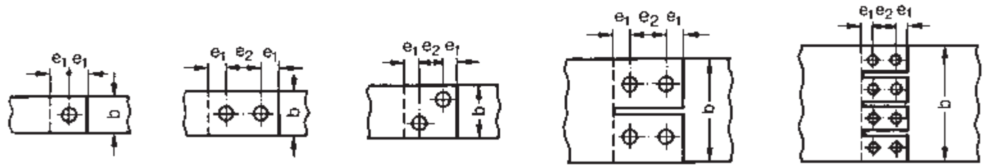
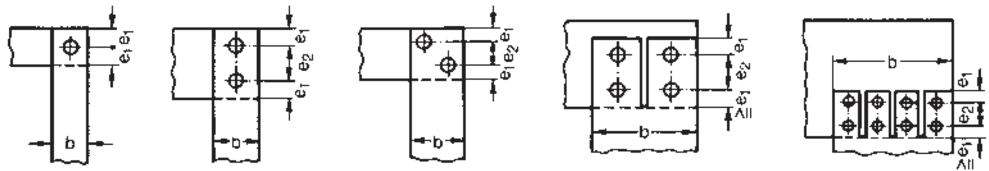
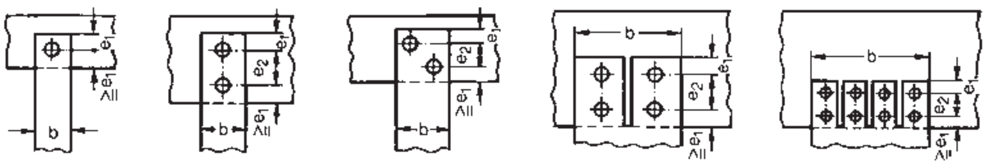
Drilling dimensions

Nominal width b	d	e_1	d	e_1	e_2	e_1	e_2	e_3	e_1	e_2	e_3	e_1	e_2	e_3
40	13.5	20	13.5	20	40	—	—	—	—	—	—	—	—	—
50	13.5	25	13.5	20	40	—	—	—	—	—	—	—	—	—
60	—	—	13.5	20	40	17	26	26	—	—	—	—	—	—
80	—	—	—	—	—	—	—	—	20	40	40	—	—	—
100	—	—	—	—	—	—	—	—	20	40	50	—	—	—
120	—	—	—	—	—	—	—	—	20	40	60	—	—	—
160	—	—	—	—	—	—	—	—	—	—	—	20	40	40
200	—	—	—	—	—	—	—	—	—	—	—	20	40	50

1) The shape coding 1 to 4 and 6 conforms to DIN 46 206 Part 2 Flat connections.
2) With conductor widths of 120 mm and above, slots are to be provided in the end of one conductor or composite conductor. Permitted tolerance for hole-centre distance is ± 0.3 mm.

Table 13-16

Examples of bolted joints for busbar conductors of rectangular section

Straight joints	
Angle joints	
T-joints	

Numerical values for *b, d,* e_1 and e_2 as Table 13-15.

Elongated holes are permissible in the end of one conductor or composite conductor.

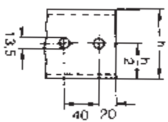
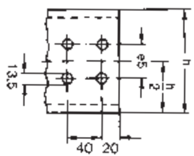
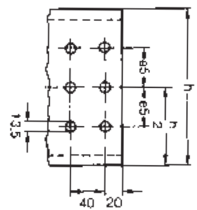
With joints having only one bolt, the conductors must be suitably supported to ensure that the joints cannot come loose.

With T-joints, the width of the horizontal conductors (generally busbar) is shown as greater than or equal to that of the tee-off. In the case of infeeds, however, if the horizontal conductor is symmetrically loaded, it is conceivable that it has only half the cross-section area. In this case, the T-joint is made with only the two upper holes.

Table 13-17

Drilled holes in U-section busbar conductors (dimensions in mm)

Holes in conductor ends

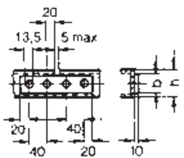
Conductor widths 60 and 80 mm	Conductor widths 100 to 160 mm	Conductor widths 180 to 200 mm
		

Numerical values for e_5 as Table 13-18. h = Height of U-section to DIN 46424. Permitted tol. for hole-centre distances: ± 0.3 mm.

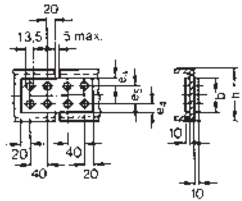
Table 13-18

Examples of straight-bolted joints in U-section busbar conductors

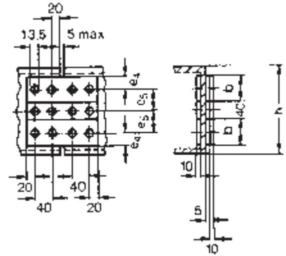
Conductor widths
60 and 80 mm

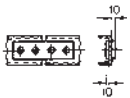


Conductor widths
100 to 160 mm

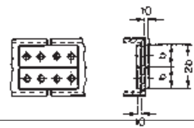


Conductor widths
180 and 200 mm





Other dimensions
as above

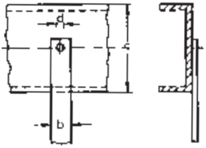


Other dimensions
as above

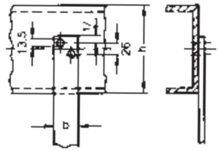
h	60	80	100	120	140	160	180	200
b	50	50	80	80	100	60	50	60
e_4	—	—	20	20	25	30	25	30
e_5	—	—	40	40	50	60	45	50

Table 13-19

Examples of bolted T-joints in U-section busbar conductors

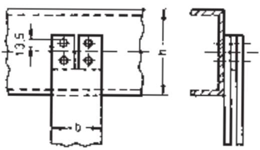


for b = 12 to 50 mm
suitable for all U-sections



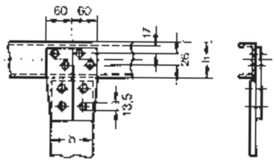
for b = 60 mm
for U-sections from U80 upwards

b	12	15	20	25	30	40	50	60
d	5.5	6.6	9	11	11	13.5	13.5	13.5



Shown for
b = 120 mm

for b = 80 to 120 mm
for U-sections from U100 upwards



b = 80 or 100 mm
for U-sections U80[1)] only

1) Required in this case is a fishplate comprising 2 rectangular-section bars 60 mm wide or a rectangular-section slotted bar 120 mm wide. The holes for fixing the 120 mm rectangular bar to the U80 section are then as for 2 rectangular-section bars 60 mm wide.

Designs for busbar bolts

The lubricants, referred to in Table 13-20, are commercially available. With stainless bolts and MoS_2-based lubricants attention must be paid to the specified total friction range. The various torques indicate that torque wrenches are advisable particularly with stainless bolts. The minimum contact pressure of 5 N/mm^2 is then maintained between – 5 °C and 90 °C and the bolts are not overstressed by short circuits. If there is any doubt regarding the friction factors of a bolt, it may be necessary to measure the torque and tension force on a sample with an appropriate number of bolts and to proceed in accordance with VDI 2230, Page 1, July 1986.

The figures in the Table are valid for DC and AC up to 60 Hz. Bolts A2-70 or A4-70 to ISO 3506 are recommended for AC above 6300 A.

Table 13-20

Design of bolted joints in busbar conductors

		Indoor	Indoor and outdoor	
Bolt Strength class		8.8 or higher to EN 20898-1	8.8 or higher to EN 20898-1	A2-70 or A4-70 to ISO 3506
Corrosion protection		A2G, A4G (gal Zn) B2G, B4G (gal Cd) to ISO 4042	tZn (hot galva- nized) to ISO 10684	—
Nut Strength class		8 or higher to EN 20898-2	8.8 or higher to EN 20898-2	A2-70, A4-70, A2-80 or A4-80 to ISO 3506
Corrosion protection		A2G, A4G (gal Zn) B2G, B4G (gal Cd) to ISO 4042	tZn (hot galva- nized) to ISO 10684	—
Spring element Spring washer[1)]		to DIN 6796 corrosion-protected	to DIN 6796	
Lubricant on thread and head contact face		oil or grease	on MoS_2 base	
Recommended	M 4	1.5	2	
nominal	M 5	2.5	3	
torque	M 6	4.5	5.5	
N · m	M 8	10	15	
on thread	M 10	20	30	
	M 12	40	60	
	M 16	80	120	

1) Other spring elements capable of maintaining the required contact pressure may be used. Flat washers may also be needed.

The nominal torques are selected so that softer materials experience a contact pressure of roughly 7 to 20 N/mm², except for some torque values with bolts M 10 and

M 12. The nominal torques are determined according to circumstances listed in Table 13-21.

Table 13-21

Conditions for calculating nominal torques

		Indoor	Indoor and outdoor	
Bolt, nut, surface		gal Zn, gal Cd	tZn	A2-70, A4-70
Lubricant		Oil or grease	on MoS_2 base	
Total friction coefficient μ_{tot} from		0.05	0.105	0.13
to		0.12	0.15	0.21
Tread	Engaged length (mm)	Minimum contact force obtained with nominal torque kN as Table 13-20 kN	kN	
M 4	4 to 8	1.55	1.40	
M 5	4 to 12	2.15	1.55	
M 6	4 to 18	3.20	2.60	
M8	4 to 60	4.15	3.95	
M 10	6 to 60	6.15	5.30	
M 12	10 to 120	12.6	15.1	
M 16	10 to 120	20.1	19.3	

The spring washers keep the clamping force on the bolt within acceptable limits and so secure the bolts sufficiently; if the force is inadequate, the bolt can work loose. These optimum values must be aimed for particularly on joints that are hard to access later.

It is important to note that, if necessary, agreement should be reached on test torques, taking into account the tolerances of the joints and tools.

Spring washers under bolt head and nut are recommended to increase the area of force transfer to the conductors. Footnote[1)] in Table 13-20 refers to equivalent solutions if the recommended spring washers are not used. Plain washers of equal area are also necessary if spring washers can be dispensed with, e.g. if aluminium joints are made with light-alloy bolts of sufficient strength so that differential thermal expansion does not occur.

It must be remembered that good contact between joined aluminium surfaces can be achieved only if the nonconducting oxide film is removed with a wire brush, file or similar immediately before joining, and renewed oxidation is prevented by applying a thin protective film of grease (neutral vaseline).

13.1.4 Technical values for stranded-wire conductors.

13.1.4.1 Designation system (to EN 50182)

AL1	Aluminium (hard-drawn)
ALx	Aluminium alloy x = 2 … 7 (type of aluminium-magnesium-silicon alloy)
AL1/STyz	Steel-reinforced aluminium conductor AL1 = Outer aluminium wires (sheath) STyz = Steel core y = 1 … 6 (tensile class of the steel) z = A … E (galvanizing class)
Alx/STyz	Steel-reinforced aluminium alloy conductor ALx = Outer wires of aluminium alloy (sheath) x = 2 … 7 (type of aluminium-magnesium-silicon alloy) STyz = Steel core y = 1 … 6 (tensile class of the steel) z = A … E (galvanizing class)
AL1/yzSA	Aluminium conductor reinforced with aluminium-sheathed steel wires AL1 = Outer aluminium wires (sheath) yzSA = Steel core (aluminium-sheathed steel wires) y = Type of steel (Grade A or B, only usable for 20SA) z = Class of aluminium sheathing (20, 27, 30 or 40)
ALx/yzSA	Aluminium alloy conductor reinforced with aluminium-sheathed steel wires ALx = Outer wires of aluminium alloy (sheath) x = 2 ... 7 (type of aluminium-magnesium-silicon alloy) yzSA = Steel core (aluminium-sheathed steel wires) y = Type of steel (Grade A or B, only usable for 20SA) z = Class of aluminium sheathing (20, 27, 30 or 40)
AL1/Alx	Aluminium conductor reinforced with aluminium alloy wires AL1 = Outer aluminium wires (sheath) ALx = Aluminium alloy core x = 2 ... 7 (type of aluminium-magnesium-silicon alloy)

13.1.4.2 Designation of the conductors

Conductors are designated as follows:

(a) Figure indicating the nominal cross-section of the aluminium or steel, rounded to an integer.

(b) Designation indicating the type of wires which make up the conductor. For composite conductors, the first part of the designation refers to the sheath and the second to the core.

EXAMPLES

- o 16-AL1: Conductor of aluminium AL1 with a cross-section of 15.9 mm², rounded to 16 mm².
- o 587-AL2: Conductor of aluminium AL2 with a cross-section of 586.9 mm², rounded to 587 mm².
- o 401-AL1/28-STI1A: Conductor of aluminium wires AL1, stranded around a core of steel wires STI1A of galvanizing class A. The integer cross-section of the AL1 wires is 401 mm², and that of the ST1 A wires is 28 mm².
- o 401-AL1/28-A2OSA: Conductor of aluminium wires AL1, stranded around a core of aluminium-sheathed steel wires of grade A, class 20. The integer cross-section of the AL1 wires is 401 mm², and that of the A2OSA wires is 28 mm².
- o 65-A2OSA: Conductor of aluminium-sheathed steel wires of grade A, class 20, with a cross-section of 65 mm².

Table 13-22

Copper wire conductors to DIN 48201 Part 1 (also refer to DIN 48203-1, EN 50341-3-4)

	Number of strands 7	19	37	61
Medium high tensile stress in N/mm²	85	85	85	85
Continuous tensile stress in N/mm²	300	300	300	300
Practical Young's modulus E in kN/mm²	113	105	105	100
Linear expansion coefficient ε_t $\left(\frac{10^{-6}}{K}\right)$	17	17	17	17
Cross-section weight force/length *QLK* $\left(\frac{N}{m \times mm^2}\right)$	0.0906	0.0906	0.0906	0.0906

Table 13-23

Copper wire conductors to DIN 48201 Part 1 (also refer to DIN 48203-1, EN 50341-3-4)

Nominal cross section mm²	Rated cross section mm²	Conductor configuration No. of strands × diameter mm	Diameter of cond. d mm	Calculated breaking force kN	Weight of cond. kg/m	Weight force/ length N/m	Additional ice load zone 1[1)] N/m	Ohmic resistance at 20 °C Ω/km
10	10.02	7 × 1.35	4.1	4.02	0.090	0.882	5.41	1.8055
16	15.89	7 × 1.70	5.1	6.37	0.143	1.402	5.51	1.1385
25	24.25	7 × 2.10	6.3	9.72	0.218	2.138	5.63	0.7461
35	34.36	7 × 2.50	7.5	13.77	0.310	3.041	5.75	0.5265
50	49.48	7 × 3.00	9.0	19.38	0.446	4.375	5.90	0.3656
50	48.35	19 × 1.80	9.0	19.38	0.437	4.286	5.90	0.3760
70	65.81	19 × 2.10	10.5	26.38	0.596	5.846	6.05	0.2762
95	93.27	19 × 2.50	12.5	37.89	0.845	8.289	6.25	0.1950
120	116.99	19 × 2.80	14.0	46.90	1.060	10.398	6.40	0.1554
150	147.11	37 × 2.25	15.8	58.98	1.337	13.115	6.58	0.1238
185	181.62	37 × 2.50	17.5	72.81	1.649	16.176	6.75	0.1003
240	242.54	61 × 2.25	20.2	97.23	2.209	21.670	7.02	0.0753
300	299.43	61 × 2.50	22.5	120.04	2.725	26.732	7.25	0.0610
400	400.14	61 × 2.89	26.0	160.42	3.640	35.708	7.60	0.0457
500	499.83	61 × 3.23	29.1	200.38	4.545	44.586	7.91	0.0365

1) Normal added load due to ice to EN 50341 in N/m.
Ice load zone 1: (5+0,1d) n/m; Ice load zone 2: (10+0,2d) N/m Table 13-24)

Table 13-24

Aluminium wire conductors AL1 to EN 50182 (also refer to EN 50341)

	Number of strands 7	19	37	61	91
Medium high tensile stress in N/mm²	30	30	30	30	30
Continuous tensile stress in N/mm²	120	120	120	120	120
Practical Young's modulus E in kN/mm²	60	57	57	55	55
Linear expansion coefficient $\varepsilon_t \left(\frac{10^{-6}}{K}\right)$	23	23	23	23	23
Cross-sectional weight force/length $QLK \left(\frac{N}{m \times mm^2}\right)$	0,0275	0,0275	0,0275	0,0275	0,0275

Table 13-25

Aluminium wire conductors used in Germany-type AL1 acc. to EN 50182 (also refer to EN 50 341)

Designation	Old designation	Cross-section	No. of strands	Diameter		Weight of conductors	Calculated breaking load	Ohmic resistance	Practical Young's Modulus	Coefficient of linear expansion	Continuous current rating
				Wire	Conductor						
		mm²		mm	mm	kg/km	kN	Ω/km	N/mm²	1/K	A
16-AL1	16	15.9	7	1.70	5.10	43.4	3.02	1.7986	60 000	2.30E-05	110
24-AL1	25	24.2	7	2.10	6.30	66.3	4.36	1.1787	60 000	2.30E-05	145
34-AL1	35	34.4	7	2.50	7.50	93.9	6.01	0.8317	60 000	2.30E-05	180
49-AL1	50	49.5	7	3.00	9.00	135.2	8.41	0.5776	60 000	2.30E-05	225
48-AL1	50	48.3	19	1.80	9.00	132.9	8.94	0.5944	57 000	2.30E-05	225
66-AL1	70	65.8	19	2.10	10.5	180.9	11.85	0.4367	57 000	2.30E-05	270
93-AL1	95	93.3	19	2.50	12.5	256.3	16.32	0.3081	57 000	2.30E-05	340
117-AL1	120	117.0	19	2.80	14.0	321.5	19.89	0.2456	57 000	2.30E-05	390
147-AL1	150	147.1	37	2.25	15.8	405.7	26.48	0.1960	57 000	2.30E-05	455
182-AL1	185	181.6	37	2.50	17.5	500.9	31.78	0.1588	57 000	2.30E-05	520
243-AL1	240	242.5	61	2.25	20.3	671.1	43.66	0.1193	55 000	2.30E-05	625
299-AL1	300	299.4	61	2.50	22.5	828.5	52.40	0.0966	55 000	2.30E-05	710
400-AL1	400	400.1	61	2.89	26.0	1 107.1	68.02	0.0723	55 000	2.30E-05	855
500-AL1	500	499.8	61	3.23	29.1	1 382.9	82.47	0.0579	55 000	2.30E-05	990
626-AL1	625	626.2	91	2.96	32.6	1 739.7	106.45	0.0464	55 000	2.30E-05	1 140
802-AL1	800	802.1	91	3.35	36.9	2 228.3	132.34	0.0362	55 000	2.30E-05	1 340
1000-AL1	1 000	999.7	91	3.74	41.1	2 777.3	159.95	0.0291	55 000	2.30E-05	1 540

NOTE The external layer has a right-hand lay (Z).

The values listed in the table for the practical modulus of elasticity and the coefficient of longitudinal expansion are used in Germany. Values for other conductor designs may be calculated in accordance with the method specified in IEC 61597.

Guideline values for continuous current-carrying capacity valid up to 60 Hz at a wind velocity of 0.6 m/s and solar radiation (for Germany) for an initial ambient temperature of 35 °C and a final conductor temperature of 80 °C. For special cases in still air, the values are to be reduced on average by around 30%.

Corresponds to table F.17 from EN 50182:2001 (D)

Table 13-26

Aluminium/steel wire conductors AL1/ST1A acc. EN 50341

	Number of strands 14/7	14/19	12/7	30/7	6/1	26/7	24/7	54/7	54/19	48/7	45/7	72/7
Cross-section ratio AL1:ST1A	1.4:1	1.4:1	1.7:1	4.3:1	6:1	6:1	7.7:1	7.7:1	7.7:1	11.3:1	14.5:1	23.1:1
Medium high tensile stress in N/mm^2	90	90	84	57	56	56	52	52	52	44	40	35
Continuous high tensile stress in N/mm^2	401	401	368	240	208	208	189	189	189	165	152	130
Practical Young's modulus E in kN/mm^2	110	110	107	82	81	77	74	70	68	62	61	60
Linear expansion coefficient $\varepsilon_t \left(\frac{10^{-6}}{K}\right)$	15.0	15.0	15.3	17.8	19.2	18.9	19.6	19.3	19.4	20.5	20.9	21.7
Cross-sectional weight force/lenght $QLK \left(\frac{N}{m \times mm^2}\right)$	0.0491	0.0491	0.0466	0.0375	0.0350	0.0350	0.0336	0.0336	0.0336	0.0320	0.0309	0.0298
Rel. weight of aluminium in %	37.7	32.7	37.4	59.8	67.4	67.9	72.7	72.7	72.7	79.5	83.2	89.0

Table 13-27

Aluminium/Steel conductors used in Germany-Type AL1/STA

Designation	Old Designation	Cross-section			No. of strands		Diameter		Diameter		Weight of conductor	Calculated breaking load	Ohmic resistance	Practical Young's modules	Coefficient of linear expansion	Continuous current rating
		Aluminium	Steel	Total			Al	St	Wire	Conductor						
		mm²	mm²	mm²	Al	St	mm	mm	mm	mm	kg/km	kN	Ω/km	N/mm²	1/K	A
15-AL1/3-ST1A	16/2.5	15.3	2.54	17.8	6	1	1.80	1.80	1.80	5.40	61.6	5.80	1.8769	81 000	1.92E-05	105
24-AL1/4-ST1A	25/4	23.9	3.98	27.8	6	1	2.25	2.25	2.25	6.75	96.3	8.95	1.2012	81 000	1.92E-05	140
34-AL1/6-ST1A	35/6	34.4	5.73	40.1	6	1	2.70	2.70	2.70	8.10	138.7	12.37	0.8342	81 000	1.92E-05	170
44-AL1/32-ST1A	44/32	44.0	31.7	75.6	14	7	2.00	2.40	7.20	11.2	369.3	44.24	0.6574	110 000	1.50E-05	-
48-AL1/8-ST1A	50/8	48.3	8.04	56.3	6	1	3.20	3.20	3.20	9.60	194.8	16.81	0.5939	81 000	1.92E-05	210
51-AL1/30-ST1A	50/30	51.2	29.8	81.0	12	7	2.33	2.33	6.99	11.7	374.7	42.98	0.5644	107 000	1.53E-05	-
70-AL1/11-ST1A	70/12	69.9	11.4	81.3	26	7	1.85	1.44	4.32	11.7	282.2	26.27	0.4132	77 000	1.89E-05	290
94-AL1/15-ST1A	95/15	94.4	15.3	109.7	26	7	2.15	1.67	5.01	13.6	380.6	34.93	0.3060	77 000	1.89E-05	350
97-AL1/56-ST1A	95/55	96.5	56.3	152.8	12	7	3.20	3.20	9.60	16.0	706.8	77.85	0.2992	107 000	1.53E-05	-
106-AL1/76-ST1A	105/75	105.7	75.5	181.2	14	19	3.10	2.25	11.3	17.5	885.3	105.82	0.2742	110 000	I.50E-05	-
122-AL1/20-ST1A	120/20	121.6	19.8	141.4	26	7	2.44	1.90	5.70	15.5	491.0	44.50	0.2376	77 000	1.89E-05	410
122-AL1/71-ST1A	120/70	122.1	71.3	193.4	12	7	3.60	3.60	10.8	18.0	894.5	97.92	0.2364	107 000	1.53E-05	-
128-AL1/30-ST1A	125/30	127.9	29.8	157.8	30	7	2.33	2.33	6.99	16.3	587.0	56.41	0.2260	82 000	1.78E-05	425
149-AL1/24-ST1A	150/25	148.9	24.2	173.1	26	7	2.70	2.10	6.30	17.1	600.8	53.67	0.1940	77 000	1.89E-05	470
172-AL1/40-ST1A	170/40	171.8	40.1	211.8	30	7	2.70	2.70	8.10	18.9	788.2	74.89	0.1683	82 000	1.78E-05	520
184-AL1/30-ST1A	185/30	183.8	29.8	213.6	26	7	3.00	2.33	6.99	19.0	741.0	65.27	0.1571	77 000	1.89E-05	535
209-AL1/34-ST1A	210/35	209.1	34.1	243.2	26	7	3.20	2.49	7.47	20.3	844.1	73.36	0.1381	77 000	1.89gE-05	590
212-AL1/49-ST1A	210/50	212.1	49.5	261.5	30	7	3.00	3.00	9.00	21.0	973.1	92.46	0.1363	82 000	1.78E-05	610
231-AL1/30-ST1A	230/30	230.9	29.8	260.8	24	7	3.50	2.33	6.99	21.0	870.9	72.13	0.1250	74 000	1.96E-05	630
243-AL1/39-ST1A	240/40	243.1	39.5	282.5	26	7	3.45	2.68	8.04	21.8	980.1	85.12	0.1188	77 000	1.89E-05	645

Table 13-27 (continued)

Aluminium/Steel conductors used in Germany-Type AL1/STA

Designation	Old Designation	Cross-section			No. of strands		Diameter		Diameter		Weight of conductor	Calculated breaking load	Ohmic resistance	Practical-Young's modules	Coefficient of linear expansion	Continuous current rating
		Aluminium	Steel	Total			Al	St	Wire	Conductor						
		mm²	mm²	mm²	Al	St	mm	mm	mm	mm	kg/km	kN	Ω/km	N/mm²	1/K	A
264-AL1/34-ST1A	265/35	263.7	34.1	297.7	24	7	3.74	2.49	7.47	22.4	994.4	81.04	0.1095	74 000	1.96E-05	680
304-AL1/49-ST1A	300/50	304.3	49.5	353.7	26	7	3.86	3.00	9.00	24.4	1227.3	105.09	0.0949	77 000	1.89E-05	740
305-AL1/39-ST1A	305/40	304.6	39.5	344.1	54	7	2.68	2.68	8.04	24.1	1151.2	96.80	0.0949	70 000	1.93E-05	740
339-AL1/30-ST1A	340/30	339.3	29.8	369.1	48	7	3.00	2.33	6.99	25.0	1171.2	91.71	0.0852	62 000	2.05E-05	790
382-AL1/49-ST1A	380/50	381.7	49.5	431.2	54	7	3.00	3.00	9.00	27.0	1442.5	121.30	0.0758	70 000	1.93E-05	840
386-AL1/34-ST1A	385/35	386.0	34.1	420.1	48	7	3.20	2.49	7.47	26.7	1333.6	102.56	0.0749	62 000	2.05E-05	850
434-AL1/56-ST1A	435/55	434.3	56.3	490.6	54	7	3.20	3.20	9.60	28.8	1641.3	133.59	0.0666	70 000	1.93E-05	900
449-AL1/39-ST1A	450/40	448.7	39.5	488.2	48	7	3.45	2.68	8.04	28.7	1549.1	119.05	0.0644	62 000	2.05E-05	920
490-AL1/64-ST1A	490/65	490.3	63.6	553.8	54	7	3.40	3.40	10.2	30.6	1852.9	150.81	0.0590	70 000	1.93E-05	960
494-AL1/34-ST1A	495/35	494.4	34.1	528.4	45	7	3.74	2.49	7.47	29.9	1632.6	117.96	0.0584	61 000	2.09E-05	985
511-AL1/45-ST1A	510/45	510.5	45.3	555.8	48	7	3.68	2.87	8.61	30.7	1765.3	133.31	0.0566	62 000	2.05E-05	995
550-AL1/71-ST1A	550/70	549.7	71.3	620.9	54	7	3.60	3.60	10.8	32.4	2077.2	166.32	0.0526	70 000	1.93E-05	1020
562-AL1/49-ST1A	560/50	561.7	49.5	611.2	48	7	3.86	3.00	9.00	32.2	1939.5	146.28	0.0515	62 000	2.05E-05	1040
571-AL1/39-ST1A	570/40	571.2	39.5	610.6	45	7	4.02	2.68	8.04	32.2	1887.1	136.40	0.0506	61 000	2.09E-05	1050
653-AL1/45-ST1A	650/45	653.5	45.3	698.8	45	7	4.30	2.87	8.61	34.4	2159.9	156.18	0.0442	61 000	2.09E-05	1120
679-AL1/86-ST1A	680/85	678.6	86.0	764.5	54	19	4.00	2.40	12.0	36.0	2549.7	206.56	0.0426	68 000	1.94E-05	1150
1046-AL1/45-ST1A	1045/45	1045.6	45.3	1090.9	72	7	4.30	2.87	8.61	43.0	3248.2	218.92	0.0277	60 000	2.17E-05	1580

NOTE The external layer has a right-hand lay (Z).

The values listed in the table for the practical modulus of elasticity and the coefficient of longitudinal expansion are used in Germany. Values for other conductor designs may be calculated in accordance with the method specified in IEC 61597.

Guideline values for continuous current-carrying capacity valid up to 60 Hz at a wind velocity of 0.6 m/s and solar radiation (for Germany) for an initial ambient temperature of 35 °C and a final conductor temperature of 80 °C. For special cases in still air, the values are to be reduced on average by around 30%.

Corresponds to table F.17 from EN 50182:2001 (D)

Table 13-28

Wire conductors of AL 3 (former aldrey) to EN 50182
(also refer to EN 50341)

	Number of strands 7	19	37	61	91
Medium high tensile stress in N/mm^2	44	44	44	44	44
Continuous tensile stress in N/mm^2	240	240	240	240	240
Practical Young's modulus E in kN/mm^2	60	57	57	55	55
Linear expansion coefficient $\varepsilon_t \left(\frac{10^{-6}}{K}\right)$	23	23	23	23	23
Cross-sectional weight force/length $QLK \left(\frac{N}{m \times mm^2}\right)$	0.0275	0.0275	0.0275	0.0275	0.0275

Table 13-29 Corresponds to table F.18 from EN 50182 : 2001 D

Aluminium/Steel conductors used in Germany-Type AL3

Designation	Old designation	Cross-section	No. of strands	Diameter		Weight of conductors	Calculated breaking load	Ohmic resistance	Practical Young's modulus	Coefficient of linear expansion	Continuous current rating
				Wire	Conductor						
		mm²		mm	mm	kg/km	kN	Ω/km	N/mm²	1/K	A
16-AL3	16	15.9	7	1.70	5.10	43.4	4.69	2.0701	60 000	2.30E-05	105
24-AL3	25	24.2	7	2.10	6.30	66.2	7.15	1.3566	60 000	2.30E-05	135
34-AL3	35	34.4	7	2.50	7.50	93.8	10.14	0.9572	60 000	2.30E-05	170
49-AL3	50	49.5	7	3.01	9.00	135.1	14.60	0.6647	60 000	2.30E-05	210
48-AL3	50	48.3	19	1.80	9.00	132.7	14.26	0.6841	57 000	2.30E-05	210
66-AL3	70	65.8	19	2.10	10.5	180.7	19.41	0.5026	57 000	2.30E-05	255
93-AL3	95	93.3	19	2.50	12.5	256.0	27.51	0.3546	57 000	2.30E-05	320
117-AL3	120	117.0	19	2.80	14.0	321.2	34.51	0.2827	57 000	2.30E-05	365
147-AL3	150	147.1	37	2.25	15.8	405.3	43.40	0.2256	57 000	2.30E-05	425
182-AL3	185	181.6	37	2.50	17.5	500.3	53.58	0.1827	57 000	2.30E-05	490
243-AL3	240	242.5	61	2.25	20.3	670.3	71.55	0.1373	55 000	2.30E-05	585
299-AL3	300	299.4	61	2.50	22.5	827.5	88.33	0.1112	55 000	2.30E-05	670
400-AL3	400	400.1	61	2.89	26.0	1 105.9	118.04	0.0832	55 000	2.30E-05	810
500-AL3	500	499.8	61	3.23	29.1	1 381.4	147.45	0.0666	55 000	2.30E-05	930
626-AL3	625	626.2	91	2.96	32.6	1 737.7	184.73	0.0534	55 000	2.30E-05	1 075
802-AL3	800	802.1	91	3.35	36.9	2 225.8	236.62	0.0417	55 000	2.30E-05	1 255
1000-AL3	1000	999.7	91	3.74	41.1	2 774.3	294.91	0.0334	55 000	2.30E-05	1 450

NOTE The external layer has a right-hand lay (Z).

The values listed in the table for the practical modulus of elasticity and the coefficient of longitudinal expansion are used in Germany. Values for other conductor designs may be calculated in accordance with the method specified in IEC 61597.

Guideline values for continuous current-carrying capacity valid up to 60 Hz at a wind velocity of 0.6 m/s and solar radiation (for Germany) for an initial ambient temperature of 35 °C and a final conductor temperature of 80 °C. For special cases in still air, the values are to be reduced on average by around 30%.

Corresponds to table F.17 from EN 50182:2001 (D)

Table 13-30a Corresponds to table F. 42 from EN 50182 : 2001 D

Aluminium/Steel conductors used in Great Britain - Type AL1/ST1A

Designation	Old designation	Cross-section			No. of strands		Diameter		Diameter		Weight of conductors	Calculated breaking load	Ohmic resistance
		Al	St	Total			Al	St	Wire	Conductor			
		mm²	mm²	mm²	Al	St	mm	mm	mm	mm	kg/km	kN	Ω/km
11-AL1/2-ST1A	MOLE	10.6	1.77	12.4	6	1	1.50	1.50	1.50	4.50	42.8	4.14	2.7027
21-AL1/3-STIA	SQUIRREL	21.0	3.50	24.5	6	1	2.11	2.11	2.11	6.33	84.7	7.87	1.3659
26-AL1/4-ST1A	GOPHER	26.2	4.37	30.6	6	1	2.36	2.36	2.36	7.08	106.0	9.58	1.0919
32-AL1/5-ST1A	WEASEL	31.6	5.27	36.9	6	1	2.59	2.59	2.59	7.77	127.6	11.38	0.9065
37-AL1/6-ST1A	FOX	36.7	6.11	42.8	6	1	2.79	2.79	2.79	8.37	148.1	13.21	0.7812
42-AL1/7-ST1A	FERRET	42.4	7.07	49.5	6	1	3.00	3.00	3.00	9.00	171.2	15.27	0.6757
53-AL1/9-ST1A	RABBIT	52.9	8.81	61.7	6	1	3.35	3.35	3.35	10.1	213.5	18.42	0.5419
63-ALI/11-ST1A	MINK	63.1	10.5	73.6	6	1	3.66	3.66	3.66	11.0	254.9	21.67	0.4540
63-AL1/37-ST1A	SKUNK	63.2	36.9	100.1	12	7	2.59	2.59	7.77	13.0	463.0	52.79	0.4568
75-AL1/13-ST1A	BEAVER	75.0	12.5	87.5	6	1	3.99	3.99	3.99	12.0	302.9	25.76	0.3820
73-AL1/43-ST1A	HORSE	73.4	42.8	116.2	12	7	2.79	2.79	8.37	14.0	537.3	61.26	0.3936
79-AL1/13-ST1A	RACOON	78.8	13.1	92.0	6	1	4.09	4.09	4.09	12.3	318.3	27.06	0.3635
84-AL1/14-ST1A	OTTER	83.9	14.0	97.9	6	1	4.22	4.22	4.22	12.7	338.8	28.81	0.3415
95-AL1/16-ST1A	CAT	95.4	15.9	111.3	6	1	4.50	4.50	4.50	13.5	385.3	32.76	0.3003
105-AL1/17-ST1A	HARE	105.0	17.5	122.5	6	1	4.72	4.72	4.72	14.2	423.8	36.04	0.2730
105-AL1/14-ST1A	DOG	105.0	13.6	118.5	6	7	4.72	1.57	4.71	14.2	394.0	32.65	0.2733
132-AL1/20-ST1A	COYOTE	131.7	20.1	151.8	26	7	2.54	1.91	5.73	15.9	520.7	45.86	0.2192
132-AL1/7-ST1A	COUGAR	131.5	7.31	138.8	18	1	3.05	3.05	3.05	15.3	418.8	29.74	0.2188
131-AL1/31-ST1A	TIGER	131.2	30.6	161.9	30	7	2.36	2.36	7.08	16.5	602.2	57.87	0.2202

Table 13-30a (continued)

Aluminium/Steel conductors used in Great Britain - Type AL1/ST1A

Designation	Old designation	Cross-section			No. of strands		Diameter		Diameter		Weight of conductors	Calculated breaking load	Ohmic resistance
		Al	St	Total			Al	St	Wire	Conductor			
		mm²	mm²	mm²	Al	St	mm	mm	mm	mm	kg/km	kN	Ω/km
158-AL1/37-ST1A	WOLF	158.1	36.9	194.9	30	7	2.59	2.59	7.77	18.1	725.3	68.91	0.1829
159-AL1/9-ST1A	DINGO	158.7	8.81	167.5	18	1	3.35	3.35	3.35	16.8	505.2	35.87	0.1814
183-AL1/43-ST1A	LYNX	183.4	42.8	226.2	30	7	2.79	2.79	8.37	19.5	841.6	79.97	0.1576
184-AL1/10-ST1A	CARACAL	184.2	10.2	194.5	18	1	3.61	3.61	3.61	18.1	586.7	40.74	0.1562
212-AL1/49-ST1A	PANTHER	212.1	49.5	261.5	30	7	3.00	3.00	9.00	21.0	973.1	92.46	0.1363
211-AL1/12-ST1A	JAGUAR	210.6	11.7	222.3	18	1	3.86	3.86	3.86	19.3	670.8	46.57	0.1366
238-AL1/56-ST1A	LION	238.3	55.6	293.9	30	7	3.18	3.18	9.54	22.3	1 093.4	100.47	0.1213
264-AL1/62-ST1A	BEAR	264.4	61.7	326.1	30	7	3.35	3.35	10.1	23.5	1 213.4	111.50	0.1093
324-AL1/76-ST1A	GOAT	324.3	75.7	400.0	30	7	3.71	3.71	11.1	26.0	1 488.2	135.13	0.0891
375-AL1/88-ST1A	SHEEP	375.1	87.5	462.6	30	7	3.99	3.99	12.0	27.9	1 721.3	156.30	0.0771
374-AL1/48-ST1A	ANTELOPE	374.1	48.5	422.6	54	7	2.97	2.97	8.91	26.7	1 413.8	118.88	0.0773
382-AL1/49-ST1A	BISON	381.7	49.5	431.2	54	7	3.00	3.00	9.00	27.0	1 442.5	121.30	0.0758
430-AL1/100-ST1A	DEER	429.6	100.2	529.8	30	7	4.27	4.27	12.8	29.9	1 971.4	179.00	0.0673
429-AL1/56-ST1A	ZEBRA	428.9	55.6	484.5	54	7	3.18	3.18	9.54	28.6	1 620.8	131.92	0.0674
477-AL1/111-ST1A	ELK	477.1	111.3	588.5	30	7	4.50	4.50	13.5	31.5	2 189.5	198.80	0.0606
476-AL1/62-ST1A	CAMEL	476.0	61.7	537.7	54	7	3.35	3.35	10.1	30.2	1 798.8	146.40	0.0608
528-ALI/69-ST1A	MOOSE	528.5	68.5	597.0	54	7	3.53	3.53	10.6	31.8	1 997.3	159.92	0.0547

Note: The external layer has a right-hand Lay (Z)

Table 13-30b Corresponds to table F.40 from EN 50182 : 2001 D

Aluminium alloy conductors used in Great-Britain - Type AL3

Designation	Old designation	Cross-section	No. of strands	Diameter		Weight of conductors	Calculated breaking load	Ohmic resistance
				Wire	Conductor			
		mm²		mm	mm	kg/km	kN	Ω/km
19-AL3	BOX	18.8	7	1.85	5.55	51.4	5.55	1.7480
24-AL3	ACACIA	23.8	7	2.08	6.24	64.9	7.02	1.3828
30-AL3	ALMOND	30.1	7	2.34	7.02	82.2	8.88	1.0926
35-AL3	CEDAR	35.5	7	2.54	7.62	96.8	10.46	0.9273
42-AL3	DEODAR	42.2	7	2.77	8.31	115.2	12.44	0.7797
48-AL3	FIR	47.8	7	2.95	8.85	130.6	14.11	0.6875
60-AL3	HAZEL	59.9	7	3.30	9.90	163.4	17.66	0.5494
72-AL3	PINE	71.6	7	3.61	10.8	195.6	21.14	0.4591
84-AL3	HOLLY	84.1	7	3.91	11.7	229.5	24.79	0.3913
90-AL3	WILLOW	89.7	7	4.04	12.1	245.0	26.47	0.3665
119-AL3	OAK	118.9	7	4.65	14.0	324.5	35.07	0.2767
151-AL3	MULBERRY	150.9	19	3.18	15.9	414.3	44.52	0.2192
181-AL3	ASH	180.7	19	3.48	17.4	496.1	53.31	0.1830
211-AL3	ELM	211.0	19	3.76	18.8	579.2	62.24	0.1568
239-AL3	POPLAR	239.4	37	2.87	20.1	659.4	70.61	0.1387
303-AL3	SYCAMORE	303.2	37	3.23	22.6	835.2	89.40	0.1095
362-AL3	UPAS	362.1	37	3.53	24.7	997.5	106.82	0.0917
479-AL3	YEW	479.0	37	4.06	28.4	1 319.6	141.31	0.0693
498-AL3	TOTARA	498.1	37	4.14	29.0	1 372.1	146.93	0.0666
587-AL3	RUBUS	586.9	61	3.50	31.5	1 622.0	173.13	0.0567
659-AL3	SORBUS	659.4	61	3.71	33.4	1 822.5	194.53	0.0505
821-AL3	ARAUCARIA	821.1	61	4.14	37.3	2 269.4	242.24	0.0406
996-AL3	REDWOOD	996.2	61	4.56	41.0	2 753.2	293.88	0.0334

Note: The external layer has a right-hand lay (Z)

Table 13-31

Nominal cross-sections Copper, AL1 und AL3 AL1 und AL3	AL1/ST1A	Continuous current[1)] Copper	AL1 (Aluminium)	AL3 (Aldrey)	AL1/ST1A (Aluminium/ steel)
mm²	mm²	A	A	A	A
10		90			
16	15-AL1/3-ST1A	125	110	105	105
25	24-AL1/4-ST1A	160	145	135	140
35	34-AL1/6-ST1A	200	180	170	170
50	48-AL1/8-ST1A	250	225	210	210
70	70-AL1/11-ST1A	310	270	255	290
95	94-AL1/15-ST1A	380	340	320	350
120	122-AL1/20-ST1A	440	390	365	410
	128-AL1/30-ST1A				425
150	149-AL1/24-ST1A	510	455	425	470
	172-AL1/40-ST1A				520
185	184-AL1/30-ST1A	585	520	490	535
	209-AL1/34-ST1A				590
	212-AL1/49-ST1A				610
	231-AL1/30-ST1A				630
240	243-AL1/39-ST1A	700	625	585	645
	264-AL1/34-ST1A				680
300	304-AL1/49-ST1A	800	710	670	740
	305-AL1/39-ST1A				740
	339-AL1/30-ST1A				790
	382-AL1/49-ST1A				840
	386-AL1/34-ST1A				850
400		960	855	810	
	434-AL1/56-ST1A				900
	449-AL1/39-ST1A				920
	490-AL1/64-ST1A				960
	494-AL1/34-ST1A				985
500		1 110	960	930	
	511-AL1/45-ST1A				995
	550-AL1/71-ST1A				1 020
	562-AL1/49-ST1A				1 040
	571-AL1/39-ST1A				1 050
625			1 140	1 075	
	653-AL1/45-ST1A				1 120
	679-AL1/86-ST1A				1 150
800			1 340	1 255	
1 000	1046-AL1/45-ST1A		1 540	1 450	1 580

[1)] The figures given are typical values for a wind speed of 0.6 m/s and sunshine for an ambient temperature of 35 °C and the following ultimate conductor temperatures:
Copper conductors 70 °C:
AL1, AL3 and AL1/ST1A stranded wires acc. EN 50182 : 80 °C.
In special situations with no wind, values must be reduced by an average of 30 %.

Table 13-32

Stranded wires of aluminium/zirconium alloy (T Al, "hot wires")

Nominal cross-section	Rated cross-section	Cond. design Wire number × diameter	Cond. diameter d	Calculated breaking force	Standard additional[1)] load	Ohmic resistance at 20°C	Ohmic resistance at 150°C	Current-carrying capacity [2)]
mm²	mm²	mm	mm	kN	N/m	Ω/km	Ω/km	A
95	93.27	19 × 2.50	12.5	15.68	6.25	0.314	0.477	514
120	116.99	19 × 2.80	14.0	18.78	6.40	0.250	0.380	596
150	147.11	37 × 2.25	15.8	25.30	6.58	0.200	0.303	692
185	181.62	37 × 2.50	17.5	30.54	6.75	0.161	0.245	793
240	242.54	61 × 2.25	20.3	39.51	7.03	0.121	0.184	958
300	299.43	61 × 2.50	22.5	47.70	7.25	0.097	0.149	1 100
400	400.14	61 × 2.89	26.0	60.89	7.60	0.073	0.112	1 330
500	499.83	61 × 3.23	29.1	74.67	7.91	0.059	0.089	1 540
625	626.20	91 × 2.96	32.6	95.25	8.26	0.047	0.071	1 780
800	802.09	91 × 3.36	36.9	118.39	8.69	0.036	0.056	2 100
1 000	999.71	91 × 3.74	41.1	145.76	9.11	0.029	0.045	2 430

1) Normal added load due to ice as per EN 50341
Ice load zone 1: (5+0,1 d) N/m; Ice load zone 2: (10+0,2 d) N/m; Ice load zone 3: (20+0,4 d) N/m.
In particularly exposed, account may have to be thaken of greater ice loads than in ice load zone 3

2) The continuous current values are typical values, applicable for a wind speed of 0.6 m/s and the effects of the sun at an ambient temperature of 35 °C and a temperature of 150 °C at the ends of the conductors.

T Al stranded wires for overhead cables can also be used in switchgear installations at increased operating temperatures without losing mechanical strength.

The advantages of T Al stranded wires

- continuous current-carrying capacity nearly 50 % higher than Al stranded wires of the same design and cross-section
- corrosion resistance as with E-Al
- reliable continuous operating temperature to 150 °C
- short-time operating temperature (30 min) to 180 °C
- permissible temperature under short circuit currents to 250 °C
- no special fittings

T Al wires are particularly suited for later increases in the performance data of existing installations. The low weight is also an advantage in new installations. However, the cross-section of conductors connecting to devices must be selected to ensure that the permissible temperature of the connection terminals is not exceeded. For increased mechanical stress, stranded wires reinforced with steel wires are also available (T Al/stalum).

Table 13-33

Stranded wires of TAl/steel (stalum)

Nominal cross-section mm²	Cond. cross section T Al mm²	Cond. cross section steel mm²	Cond. config. Number of strands x diameter T Al mm	Cond. config. steel mm	Cond. diameter d mm	Calculated breaking force kN	Standard additional load[1] N/m	Ohmic resistance at 20 °C Ω/km	Ohmic resistance at 150 °C Ω/km	Current-carrying capacity[2] A
25/4	23.86	3.98	6 x 2.25	1 x 2.25	6.75	9.20	5.68	1.1450	1.7404	220
35/6	34.35	5.73	6 x 2.70	1 x 2.70	8.10	12.98	5.81	0.7951	1.2085	280
44/32	43.98	31.67	14 x 2.00	7 x 2.40	11.20	47.07	6.12	0.5299	0.8054	380
50/8	48.25	8.04	6 x 3.20	1 x 3.20	9.60	17.86	5.96	0.5661	0.8491	350
50/30	51.17	29.85	12 x 2.33	7 x 2.33	11.65	45.75	6.17	0.4730	0.7189	405
95/55	96.51	56.30	12 x 3.20	7 x 3.20	16.00	85.25	6.60	0.2507	0.3180	615
105/75	105.67	75.55	14 x 3.10	19 x 225	17.45	110.45	6.75	0.2215	0.3366	675
120/70	122.15	71.25	12 x 3.60	7 x 3.60	18.00	99.57	6.80	0.1981	0.3011	760
125/30	127.92	29.85	30 x 2.33	7 x 2.33	16.31	59.36	6.63	0.2106	0.3201	675
150/25	148.66	24.25	26 x 2.70	7 x 2.10	17.10	55.58	6.71	0.1850	0.2812	735
170/40	171.77	40.08	30 x 2.70	7 x 2.70	18.90	79.01	6.89	0.1569	0.2384	823
185/30	183.78	29.85	26 x 3.00	7 x 2.33	18.99	67.78	6.90	0.1499	0.2278	820
210/50	212.06	49.48	30 x 3.00	7 x 3.00	21.00	96.70	7.10	0.1270	0.1930	945
230/30	230.91	29.85	24 x 3.50	7 x 2.33	20.99	74.58	7.10	0.1207	0.1834	970
240/40	243.05	39.49	26 x 3 45	7 x 2.68	21.84	88.43	7.18	0.1134	0.1724	1015
265/35	263.66	34.09	24 x 3.74	7 x 2.49	22.43	84.64	7.24	0.1056	0.1605	1060
300/50	304.26	29.48	26 x 3 86	7 x 3.00	24.44	109.54	7.45	0.0905	0.1376	1175
305/40	304.62	39.49	54 x 2.68	7 x 2.68	24.12	107.27	7.41	0.0917	0.1393	1160
340/30	339.29	29.85	48 x 3.00	7 x 2.33	24.99	94.06	7.50	0.0834	0.1267	1230
380/50	381.70	49.48	54 x 3.00	7 x 3.00	27.00	125.37	7.70	0.0732	0.1112	1350
385/35	386.04	34.09	48 x 3.20	7 x 2.49	26.67	106.01	7.67	0.0734	0.1115	1340
435/55	434.29	56.30	54 x 3.20	7 x 3.20	28.80	141.34	7.88	0.0643	0.0977	1470
450/40	448.71	39.49	48 x 3.45	7 x 2.68	28.74	122.16	7 87	0.0631	0.0959	1480
490/65	490.28	63.55	54 x 3.40	7 x 3.40	30.60	154.12	8.06	0.0579	0.0880	1590
550/70	549.65	72.25	54 x 3.60	7 x 3.60	32.40	168.84	8.24	0.0508	0.0772	1830
560/50	561.70	49.48	48 x 3.86	7 x 3.00	32.16	150.77	8.22	0.0504	0.0768	1715
570/40	571.16	39.49	45 x 4.02	7 x 2.68	32.16	139.96	8.22	0.0499	0.7580	1725
650/45	653.49	45.28	45 x 4.30	7 x 2.87	34.41	159.60	8.44	0.0436	0.0662	1885
680/85	678.58	85.95	54 x 4.00	19 x 2.40	36.00	214.29	8.60	0.0415	0.0630	2422

[1] Normal added load due to ice as per EN 50341
Ice load zone 1: (5+0,1 d) N/m; Ice load zone 2: (10+0,2 d) N/m; Ice load zone 3: (20+0,4 d) N/m.
In particularly exposed, account may have to be thaken of greater ice loads than in ice load zone 3

[2] The continuous current values are typical values, applicable for a wind speed of 0.6 m/s and the effects of the sun at an ambient temperature of 35 °C and a temperature of 150 °C at the ends of the conductors.

13.1.5 Post-type insulators and overhead-line insulators

Post-type and string insulators in substations are used to carry bare conductors. They must possess the necessary creepage distance between live parts and earth, and also withstand the electrodynamic stresses during short circuits.

Busbars, overhead line feeders and guys are usually tensioned with double dead-end strings. The insulators can be of the long-rod, cap-and-pin or plastic type (see Tables 13-36, 13-39 and 13-42). Fittings are used to join the insulators into strings. The fittings serve as mechanical attachment, electrical connection and means of protecting the insulators and conductors (IEC 61284 (VDE 0212 Part 1)).

Fittings

Fixings to the steel structures are made with anchor links, shackles or U-bolts. The insulators are joined to their anchorages by ball-eyes, socket-eyes, double eyes and spacers, etc. Long-rod insulators with clevis end-caps are fastened to the anchors with double eyes and bolts or rivets. Cap-type insulators made up into strings (e.g. LP 75/22/1230) are joined together with twin-ball pins and attached to the other fittings with ball-eyes and socket-eyes. The joints between ball and insulator element are secured with split pins. The fittings are mostly made of hot-galvanized steel or malleable cast iron.

Informationen about material see IEC 61284 Section 4.1.2.

Anchor clamps

The conductors are attached to the insulator strings by terminal clamps which also create an electrical connection between the tensioned wires and the jumper loop .

A distinction is made between detachable terminals (keyed, conical or screw terminals) and permanent (compression) terminals. Which one is chosen depends on the particular application, see also Section 11.3.2.

Anti-arc fittings

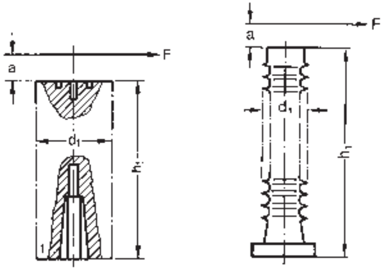
The purpose of anti-arc fittings is to intercept arcs created when an insulator flashes over and divert them away from the insulator and other parts of the string. They also serve as a means of voltage and field control along the string, so restricting corona discharges.

For rated voltages of 220 kV and above, strings of cap-and-pin insulators are provided with so-called corona rings. The effect of these is to control voltage and field, so reducing electrical stresses on the line-side insulators and thereby limiting to an acceptable value any corona discharges and the radio interference they may cause.

IEC 61284 states a partial-discharge extinction voltage of $U_m/\sqrt{3} \cdot 1.2$. This value applies to the whole insulator string i.e. including fittings and electrical connections.

Table 13-34

Moulded-resin insulators for indoor installation, principal dimensions to IEC 60273



Max. permitted service voltage Um (kV)	Rated Lighting impulse withstand voltage (kV)	Height (mm)	Diameter d (mm) at nominal breaking force, bending						
			2kN	4kN	6kN	8Kn	10kN	16kN	25kN
12	60	95	60	75	80	85	95	125	145
17.5	75	130	60	75	90	100	105	125	145
24	95	175	60	80	95	110	115	130	155
24	125	210	75	85	105	125	130	140	160
36	145	270	75	95	115	130	140	150	170
36	170	300	75	105	115	130	140	160	180
52	250	500	—	125	130	140	150	180	220
72.5	325	620	—	130	150	160	170	200	240

Table 13-35

Selection criteria for outdoor post-type insulators

Relevant standard	Max. permitted service voltage U_m kV	Rated lightning impulse withstand voltage U_{rB} kV	Rated switching impulse withstand voltage U_{rS} kV	Insu-lator height H mm	Ultimate bending stress F kN					Minimum creepage distance in mm to IEC 60237	
					4	6	8	10	12.5	class I	class II
IEC 60 273	12	75		215	×	×	×	×		190	280
IEC 60 273	12	75		215	×	×	×	×		190	280
	24	125		305	×	×	×	×	×	380	500
	36	170		445	×	×	×	×	×	580	850
	52	250		560	×	×	×	×	×	835	1 200
IEC 60 273	72.5	325	—	770	×	×	×	×	×	1 160	1 600
	123	550	—	1 220	×	×	×	×	×	1 970	2 900
	145	650	—	1 500	×	×	×	×	×	2 300	3 350
	170	750	—	1 700	×	×	×	×	×	2 700	3 900
	245	1 050	—	2 300	×	×	×	×	×	4 000	5 650
IEC 60 273	362	1 175	850	2 650	×	×	×	×	×	4 600	6 500
	420	1 300	950	2 900	×	×	×	×	×	5 100	7 000
	525	1 550	1 050	3 350	×	×	×	×	×	6 200	8 500
	765	2 100	1 300	4 700	×	×	×	×	×	8 250	12 250

Table 13-36

Specified values for long rod insulators BIC acc IEC 60433

Designation	Standard lighting impulse withstand voltage	Wet power frequency withstand voltage	Spezified mechanical failing load	Maximum nominal diameter D on the insu-lating part	Minimum nominal creepage (16 mm/kV	Maximum nominal lenght L	Standard coupling size (pin diameter, see IEC 60120)	Maximum nominal lenght L	Standard coupling size (coupling pin diameter see IEC 60471)[1)]
						Coupling B (socket)		Coupling C (clevis)	
	kV	kV	kN	mm	mm	mm	mm	mm	
L 40 B/C 170	170	70	40	160	576	380	11	400	13L
L 60 B/C 170	170	70	60	160	576	400	11	420	13L
L 100 B/C 170	170	70	100	180	576	450	16	475	19L (16L)
L 100 B/C 250	250	95	100	180	832	580	16	605	19L (16L)
L 100 B/C 325	325	140	100	180	1 160	870	16	900	19L (16L)
L 100 B/C 450	450	185	100	180	1 968	1 085	16	1 120	19L (16L)
L 100 B/C 550	550	230	100	180	1 968	1 240	16	1 270	19L (16L)
L 120 B/C 325	325	140	120	200	1 160	870	16	905	19L (16L)
L 120 B/C 450	450	185	120	200	1 968	1 085	16	1 120	19L (16L)
L 120 B/C 550	550	230	120	200	1 968	1 240	16	1 275	19L (16L)
L 120 B/C 650	650	275	120	200	2 320	1 430	16	1 465	19L (16L)
L 160 B/C 325	325	140	160	210	1 160	885	20	920	19L
L 160 B/C 450	450	185	160	210	1 968	1 100	20	1 135	19L
L 160 B/C 550	550	230	160	210	1 968	1 255	20	1 290	19L
L 160 B/C 650	650	275	160	210	2 320	1 445	20	1 465	19L
L 210 B/C 325	325	140	210	220	1 160	905	20	940	22L
L 210 B/C 450	450	185	210	220	1 968	1 120	20	1 155	22L
L 210 B/C 550	550	230	210	220	1 968	1 275	20	1 310	22L
L 210 B/C 650	650	275	210	220	2 320	1 465	20	1 500	22L
L 250 B/C 550	550	230	250	230	1 968	1 305	24	1 335	22L
L 250 B/C 650	650	275	250	230	2 320	1 500	24	1 530	22L
L 300 B/C 550	550	230	300	240	1 968	1 330	24	1 365	25L
L 300 B/C 650	650	275	300	240	2 320	1 520	24	1 560	25L
L 330 B/C 550	550	230	330	250	1 968	1 360	28	1 400	28L
L 330 B/C 650	650	275	330	250	2 320	1 550	28	1 595	28L
L 360 B/C 550	550	230	360	250	1 968	1 360	28	1 410	28L
L 360 B/C 650	650	275	360	250	2 320	1 550	28	1 600	28L
L 400 B/C 550	550	230	400	260	1 968	1 400	28	1 460	28L
L 400 B/C 650	650	275	400	260	2 320	1 600	28	1 660	28L
L 530 B/C 550	550	230	530	270	1 968	1 450	32	1 520	32L
L 530 B/C 650	650	275	530	270	2 320	1 650	32	1 720	32L

[1)] Non-prefered sizes in brackets ( )

Table 13-36a

Standard long rod insulators with ball and socket coupling and characteristic values acc. E-DIN 48006-1, 2004

Class Designation acc IEC 60433	embodiment symbol[1)]	d_1 [2)] mm	Number of sheds	h_1 [2)] mm	d_2 [2)] mm	h_3 [2) 4)] mm	Mech. failing load (min) kN	nominal creepage distance[2)] mm	Mass[3)] kg	Coupling size acc DIN 48059 mm
L 40 B 170	LP 45/5/380	45	5	380	105	240	40	490	6	11
	LP 60/5/380	60	5	380	120	260	40	500	8	11
L 70 B 170	LP 60/5/390	60	5	390	120	245	70	490	9	16
L 100 B 170	LP 4515/400	45	5	400	105	250	100	490	6	16
L 100 B 325	LP 60/19/870	60	19	870	120	715	100	1 680	17	16
L 100 B 550	LP 60/22/1170	60	22	1 170	120	1 015	100	2 120	22	16
	LP 60/30/1240	60	30	1 240	120	1 090	100	2 600	24	16
L 120 B 325	LP 75/14/860	75	14	860	150	690	120	1 580	26	16
	LP 75/17/860	75	17	860	150	690	120	1 770	28	16
L 120 B 550	LP 75/22/1230	75	22	1 230	150	1 065	120	2 460	34	16
	LP 75/27/1230	75	27	1 230	150	1 065	120	2 790	37	16
L 120 B 650	LP 75/26s/1430[1)]	75	26	1 430	175	1 255	120	3 370	47	16
L 160 B 325	LP 75/17/870	75	17	870	150	690	160	1 770	28	20
L 160 B 550	LP 75/22/1250	75	22	1 250	150	1 065	160	2 460	35	20
	LP 75/27/1250	75	27	1 250	150	1 065	160	2 790	37	20
	LP 75/22s/1250	75	22	1 250	175	1 060	160	2 950	41	20
L 210 B 325	LP 85/17/900	85	17	900	160	690	210	1 770	36	20
L 210 B 550	LP 85/22/1270	85	22	1 270	160	1 065	210	2 460	42	20
	LP 85/27/1270	85	27	1 270	160	1 065	210	2 790	47	20
L 250 B 550	LP 95/22/1300	95	22	1 300	170	1 065	250	2 460	55	24
L 300 B 550	LP 105/22/1330	105	22	1 330	180	1 070	300	2 460	66	24

Note 1 Suffix „s" denotes increased shed diameter.

Note 2 Permissible deviations/tolerances to DIN VDE 0446. In the case of pin design B to IEC 60120, h1 is to be increased by 9 mm.

Note 3 When a bonding agent other than lead is used, e.g. Portland or sulphur cement, the weights stated for the long bar insulators are about 2 kg lighter for d1 = 60 mm, about 3 kg for d1 = 75 mm, about 5 kg to d1 = 85 mm, about 6 kg for d1 = 95 mm and about 8 kg for d1 = 105 mm.

Note 4 The shed package should be arranged symmetrically wherever possible within dimension h3.

Table 13-36b

Standard long rod insulators with ball and socket coupling and characteristic values acc.

Class Designation acc IEC 60433	embodiment symbol[1]	d_1[2)] mm	Number of sheds	h_1[2)] mm	d_2[2)] mm	h_3[2) 4)] mm	Mech. failing load (min) kN	nominal creepage distance[2)] mm	Mass[3)] kg	Coupling size acc DIN 48059 mm
L 100 C 325	LG 60/19/900	60	19	900	120	720	100	1 680	16	19
L 100 C 550	LG 60/22/1200	60	22	1 200	120	1 015	100	2 120	22	19
	LG 60/22/1270	60	22	1 270	120	1 085	100	2 180	22	19
	LG 60/30/1270	60	30	1 270	120	1 085	100	2 600	24	19
L 160 C 325	LG 75/17/900	75	17	900	150	690	160	1 770	28	19
L 160 C 550	LG 75/22/1270	75	22	1 270	150	1 065	160	2 460	34	19
	L.G 75/27/1270	75	27	1 270	150	1 065	160	2 790	35	19
	LG 75/225/1270[1)]	75	22	1 270	175	1 065	160	2 950	40	19
L 160 C 650	LG 75/26/1565	75	26	1 565	150	1 355	160	3 000	38	19
	LG 75/26s/1460[1)]	75	26	1 460	175	1 255	160	3 460	47	19
L 210 C 325	LG 85/17/940	85	17	940	160	690	210	1 770	35	22
L210C550	LG 85/22/1310	85	22	1 310	160	1 065	210	2 460	42	22
	LG 85/27/1310	85	27	1 310	160	1 065	210	2 790	45	22
	LG 85/22s/1310[1)]	85	22	1 310	185	1 065	210	2 950	48	22
L 210 C 650	LG 85/26s/1500[1)]	85	26	1 500	185	1 255	210	3 475	53	22
L 250 C 550	LG 95/22/1340	95	22	1 340	170	1 065	250	2 460	52	22
L 300 C 650	LG 105/22/1370	105	22	1 370	180	1 070	300	2 460	66	25

Note 1 Suffix „s" denotes increased shed diameter.
Note 2 Permissible deviations/tolerances to DIN VDE 0446.
Note 3 When a bonding agent other than lead is used, e.g. Portland or sulphur cement, the weights stated for the long bar insulators are about 2 kg lighter for d_1 = 60 mm, about 3 kg for d_1 = 75 mm, about 5 kg to d_1 = 85 mm, about 6 kg for d_1 = 95 mm and about 8 kg for d_1 = 105 mm.
Note 4 The shed package should be arranged symmetrically wherever possible within dimension h_3.

Long-rod insulators of ceramic insulating material are a further development of solid-core insulators. Since the breakdown distance is roughly the same as the flashover distance and the dielectric strength of the material is greater than that of air, flashover along the surface will always occur before puncture-type breakdown. They can therefore be classified among the puncture-proof insulators.

When correctly designed in terms of geometry and creepage distance, their shape is such that they require virtually no maintenance.

The dimensions and technical data of long-rod insulators, and also suggestions as to their selection, are given in Tables 13-36a and b as well as 13-37.

Long rod insulators LP with socket caps to E DIN 48006 Part 1 (currently draft)

Insulator material:	Ceramic C 120 or C 130 to IEC 60 672-3 (VDE 0335 Part 3) at manufacturer's option.
Design and workmanship:	Exposed ceramic surface brown glazed to DIN 40686-1 and DIN 40686-6. The brown colour must be within the permissible limits of RAL 8016 and RAL 8017. The socket openings may not be misaligned by more than 15 °. The general recommendations of IEC 60383-1 (VDE 0446 Part 1) apply. The reinforcement is to be in lead antimony (preferably PbSb10), Portland or sulphur cement. When not otherwise stated, the reinforcement is to be in lead antimony. Gaps of 3 mm are to be provided between the cap base and insulator body, and suitable spacers inserted for the lead and sulphur cement versions to prevent direct contact between the metal and ceramic. The shed profile of the insulator body must comply with the recommendations of IEC Publication 60815. With sheds in design A, DIN 48115 must be applied.
Marking:	To IEC 60383-1 (VDE 0446 Part 1). The marking must be permanent and easily legible. It must include the manufacturer's name and the week of glazing, year of manufacture and the specified mechanical load. The marking must also include the shank diameter and the number of sheds (e.g. L 75/22 - 160 kN).
Application:	Consult EN 50341.

Long rod insulators LP with socket caps to E DIN 48006 Part 2 (currently draft)

Insulator material:	Ceramic C 120 or C 130 to IEC 60 672-3 (VDE 0335 Part 3) at manufacturer's option.
Design and workmanship:	Exposed ceramic surface brown glazed to DIN 40686-1 and DIN 40686-6. The brown colour must be within the permissible limits of RAL 8016 and RAL 8017. The socket openings may not be misaligned by more than 15 °. The general recommendations of IEC 60383-1 (VDE 0446 Part 1) apply. The reinforcement is to be in lead antimony (preferably PbSb10), Portland or sulphur cement. When not otherwise stated, the reinforcement is to be in lead antimony. Gaps of 3 mm are to be provided between the cap base and insulator body, and suitable spacers inserted for the lead and sulphur cement versions to prevent direct contact between the metal and ceramic. The shed profile of the insulator body must comply with the recommendations of IEC Publication 60815. With sheds in design A, DIN 48115 must be applied.
Marking:	To IEC 60383-1 (VDE 0446 Part 1). The marking must be permanent and easily legible. It must include the manufacturer's name and the week of glazing, year of manufacture and the specified mechanical load. The marking must also include the shank diameter and the number of sheds (e.g. L 75/22 - 160 kN).
Application:	Consult EN 50341.

Table 13-37

Suggestions for selection of LG long-rod insulators for different operating voltages and pollution degrees (no account taken of nominal strength)

Max. operating voltage U_m[1)] kV	Rated lightning impulse withstand voltage U_{rB}[1)] kV	Rated power-frequency withstand voltage U_{rW}[1)] kV	Rated switching impulse withstand voltage U_{rS}[1)] kV	Insulator type	No. of units/creepage distance with different degrees of pollution[2)] 1 slight 1.6 cm/kV -/cm	2 average 2.0 cm/kV -/cm	3 severe 2.5 cm/kV -/cm	4 very severe 3.1cm/kV -/cm
123	550	230	—	LG 60/14/860	—	2/274	3/411	3/411
				LG 60/19/900	—	2/336	2/336	3/504
				LG 60/22/1200	1/212	2/424	2/424	2/424
				LG 60/30/1270	1/260	1/260	2/520	2/520
				LG 75/14/900	2/316	2/316	2/316	3/474
				LG 75/22/1270	1/246	1/246	2/492	2/492
				LG 75/22s/1270	1/295	1/295	1/295	2/590
				LG 75/27/1270	1/279	1/295	2/558	2/558
				LG 85/14/940	2/316	2/316	2/316	3/474
				LG 85/22/1310	1/246	1/246	2/492	2/492
				LG 85/22s/1310	1/295	1/295	1/295	2/590
				LG 85/27/1310	1/279	1/279	2/558	2/558
				LG 95/22/1340	1/246	1/246	2/492	2/492
				LG 95/22s/1340	1/295	1/295	1/295	2/590
				LG 95/27/1340	1/279	1/279	2/558	2/558
245	1 050	460	—	LG 60/19/900	3/504	3/504	4/672	5/840
				LG 60/22/1200	2/424	3/636	3/636	4/848
				LG 60/30/1270	2/520	2/520	3/780	3/780
				LG 75/14/900	3/474	4/632	4/632	5/790
				LG 75/22/1270	2/492	2/492	3/738	4/984
				LG 75/22s/1270	2/590	2/590	3/885	3/885
				LG 75/27/1270	2/558	2/558	3/837	3/837
				LG 85/14/940	3/474	4/632	4/632	5/790
				LG 85/22/1310	2/492	2/492	3/738	4/984
				LG 85/22s/1310	2/590	2/590	3/885	3/885
				LG 85/27/1310	2/558	2/558	3/837	3/837
				LG 95/22/1340	2/492	2/492	3/738	4/984
				LG 95/22s/1340	2/590	2/590	3/885	3/885
				LG 95/27/1340	2/553	2/558	3/837	3/837
				LG 105/22/1370	2/492	2/492	3/738	4/984
				LG 105/22s/1370	2/590	2/590	3/885	3/885
				LG 105/27/1370	2/558	2/558	3/837	3/837
420	1425	—	1050	LG 75/22/1270	3/738	4/984	5/1230	6/1476
				LG 75/22s/1270	3/885	3/885	4/1180	5/1475
				LG 75/27/1270	3/837	3/837	4/1116	5/1395
				LG 85/22/1310	3/738	4/984	5/1230	6/1476
				LG 85/22s/1310	3/885	3/885	4/1180	5/1475
				LG 85/27/1310	3/837	4/1116	4/1116	5/1395
				LG 95/22/1340	3/738	4/984	4/1230	5/1476
				LG 95/22s/1340	3/885	3/885	4/1180	5/1475
				LG 95/27/1340	3/837	4/1116	4/1116	5/1395

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Table 13-37 (continued)

Max. operating voltage U_m[1) kV	Rated lightning impulse withstand voltage U_{rB}[1) kV	Rated power-frequency withstand voltage U_{rW}[1) kV	Rated switching impulse withstand voltage U_{rS}[1) kV	Insulator type	No. of units/creepage distance with different degrees of pollution[2) 1 slight 1.6 cm/kV -/cm	2 average 2.0 cm/kV -/cm	3 severe 2.5 cm/kV -/cm	4 very severe 3.1cm/kV -/cm
420	1 425	—	1 050	LG 105/22/1370	3/738	4/984	4/1230	5/1476
				LG 105/22s/1370	3/885	3/885	4/1180	5/1475
				LG 105/27/1370	3/837	4/1116	4/1116	5/1395
525	1 550	—	1 175	LG 75/22/1270	4/984	5/1230	6/1476	7/1722
				LG 75/22s/1270	3/885	4/1180	5/1475	6/1770
				LG 85/22/1310	4/984	5/1230	6/1476	7/1722
				LG 85/22s/1310	3/885	4/1180	5/1475	6/1770
				LG 95/22/1340	4/984	5/1230	6/1476	7/1722
				LG 95/22s/1340	3/885	4/1180	5/1475	6/1770
				LG 105/22/1370	4/984	5/1230	6/1476	7/1722
				LG 105/22si1370	3/885	4/1180	5/1475	6/1770

1) Values to IEC 60071-1
2) Minimum creepage distances per degree of pollution to IEC 60815; referred to maximum operating voltage U_m.

Cap-and-pin insulators K and NK of glass with skirts to IEC 60305

Material: insulator body: toughened glass

caps: malleable iron to DIN 1692 or cast zinc alloy to DIN 1743 (subject to agreement)

balls: heat-treatable steel to DIN 17200 or mechanically equivalent steels (to manufacturer's choice)

Finish: exposed surface green, caps of malleable iron and balls, see DIN VDE 0210
caps of cast zinc alloy: bare

Classification and testing: to IEC 60383-1

Designation: designation of a cap-and-pin insulator with symbol K 12 and height h = 130 mm: pin-and-cap insulator K 12 x 130 DIN 48013

Application: consult EN 50341

The symbol K denotes a cap-and-pin insulator, and NK a fog-type pin insulator. The two types differ in having different shed shapes and creepage distances.

For dimensions, technical data and notes on selection, see Tables 13-38 to 13-41.

Cap-and-pin insulators have the advantage that almost any creepage distance can be obtained by arranging the required number of units one after the other. Because of their construction, however, they must be classified among the non-puncture-proof insulators. Assemblies of cap-and-pin insulators made from toughened glass are almost disintegration-proof. If flashover occurs between ball and cap, only the shed of the insulator breaks off. The ball is held by the unstressed glass between metal cap and ball. The insulator thus retains its mechanical strength. However, the insulator which has undergone electrical breakdown must be replaced, because there is a risk that a subsequent arc may originate at the electrically weakened point, and melt the ball. Also, the insulators in the string have to assume a greater proportion of the voltage. The fact that the shed breaks off with glass caps allows the state of the insulation to be checked easily by eye from the ground.

Cap-and-pin insulators made of ceramic are also used in many countries, as well as glass insulators. Ceramic cap-and-pin insulators are also non-puncture-proof because the flashover distance is very much greater than the puncture path through the insulator body. In contrast to glass cap-and-pin insulators, puncturing does not cause the shed to break off.

Cap-and-pin insulators are not manufactured in Germany. The number in the IEC symbol denotes the electromechanical strength of the insulator in kN. A cap-and-pin insulator DIN-coded K 12, for example, has the IEC symbol U120 BS. The letter B stands for ball & socket connection, the letters S or L for short and long and the letter P for pollution.

Table 13-38

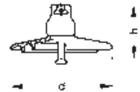
Dimensions and nominal data of typical cap-and-pin insulators to IEC 60305

Symbol	Electromechanical or mechanical strength kN	Max. shed diameter D mm	Height H mm	Nominal creepage distance mm	To fit nominal ball size d_1
U 40 B	40	175	110	190	11
U 40 BP	40	210	110	295	11
U 70 BS	70	255	127	295	16
U 70 BL	70	255	146	295	16
U 70 BLP	70	280	146	440	16
U 100 BS	100	255	127	295	16
U 100 BL	100	255	146	295	16
U 100 BLP	100	280	146	440	16
U 120 B	120	255	146	295	16
U 120 BP	120	280	146	440	16
U 160 BS	160	280	146	315	20
U 160 BSP	160	330	146	440	20
U 160 BL	160	280	170	340	20
U 160 BLP	160	330	170	525	20
U 210 B	210	300	170	370	20
U 210 BP	210	330	170	525	20
U 300 B	300	330	195	390	24
U 300 BP	300	400	195	590	24
U 400 B	400	380	205	525	28
U 530 B	530	380	240	600	32

See Tables 13-39 and 13-40 for electrical data

Table 13-39

Electrical data[1] in kV and length in mm of cap-and-pin insulator strings without protective fittings



Standard type

Standard insulator

Insulator type (IEC 60305)	U 70 BS U 100 BS				U 70 BL U 100 BL U 120 B U 160 BS				U 160 BL U 210 B				U 300 B			
D x P	255 mm x 127 mm				255 mm x 146 mm 280 mm x 146 mm				280 mm x 170 mm 300 mm x 170 mm				330 mm x 195 mm			
No. of units	Short-dur. power-fr. withstand voltage		Lightning impulse withstand voltage	Design length	Short-dur. power-fr. withstand voltage		Lightning impulse withstand voltage	Design length	Short-dur. power-fr. withstand voltage		Lightning impulse withstand voltage	Design length	Short-dur. power-fr. withstand voltage		Lightning impulse withstand voltage	Design length
	dry kV	wet kV	kV	mm	dry kV	wet kV	kV	mm	dry kV	wet kV	kV	mm	dry kV	wet kV	kV	mm
1	70	40	100	127	70	40	100	146	75	45	110	170	85	50	130	195
2	120	72	190	254	130	75	190	292	135	75	205	340	150	85	225	390
3	165	105	260	381	180	110	270	438	190	110	285	510	215	120	315	585
4	205	135	320	508	225	140	340	584	240	145	360	680	375	160	405	780
5	245	165	380	635	270	175	410	730	290	185	440	850	330	200	495	975
6	285	195	435	762	315	210	480	876	335	220	520	1 020	385	235	580	1 170
7	325	225	490	889	360	245	550	1 022	380	255	600	1 190	440	270	665	1 365
8	365	260	550	1 016	405	280	620	1 168	430	290	675	1 360	490	310	745	1 560
9	400	290	615	1 143	450	310	690	1 314	475	325	755	1 530	540	350	830	1 755
10	440	320	675	1 270	490	345	760	1 460	520	360	835	1 700	590	385	910	1 950
11	475	345	735	1 397	530	375	830	1 606	565	390	915	1 870	645	420	990	2 145
12	510	370	795	1 524	570	405	900	1 752	610	420	990	2 040	695	455	1 070	2 340
13	545	395	860	1 651	610	435	970	1 898	655	450	1 065	2 210	740	490	1 150	2 535
14	580	425	925	1 778	650	465	1 035	2 044	695	485	1 140	2 380	785	525	1 230	2 730
15	615	450	985	1 905	690	495	1 100	2 190	740	515	1 215	2 550	830	560	1 315	2 925

[1] The withstand voltage values given are guidance values. If required, obtain precise values from the manufacturer.

(continued)

Table 13-39 (continued)

Electrical data[1] in kV and length in mm of cap-and-pin insulator strings without protective fittings

Standard insulator

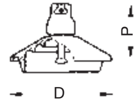
Insulator type (IEC 60305)	U 70 BS U 100 BS				U 70 BL U 100 BL U 120 B U 160 BS				U 160 BL U 210 B				U 300 B			
D x P	255 mm x 127 mm				255 mm x 146 mm 280 mm x 146 mm				280 mm x 170 mm 300 mm x 170 mm				330 mm x 195 mm			
No. of units	Short-dur. power-fr. withstand voltage dry kV	wet kV	Lightning impulse withstand voltage kV	Design length mm	Short-dur. power-fr. withstand voltage dry kV	wet kV	Lightning impulse withstand voltage kV	Design length mm	Short-dur. power-fr. withstand voltage dry kV	wet kV	Lightning impulse withstand voltage kV	Design length mm	Short-dur. power-fr. withstand voltage dry kV	wet kV	Lightning impulse withstand voltage kV	Design length mm
16	650	475	1 045	2 032	725	525	1 165	2 336	785	550	1 290	2 720	875	590	1 395	3 120
17	685	500	1 105	2 159	765	555	1 230	2 482	830	580	1 360	2 890	925	625	1 475	3 315
18	715	525	1 165	2 286	800	585	1 295	2 628	875	610	1 435	3 060	970	655	1 555	3 510
19	750	550	1 225	2 413	840	610	1 360	2 774	920	640	1 510	3 230	1 015	690	1 640	3 705
20	780	575	1 280	2 540	875	640	1 425	2 920	965	670	1 580	3 400	1 060	720	1 720	3 900
21	815	600	1 340	2 667	915	670	1 490	3 066	1 005	700	1 650	3 570	1 110	755	1 795	4 095
22	850	625	1 400	2 794	950	700	1 565	3 212	1 050	730	1 725	3 740	1 155	785	1 875	4 290
23	880	650	1 455	2 921	985	725	1 620	3 358	1 095	760	1 795	3 910	1 200	820	1 950	4 485
24	915	675	1 510	3 048	1 025	755	1 680	3 504	1 140	790	1 870	4 080	1 245	850	2 025	4 680
25	945	700	1 570	3 175	1 060	785	1 745	3 650	1 180	820	1 940	4 250	1 290	880	2 100	4 875
26	975	725	1 625	3 302	1 100	815	1 805	3 796	1 225	845	2 010	4 420	1 330	910	2 175	5 070
27	1 010	750	1 680	3 429	1 135	840	1 870	3 942	1 270	875	2 080	4 590	1 375	940	2 250	5 265
28	1 040	775	1 730	3 556	1 170	865	1 935	4 088	1 310	900	2 150	4 760	1 420	970	2 320	5 460
29	1 070	800	1 780	3 683	1 205	895	2 000	4 234	1 355	930	2 220	4 930	1 460	1 000	2 400	5 655
30	1 100	825	1 835	3 810	1 240	920	2 060	4 380	1 395	955	2 290	5 100	1 505	1 030	2 475	5 850

[1] The withstand voltage values given are guidance values. If required, obtain precise values from the manufacturer.

Table 13-40

Electrical data[1] in kV and length in mm of cap-and-pin insulator strings without protective fittings

Pollution insulator



Pollution type

Insulator type (IEC 60305)	U 70 BLP U 100 BLP U 160 BSP				U 160 BLP U 210 BP				U 300 BP			
D x P	280 mm x 146 mm 330 mm x 146 mm				330 mm x 170 mm				400 mm x 195 mm			
No. of units	Short-dur. power-fr. withstand voltage		Lightning impuls withstand voltage	Design length	Short-dur. power-fr. withstand voltage		Lightning impuls withstand voltage	Design length	Short-dur. power-fr. withstand voltage		Lightning impuls withstand voltage	Design length
	dry	wet			dry	wet			dry	wet		
	kV	kV	kV	mm	kV	kV	kV	mm	kV	kV	kV	mm
1	70/85	40/50	110/125	146	90	55	140	170	100	60	155	195
2	130	75	235	292	135	85	270	340	150	100	280	390
3	180	100	320	438	190	110	370	510	215	130	390	585
4	225	130	390	584	240	145	450	680	275	170	495	780
5	270	155	465	730	290	175	540	850	330	200	600	975
6	315	185	545	876	335	205	625	1 020	305	240	700	1 170
7	360	215	620	1 022	380	240	710	1 190	440	270	810	1 365
8	405	245	695	1 168	430	275	800	1 360	490	310	910	1 560
9	450	270	775	1 314	475	305	890	1 530	540	340	1 015	1 755
10	490	290	855	1 460	520	335	980	1 700	590	380	1 120	1 950
11	530	320	935	1 606	565	360	1 070	1 870	645	410	1 230	2 145
12	570	340	1 015	1 752	610	385	1 170	2 040	695	450	1 340	2 340
13	610	365	1 100	1 898	655	410	1 260	2 210	740	480	1 450	2 535
14	650	390	1 180	2 044	695	440	1 355	2 380	785	520	1 555	2 730
15	690	410	1 260	2 190	740	465	1 450	2 550	830	550	1 660	2 925

[1] The withstand voltage values given are guidance values. If required, obtain precise values from the manufacturer.

Continued on next page

Table 13-40

Electrical data[1] in kV and length in mm of cap-and-pin insulator strings without protective fittings

Pollution insulator

Insulator type (IEC 60305)	U 70 BLP U 100 BLP U 160 BSP				U 160 BLP U 210 BP				U 300 BP			
D x P	280 mm x 146 mm 330 mm x 146 mm				330 mm x 170 mm				400 mm x 195 mm			
No. of units	Short-dur. power-fr. withstand voltage		Lightning impuls withstand voltage	Design length	Short-dur. power-fr. withstand voltage		Lightning impuls withstand voltage	Design length	Short-dur. power-fr. withstand voltage		Lightning impuls withstand voltage	Design length
	dry	wet			dry	wet			dry	wet		
	kV	kV	kV	mm	kV	kV	kV	mm	kV	kV	kV	mm
16	725	430	1 340	2 336	785	490	1 540	2 720	875	590	1 765	3 120
17	765	450	1 425	2 482	830	515	1 640	2 890	925	620	1 865	3 315
18	800	480	1 500	2 628	875	540	1 730	3 060	970	655	1 965	3 510
19	840	500	1 580	2 774	920	565	1 810	3 230	1 015	690	2 070	3 705
20	875	520	1 655	2 920	965	590	1 900	3 400	1 060	725	2 170	3 900
21	915	540	1 730	3 066	1 005	610	1 990	3 570	1 110	755	2 255	4 095
22	950	565	1 810	3 212	1 050	640	2 080	3 740	1 155	790	2 370	4 290
23	985	585	1 885	3 358	1 095	660	2 160	3 910	1 200	825	2 475	4 485
24	1 025	610	1 950	3 504	1 140	690	2 245	4 080	1 245	860	2 575	4 680
25	1 060	630	2 025	3 650	1 180	710	2 325	4 250	1 290	895	2 680	4 875
26	1 100	650	2 095	3 796	1 225	740	2 410	4 420	1 330	930	2 785	5 070
27	1 135	670	2 170	3 942	1 270	760	2 490	4 590	1 375	965	2 890	5 265
28	1 170	695	2 240	4 088	1 310	780	2 575	4 760	1 420	1 000	2 990	5 460
29	1 205	710	2 305	4 234	1 355	805	2 650	4 930	1 460	1 030	3 090	5 655
30	1 240	730	2 365	4 380	1 395	830	2 720	5 100	1 505	1 060	3 185	5 850

[1] The withstand voltage values given are guidance values. If required ,obtain precise values from the manufacturer.

Table 13-41

Selection of cap-and-pin insulators for different operatlng voltages and degrees of pollution (no account taken of electromechanical strength)

Max. operating voltage U_m[1)] kV	Rated lightning impulse with-stand voltage U_{rB}[1)] kV	Rated power frequency withstand voltage U_{rW}[1)] kV	Rated switching impulse withstand voltage Phase-to-earth U_{rS}[1)] kV	Insulator type IEC 60305	Overall height P mm	No. of units/creepage distance with different degrees of pollution[2)] 1 slight 1.6 cm/kV –/cm	2 average 2.0 cm/kV –/cm	3 severe 2.5 cm/kV –/cm	4 very severe 3.1 cm/kV –/cm
36	170	70	—	U 70 BL	146	3/88.5	3/88.5	4/118	4/118
52	250	95	—	U 70 BL	146	4/118	4/118	5/147.5	6/177
				U 70 BLP[3)]	146	–	–	4/176	4/176
72.5	325	140	—	U 70 BL	146	5/147.5	5/147.5	7/206.5	8/236
				U 70 BLP	146	–	–	5/220	6/264
123	550	230	—	U 120 B	146	8/236	9/266.5	11/324.5	13/383.5
				U 120 BP	146	–	–	8/352	9/396
145	650	275	—	U 120 B	146	9/266.5	10/290.5	13/383.5	16/472
				U 120 BP	146	–	–	9/396	11/484
170	750	325	—	U 120 B	146	11/324.5	12/354	15/442.5	18/531
				U 120 BP	146	–	–	11/484	12/528
245	1050	460	—	U 120 B	146	15/442.5	17/501.5	21/619.5	26/767
				U 120 BP	146	–	–	15/660	18/792
362	1175	—	950	U 120 B	146	20/590	25/735	31/914.5	39/1150.5
				U 120 BP	146	–	20/880	21/924	26/1144
420	1425	—	1050	U 120 B	146	24/708	29/855	37/1091.5	45/1327.5
				U 120 BP	146	–	–	24/1056	30/1320
525	1550	—	1175	U 120 B	146	29/855	36/1062	45/1327.5	56/1652
				U 120 BP	146	–	29/1076	30/1320	37/1628

1) Values to IEC 60071

2) Minimum creepage distances per degree of pollution to IEC 60815; referred to maximum operating voltage U_m.

Insulator material	glass-fibre-reinforced epoxy resin rod (GFR rod) with shed of silicone rubber (insulating materials to DIN VDE 0441-1)
Caps	hot-galvanized wrought steel press-fitted to rod end. Hot-galvanized malleable iron, cap forms: ball, socket, strap and clevis
Testing	IEC 61109
Designation	e.g. symbol 30/15(134) – 1300:

shank diameter	d_1	=	30 mm
number of sheds	n	=	15
shed diameter	d_2	=	134 mm
height	h_1	=	1300 mm

Application	consult IEC 50341

Synthetic-composite long-rod insulators with sheds of silicone rubber have been developed from constructions using ceramic materials. With all the advantages of conventional long-rod insulators, they have the added merits of being unbreakable, light in weight and able to be made in one piece up to 6 m long. The intermediate fittings necessary with multi-element insulator strings are therefore not required, resulting in shorter strings at high operating voltages. However, with higher operating voltages e.g. 220 kV, so-called field distribution rings are needed in order to control the electrical field.

Owing to the water-repellent properties of the silicone rubber sheds, these insulators respond better to contamination than ceramic insulators.

Composite long-rod insulators are used mainly where their advantages over conventional types can be of benefit. Their particular features also make them very suitable as phase separators. In this case, the insulators are strung between the phases in an appropriate arrangement. Retrofitting is also possible. This prevents the phases from touching or coming too close together if the wires swing or “gallop”, so reducing outages and damage to the wires.

Synthetic-composite insulators have been performing well for more than 30 years at all voltage levels including DC applications.

The technical data and dimensions of some typical versions of these insulators can be seen in Table 13-42.

Synthetic-composite insulators with clevis caps

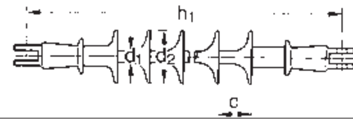


Table 13-42

Dimensions and nominal data of synthetic-composite insulators

Symbol	d_1 ± 3 % mm	Number of sheds	h_1 ± 1% mm	c ± 5 % mm	d_2 ± 2 % mm	Weight ≈ kg	To fit bolts to DIN 43073 N or S ∅ mm	Bolt length mm	Nominal strenght kN	Creepage distance ≈ cm	Application[1] Degree of pollution	Max. operating voltage U_m kV	Power-frequency withstand voltage, wet kV[2]	Lightning impulse withstand voltage, positive kV[2]	Switching impulse withstand voltage, wet kV[2]
30/15(134)-1 200	30	15	1 200	60	134	7	19	48	100	223	slight	123	300	585	—
30/22(134)-1 200	30	22	1 200	42	134	9	19	48	100	283	medium			590	
30/15(134)-1 300	30	15	1 300	60	134	9	19	53	160	223	slight			585	
30/22(134)-1 300	30	22	1 300	42	134	10	19	53	160	283	medium			590	
30/22(134)-2 300	30	22	2 300	86	134	11	22	53	160	383	slight	245	595	1 185	—
30/38(134)-2 300	30	38	2 300	50	134	15	22	53	160	519	medium		600	1 190	
30/46(134)-3 000	30	46	3 000	57	134	19	22	53	160	657	slight	420	—	1 600	950
30/65(134)-3 000	30	65	3 000	40	134	21	22	53	160	818	medium			1 600	
43/46(147)-3 000	43	46	3 000	57	147	24	22	57	220	659	slight			1 605	
43/65(147)-3 000	43	65	3 000	40	147	29	22	57	220	820	medium			1 605	
43/46(147)-3 250	43	46	3 250	60	147	29	32	70	320	669	slight			1 655	
43/64(147)-3 250	43	64	3 250	42	147	33	32	70	320	822	medium			1 655	
30/62(134)-3 500	30	62	3 500	50	134	21	22	53	160	843	slight	525	—	1 865	1 175
30/75(148)-3500	30	75	3 500	41	148	26	22	53	160	1 066	medium			1 865	

[1] Minimum creepage distances per degree of pollution to IEC 60815; referred to maximum operating voltage U_m. Definition, see Table 13-37. Because of the shed's water-repellent properties, in borderline cases, the insulator can be assigned to the next-higher pollution category. Special models are obtainable for very severe pollution.

[2] Rated values

Insulator designation

In accordance with table 13-42a, composite string insulator units are designated by the letters CS followed by a number which indicates the specified mechanical load (SML) in kN. The following letters B, S, T, C, Y and E or a combination of these stipulate whether there is a ball, socket, tongue, clevis, Y-clevis or eye joint. When a combination of joints is used, the first letter must always indicate the joint at the top end of the insulator. The top end of the insulator is defined in relation to the inclination of the sheds. In the case of symmetrical shed profiles, any sequence of the letters is acceptable.

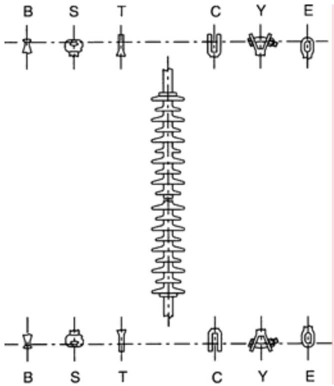


Figure 13-8: Designation letters of couplings

Examples of possible designations:
CS 120 S16 B16 designates a composite string insulator with an SML of 120 kN, fitted at the top end with a socket joint of nominal size 16 to IEC 60120 and at the other end with a ball joint of nominal size 16 to IEC 60120.

CS 120 C19N T19N designates a composite string insulator with an SML of 120 kN, fitted at the top end with a clevis joint of nominal size 19N to Appendix B (IEC 61466-1) and at the other end with a tongue joint of nominal size 19N to Appendix B (IEC 61466-1).

Note: Fittings of the same type which are covered by different standards (e.g. IEC 60120 and Appendix A (IEC 61466-1) should not be used on the same insulator.

Table 13-42a

Insulator designation IEC 61466-1

Designation	Specified mechanical load (SML)	Ball and socket		Clevis and tongue		Y-clevis	Eye
	kN	IEC 60120	annex A	IEC 60471	annex A	annex C	annex D
		sice	sice	sice	sice	sice	sice
CS 40	40	11	–	–	–	–	–
CS 70	70	16	16N	13L	16N	16(19)	17(24)
CS 100	100	16	16N	16L	16N (19N)	19	24
CS 120	120	16(20)	18N	16L	16N (19N)	19	24
CS 160	160	20	22N	19L	19N (22N)	22	25
CS 210	210	20(24)	22N	(19L) 22L	22N	22	25
CS 300	300	24	–	25L	–	–	–
CS 400	400	28	–	28L	–	–	–
CS 530	530	32	–	32L	–	–	–

NOTE - Non-preferred coupling sizes in brackets

Table 13-42b

Designation and characteristics of composite sting insulator acc. IEC 61466-2

Designation	Preferred specified mechanical loads (non-preferred value greyed out) (SML)[1] kN						Standard lightning impulse withstand voltage[2] kV	Minimum creepage distance mm	Minimum-arcing-distance[3] mm	Maximum diameter of the insulating part mm	Highest voltage for equipment based on 16 mm/kV[4] specific creepage distance kV
CS(SML)XZ-60/195	40	70	100	120	160	210	60	195	100	200	*12*
CS(SML)XZ-75/195	40	70	100	120	160	210	75	195	125	200	*12*
CS(SML)XZ-75/280	40	70	100	120	160	210	75	280	125	200	*17.5*
CS(SIOQXZ-95/195	40	70	100	120	160	210	95	195	160	200	*12*
CS(SML)XZ-95/280	40	70	100	120	160	210	95	280	160	200	*17.5*
CS(SML)XZ-95/385	40	70	100	120	160	210	95	385	160	200	*24*
CS(SML)XZ-125/385	40	70	100	120	160	210	125	385	210	200	*24*
CS(SML)XZ-145/385	40	70	100	120	160	210	145	385	240	200	*24*
CS(SML)XZ-145/580	40	70	100	120	160	210	145	580	240	200	*36*
CS(SML)XZ-170/580	40	70	100	120	160	210	170	580	285	200	*36*
CS(SML)XZ-250/835	40	70	100	120	160	210	250	835	435	200	*52*
CS(SML)XZ-325/1160	40	70	100	120	160	210	325	1 160	570	200	*72.5*
CS(SML)XZ-450/1970	40	70	100	120	160	210	450	1 970	815	200	*123*
CS(SML)XZ-450/2320	40	70	100	120	160	210	450	2 320	815	200	*145*
CS(SML)XZ-550/1970	40	70	100	120	160	210	550	1 970	1 005	200	*123*
CS(SML)XZ-550/2320	40	70	100	120	160	210	550	2 320	1 005	200	*145*
CS(SML)XZ-550/2720	40	70	100	120	160	210	550	2 720	1 005	200	*170*
CS(SML)XZ-650/2320	40	70	100	120	160	210	650	2 320	1 195	200	*145*
CS(SML)XZ-650/2720	40	70	100	120	160	210	650	2 720	1 195	200	*170*
CS(SML)XZ-650/3920	40	70	100	120	160	210	650	3 920	1 195	200	*245*
CS(SML)XZ-750/2720	40	70	100	120	160	210	750	2 720	1 395	200	*170*
CS(SML)XZ-750/3920	40	70	100	120	160	210	750	3 920	1 395	200	*245*
CS(SML)XZ-850/3920	40	70	100	120	160	210	850	3 920	1 585	200	*245*
CS(SML)XZ-950/3920	40	70	100	120	160	210	950	3 920	1 775	200	*245*
CS(SML)XZ-1050/3920	40	70	100	120	160	210	1 050	3 920	1 970	200	245

1) SML is the chosen specified mechanical load. XZ are the coupling code letters in accordance with IEC 61466-1.

2) When using arc protection devices, greater values of lightning impulse withstand voltage, in accordance with insulation co-ordination rules, may be specified by customer.

3) The minimum arcing distance is specified, rather than a maximum section lenght (distance between couplings), because the diversity of end fitting types and materials makes it impracitial, at the time of this edition, to standardise section lenght.

4) This column is given for information only.

Information on the creepage distance

Table 13-42b indicates the values of the maximum voltage for equipment U_m based on a specific creepage distance of 16 mm/kV (phase to phase). At the present level of experience, this specific creepage distance is sufficient for areas in which operating behaviour under pollution layers is not regarded as critical. It is essential for the operator to check any change to the creepage distance (increase *or* reduction), so as to ensure appropriate operating behaviour for the prevailing ambient conditions in the relevant area (pollution layer class, service duration, moisture conditions, etc.).

The current guidelines in IEC 60815, both for the specific creepage distance and for shape parameters, are especially orientated towards the use of glass and ceramic insulators and cannot be used directly to define type criteria for composite string insulators.

13.2 Cables and wires[1)]

13.2.1 Specifications, general

During the course of implementing the unified internal European market, there have been changes in the standardization of energy cables. The sections relevant after implementation of the corresponding European harmonization document (HD) for Germany have been collected in a new VDE regulation DIN VDE 0276:

Product group	Former standards DIN VDE ...	Voltage series (kV)	New VDE regulation DIN VDE ...
PVC cable	0271	1	0276 Part 603 (number of cores ≤ 4)
			0276 Part 627 (number of cores > 4)
XLPE cable	0272	1	0276 Part 603
XLPE cable	0273	10, 20, 30	0276 Part 620
Paper cable	0255	10, 20, 30	0276 Part 621
XLPE-cable	0263	> 36 ... 150	0276 Part 632

Cables, wires and flexible cords often have to satisfy very different requirements throughout the cable route. Before deciding the type and cross-section, therefore, one must examine their particular electrical function and also climatic and operational factors influencing system reliability and the expected life time of the equipment. Critical stresses at places along the route can endanger the entire link. Particularly important are the specified conditions for heat dissipation.

In the VDE specifications, the codes for the construction, properties and current-carrying capacity of power cables and wires are contained in Group 2 “Power guides”, and for cables and wires in telecommunications and information processing systems in Group 8 “Information technology”. For high and extra-high voltage cables, the standards merely stipulate the technical properties and their testing, but not the structure in detail. Specifications of the properties of XLPE high voltage cables can be found in DIN VDE 0276-632, while IEC Publication 62067 applies to XLPE extra-high voltage cables > 170 kV up to the maximum permissible operating voltage of 550 kV. Both test standards also cover the test requirements for fittings for high and extra-high voltage cables (see also section 13.2.8).

The identification codes for cables are obtained by adding the symbols in Table 13-43 to the initial letter “N” (types according to DIN VDE) in the sequence of their composition, starting from the conductor. Copper conductors are not identified in the type designation. With paper-insulated cables, the form of insulation is also not mentioned in the code.

Recommendations for the use, supply, transportation and installation and for the current-carrying capacity of cables can be found in the relevant sections of the VDE regulation DIN VDE 0276 and the VDE regulations for installation. Application information for flexible cords is given in DIN VDE 0298-3. The guidelines for up to 1000 V also contain notes on the selection of overload and short-circuit protection facilities.

1) We are thankful for contribution provided by Fa. Suedkabel GmbH.

Table 13-43

Code symbols for cables

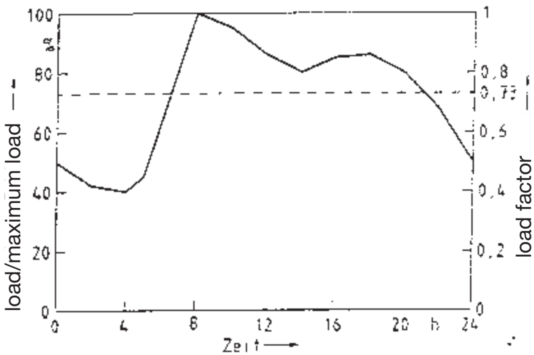
Codes for plastic-insulated cables	
A	Aluminium conductor
I	House wiring cable
Y	Insulation of thermoplastic polyvinyl chloride (PVC)
2Y	Insulation of thermoplastic polyethylene (PE)
2X	Insulation of cross-linked polyethylene (XLPE)
HX	Insulation of cross-linked halogen-free polymer
C	Concentric copper conductor
CW	Concentric copper conductor, meander-shaped applied
S	Copper screen
SE	Copper screen, applied over each core of three-core cables
(F)	Screen area longitudinally watertight
Y/2Y	Protective PVC/PE inner sheath
F	Armouring of galvanized flat steel wire
R	Armouring of galvanized round steel wire
G	Counter tape or binder of galvanized steel strip
Y	PVC outer sheath
2Y	PE outer sheath
H	Outer sheath of thermoplastic halogen-free polymer
HX	Outer sheath of cross-linked halogen-free polymer
–FE	Insulation maintained in case of fire
Codes for paper-insulated cables	
A	Aluminium conductor
H	Screening for Höchstädter cable
E	Metal sheath over each core (three-sheath cable)
K	Lead sheath
E	Protective cover with embedded layer of elastomer tape or plastic foil
Y	Protective PVC inner sheath
B	Armouring of steel strip
F	Armouring of galvanized flat steel wire
FO	Armouring of galvanized flat steel wire, open
G	Counter tape or binder of steel strip
A	Protective cover of fibrous material
Y	PVC outer sheath
YV	Reinforced PVC outer sheath
For cables U_0/U 0.6/1 kV without concentric conductor	
–J	Cable with core coded green/yellow
–O	Cable without core coded green/yellow
Codes for conductor shape and type	
RE	Solid round conductor
RM	Stranded round conductor
SE	Solid sector-shaped conductor
SM	Stranded sector-shaped conductor
RF	Flexible stranded round conductor

13.2.2 Current-carrying capacity

Specifications for the “rated currents” and the conversion factors in the case of deviations in operating conditions are to be found in the following VDE regulations:

DIN VDE 0276-603:	for PVC cables (number of cores $\leq$ 4) and XLPE cables 1 kV
DIN VDE 0276-604:	for cables with improved behaviour in case of fire for 1 kV
DIN VDE 0276-620:	for XLPE cables 10, 20 and 30 kV and for PVC cables 10 kV
DIN VDE 0276-621:	for paper-insulated cables 10, 20 and 30 kV
DIN VDE 0276-622:	for cables with improved behaviour in case of fire for power plants 10, 20 and 30 kV
DIN VDE 0276-627:	for PVC cables (number of cores $>$ 4) 1 kV
DIN VDE 0271:	for PVC cables 1 kV (special designs) and PVC cables to 6 kV
DIN VDE 0276-1000:	conversion factors (current-carrying capacity)
DIN VDE 0298-4:	for lines

The values for the current capacity of cables laid underground can be found in Tables 13-44, and 13-46 to 13-49. They are applicable for a load factor of m = 0.7 (electrical utility load), for a specific ground thermal resistance of 1 K · m/W, for a ground temperature of 20 °C and for laying at a depth of 0.7 m to 1.2 m. The electrical utility load (load factor m = 0.7) is based on a load curve that is usual in power supply company networks; see Fig. 13-8. The load factor is calculated from the 24-hour load cycle and is a quotient of the “area under the load curve” to “total area of the rectangle (maximum load × 24 h)”.



——— ratio of load to maximum load in %
- - - - - - ratio of average load to maximum load

Fig. 13-8

24-hour load cycle and calculating of the load factor (example for a load factor of 0.73)

The values for the current capacity of cables laid in air can be found in Tables 13-45 to 13-49. They are applicable for three-phase continuous operation at an ambient temperature of 30 °C.

Different conditions must be taken into account by application of conversion factors to the above current rating values.

For multiconductor cables the conversion factors given in Table 13-50 apply.
The following apply for cables laid in air

- for different ambient temperatures, the conversion factors given in Table 13-51 and
- for the influence of laying and grouping the conversion factors from Tables 13-52 and 13-53.

The following applies for underground cables:

- for different ground temperatures, the conversion factor f_1 given in Tables 13-54 and 13-55 and
- for cables laying and grouping, the conversion factor f_2 given in Tables 13-56 to 13-59

Both factors also include the ground conditions and the configuration of the cables in the ground. Therefore, both conversion factors, f_1 and f_2, must be always used.

Additional conversion factors for laying cables underground may be:

- 0.85 when laying cables in conduits
- 0.9 when laying cables under covers with air space.

Examples for calculating the permissible current-carrying capacity:

Example 1

Current-carrying capacity of XLPE cable N2XSY 1 × 240 RM/25 6/10 kV:

Operating conditions: cables laid in trefoil formation in ground, covers containing air, load factor m = 0.7, specific soil thermal resistance 1.5 K · m/W, soil temperature 25 °C, 4 systems next to each other, spacing 7 cm.

1.	Current rating from Table 13-47, column 10	526 A
2.	Conversion factor f_1 for 25 °C ground temperature and a max. operating temperature of 90 °C, soil thermal resistance 1.5 K · m/W, load factor m = 0.7, from Table 13-54, column 5	0.87
3.	Conversion factor for grouping f_2 for 4 parallel systems as in Table 13-56, column 5 (1.5/0.7)	0.70
4.	Reduction factor for protective shells	0.90
5.	Max. permitted capacity: 526 A × 0.87 × 0.70 × 0.9 =	288 A

Example 2

Current rating for PVC cable NYY-J 3 × 120 SM/70 SM 0.6/1kV

Operating conditions: cables laid in air, ambient temperature 40 °C, 3 cables on a cable rack with unimpeded air circulation, spacing = cable outside diameter, two cable racks

1.	Current rating from Table 13-45, column 3	285 A
2.	Conversion factor for 40 °C from Table 13-51, column 10	0.87
3.	Conversion factor for laying and grouping from Table 13-53, column 5	0.98
4.	Reduced current rating: 285 A × 0.87 × 0.98 =	243 A

Table 13-44

Rated current (three-phase operation) as per DIN VDE 0276-603 cables with U_0/U = 0.6/1 kV laid underground

1	2	3	4	5	6	7	8	9
Insulation material	PVC					VPE		
Permissible operating temperature	70 °C					90 °C		
Type designation	N(A)YY			N(A)YCWY		N(A)2XY; N(A)2X2Y		
Configuration	[1]					[1]		
Number of loaded conductors	1	3	3	3	3	1	3	3
Cross-section in mm²	Copper conductor: rated current in A							
1.5	41	27	30	27	31	48	31	33
2.5	55	36	39	36	40	63	40	42
4	71	47	50	47	51	82	52	54
6	90	59	62	59	63	102	64	57
10	124	79	83	79	84	136	86	89
16	160	102	107	102	108	176	112	115
25	208	133	138	133	139	229	145	148
35	250	159	164	160	166	275	174	177
50	296	188	195	190	196	326	206	209
70	365	232	238	234	238	400	254	256
95	438	280	286	280	281	480	305	307
120	501	318	325	319	315	548	348	349
150	563	359	365	357	347	616	392	393
185	639	406	413	402	385	698	444	445
240	746	473	479	463	432	815	517	517
300	848	535	541	518	473	927	585	583
400	975	613	614	579	521	1064	671	663
500	1125	687	693	624	574	1227	758	749
Cross-section in mm²	Aluminium conductor: rated current in A							
25	160	102	106	103	108	177	112	114
35	193	123	127	123	129	212	135	136
50	230	144	151	145	153	252	158	162
70	283	179	185	180	187	310	196	199
95	340	215	222	216	223	372	234	238
120	389	245	253	246	252	425	268	272
150	436	275	284	276	280	476	300	305
185	496	313	322	313	314	541	342	347
240	578	364	375	362	358	631	398	404
300	656	419	425	415	397	716	457	457
400	756	484	487	474	441	825	529	525
500	873	553	558	528	489	952	609	601
Conversion factors								
f_1 [2] from tables	13-54	13-54	13-54	13-54	13-54	13-54	13-54	13-54
f_2 [3] from tables	13-59	13-59	13-56 13-57	13-59	13-56 13-57	13-59	13-59	13-56 13-57

[1] Rated current in DC systems with remote return conductors
[2] for ground temperature

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Table 13-45

Rated current (three-phase operation) as per DIN VDE 0276-603
cables with U_0/U = 0.6/1 kV
laid in air

1	*2*	*3*	*4*	*5*	*6*	*7*	*8*	*9*
Insulation material	PVC					VPE		
Permissible operating temperature	70°C					90°C		
Type designation	N(A)YY			N(A)YCWY[3]		N(A)2XY; N(A)2X2Y		
Configuration	[1]					[1]		
Number of loaded conductors	1	3	3	3	3	1	3	3
Cross-section in mm²	Copper conductor: rated current in A							
1.5	27	19.5	21	19.5	22	33	24	26
2.5	35	25	28	26	29	43	32	34
4	47	34	37	34	39	57	42	44
6	59	43	47	44	49	72	53	56
10	81	59	64	60	67	99	74	77
16	107	79	84	80	89	131	98	102
25	144	106	114	108	119	177	133	138
35	176	129	139	132	146	217	162	170
50	214	157	169	160	177	265	197	207
70	270	199	213	202	221	336	250	263
95	334	246	264	249	270	415	308	325
120	389	285	307	289	310	485	359	380
150	446	326	352	329	350	557	412	437
185	516	374	406	377	399	646	475	507
240	618	445	483	443	462	774	564	604
300	717	511	557	504	519	901	649	697
400	843	597	646	577	583	1060	761	811
500	994	669	747	626	657	1252	866	940
Cross-section in mm²	Aluminium conductor: rated current in A							
25	110	82	87	83	91	136	102	106
35	135	100	107	101	112	166	126	130
50	166	119	131	121	137	205	149	161
70	210	152	166	155	173	260	191	204
95	259	186	205	189	212	321	234	252
120	302	216	239	220	247	376	273	295
150	345	246	273	249	280	431	311	339
185	401	285	317	287	321	501	360	395
240	479	338	378	339	374	600	427	472
300	555	400	437	401	426	696	507	547
400	653	472	513	468	488	821	600	643
500	772	539	600	524	556	971	695	754
Conversion factors								
f [2] from tables	13-51	13-51	13-51	13-51	13-51	13-51	13-51	13-51
f [3] from tables	13-53	13-53	13-52	13-53	13-52	13-53	13-53	13-52

[1] Rated current in DC systems with remote return conductors
[2] for air temperature
[3] for grouping

Table 13-46

Rated current (three-phase operation) as per DIN VDE 0271
cables with $U_0/U = 3.6/6$ kV
laid underground and in air

1	*2*	*3*
Insulation material	PVC	
Metal sheath	—	
Type designation Permissible operating temperature	NYFY[3]; NYSY[3] 70 °C	
Configuration		
Laying	*in ground*	*in air*
Nominal cross-section of copper conductor mm²	rated current in A	
25	129	105
35	155	128
50	184	155
70	227	196
95	272	242
120	309	280
150	346	319
185	390	366
240	449	430
300	502	489
400	562	560
Conversion factors		
f_1[1] from tables	13-54	13-51
f_2[2] from tables	13-59	13-53

[1] for ground temperature/for air temperature
[2] for grouping in ground/in air
[3] three-core

Table 13-47

Rated current (three-phase operation) as per DIN VDE 0276-620 (PVC and XLPE cable) and DIN VDE 0276-621 (paper cable)
cable with $U_0/U = 6/10$ kV
laid underground and in air

1	*2*	*3*	*4*	*5*	*6*	*7*	*8*	*9*	*10*	*11*	*12*	
Insulation mat.	Impreg. paper		PVC				XL PE					
Metal sheath	Lead		—						—			
Type designation	N(A)KBA		N(A)YSEY[3] N(A)YSY[4]				N(A)2XSEY, N(A)2XSE2Y[3] N(A)2XSY, N(A)2XS2Y[4]					
Permissible operating temp.	65 °C		70 °C				90 °C					
Configuration	⊛		⊛		⊙ ⊙⊙		⊛		⊙ ⊙⊙		⊙⊙⊙	
Installation	*Ground*	*Air*	*Ground*	*Air*	*Ground*	*Air*	*Ground*	*Air*	*Ground*	*Air*	*Ground*	*Air*
Nominal cross-section Copper mm²					Rated current in A							
25	122	100	134	114	137	119	151	147	157	163	179	194
35	150	123	160	138	163	143	181	178	187	197	212	235
50	179	148	189	165	192	172	213	213	220	236	249	282
70	222	187	231	205	234	214	261	265	268	294	302	350
95	269	228	276	249	279	261	312	322	320	358	359	426
120	308	263	313	286	316	301	355	370	363	413	405	491
150	347	301	351	324	353	341	399	420	405	468	442	549
185	392	345	396	371	397	391	451	481	456	535	493	625
240	454	408	458	434	457	460	523	566	526	631	563	731
300	511	467	—	—	512	526	590	648	591	722	626	831
400	577	536	—	—	571	602	—	—	662	827	675	920
500	—	—	—	—	639	691	—	—	744	949	748	1043
Aluminium mm²												
25	95	78	—	—	—	—	—	—	—	—	—	—
35	117	96	—	—	—	—	140	138	145	153	165	182
50	139	115	147	128	149	133	165	165	171	183	194	219
70	173	145	179	159	182	166	203	206	208	228	236	273
95	209	177	214	193	217	203	242	249	248	278	281	333
120	240	205	244	222	246	234	276	288	283	321	318	384
150	270	234	273	252	276	266	309	326	315	364	350	432
185	307	270	309	289	311	306	351	375	357	418	394	496
240	357	320	358	340	359	361	408	442	413	494	452	583
300	403	368	404	389	405	415	463	507	466	568	506	666
400	461	428	—	—	457	481	—	—	529	660	558	755
500	—	—	—	—	520	560	—	—	602	767	627	868
Conversion factors from tables												
f_1[1)]	13-54	13-51	13-55	13-51	13-54	13-51	13-54	13-51	13-54	13-51	13-54	13-51
f_2[2)]	13-59	13-53	13-59	13-53	13-56 13-57	13-52	13-59	13-53	13-56 13-57	13-52	13-58	13-52

[1)] for ground temperature/for air temperature
[2)] for grouping in ground/in air
[3)] three-core
[4)] single-core

Table 13-48

Rated current (three-phase operation) as per DIN VDE 0276-620 (XLPE cables) and DIN VDE 0276-621 (paper cable)
cable with $U_0 / U = 12/20$ kV
laid underground and in air

1	*2*	*3*	*4*	*5*	*6*	*7*
Insulation material	Impregnated paper		XLPE			
Metal sheath	Lead					
Type designation	N(A)EKEBA		N(A)2XSY, N(A)2XS2Y N(A)2XS(F)2Y			
Permissible operating temperature	65 °C		90 °C			
Configuration						
Installation	*Ground*	*Air*	*Ground*	*Air*	*Ground*	*Air*
Nominal cross-section Copper conductor mm²	Rated current in A					
25	129	111	—	—	—	—
35	155	134	189	200	213	235
50	185	161	222	239	250	282
70	229	200	271	297	303	351
95	274	243	323	361	360	426
120	314	279	367	416	407	491
150	354	317	409	470	445	549
185	402	363	461	538	498	625
240	468	426	532	634	568	731
300	530	488	599	724	633	830
400	600	560	671	829	685	923
500	674	641	754	953	760	1045
Aluminium conductor mm²						
25	100	86	—	—	—	—
35	121	104	—	—	—	—
50	144	125	172	185	195	219
70	178	156	210	231	237	273
95	213	189	251	280	282	332
120	244	218	285	323	319	384
150	275	247	319	366	352	432
185	314	284	361	420	396	494
240	367	334	417	496	455	581
300	417	384	471	569	510	663
400	478	445	535	660	564	753
500	545	516	609	766	634	866
Conversion factors						
f_1 [1)] from tables	13-54	13-51	13-54	13-51	13-54	13-51
f_2 [2)] from tables	13-59	13-53	13-56 13-57	13-52	13-58	13-52

[1)] for ground temperature/for air temperature
[2)] for grouping in ground/in air

Table 13-49

Rated current (three-phase operation) as per DIN VDE 0276-620 (XLPE cables) and DIN VDE 0276-621 (paper cable)
cable with U_0/U = 18/30 kV
laid underground and in air

1	*2*	*3*	*4*	*5*	*6*	*7*
Insulation material	Impregnated paper		XLPE			
Metal sheath	Lead					
Type designation	N(A)EKEBA		N(A)2XSY, N(A)2XS2Y N(A)2XS(F)2Y			
Permissible operating temperature	60 °C		90 °C			
Configuration						
Installation	*Ground*	*Air*	*Ground*	*Air*	*Ground*	*Air*
Nominal cross-section Copper conductor mm²	Rated current in A					
35	146	126	—	—	—	—
50	174	150	225	241	251	282
70	215	187	274	299	304	350
95	259	227	327	363	362	425
120	297	261	371	418	409	488
150	334	295	414	472	449	548
185	379	338	466	539	502	624
240	442	397	539	635	574	728
300	501	453	606	725	640	828
400	569	519	680	831	695	922
500	644	594	765	953	773	1045
Aluminium conductor mm²						
35	113	98	—	—	—	—
50	135	117	174	187	195	219
70	167	145	213	232	238	273
95	201	176	254	282	283	331
120	231	203	289	325	321	382
150	260	230	322	367	354	429
185	297	264	364	421	399	492
240	347	311	422	496	458	578
300	394	356	476	568	514	659
400	454	414	541	659	570	750
500	520	478	616	764	642	861
Conversion factors						
f_1 [1] from tables	13-54	13-51	13-54	13-51	13-54	13-51
f_2 [2] from tables	13-59	13-53	13-56 13-57	13-52	13-58	13-52

[1] for ground temperature/for air temperature
[2] for grouping in ground/in air

Table 13-50

Conversion factors[1),]
for multicore cables with conductor cross-sections of 1.5 to 10 mm^2
laid underground or in air (as per DIN VDE 0276-1000)

1	*2*	*3*
Number of loaded cores	Laid underground	in air
5	0.70	0.75
7	0.60	0.65
10	0.50	0.55
14	0.45	0.50
19	0.40	0.45
24	0.35	0.40
40	0.30	0.35
61	0.25	0.30

1) The conversion factors must be used when
laid underground to the values in Table 13-44, column 3
laid in air to the values in Table 13-45, column 3

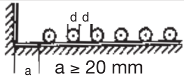
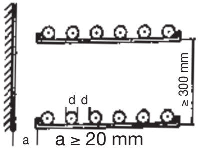
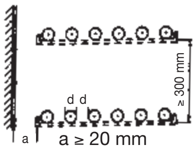
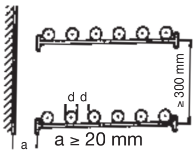
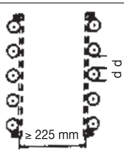
Table 13-51

Conversion factors for different air temperatures (as per DIN VDE 0276-1000)

1	*2*	*3*	*4*	*5*	*6*	*7*	*8*	*9*	*10*	*11*	*12*
Type	Permissible operating temperature	Permissible temperature rise		Conversion factors for the air temperature in °C							
			10	15	20	25	30	35	40	45	50
—	°C	K	—	—	—	—	—	—	—	—	—
XLPE cables	90	—	1.15	1.12	1.08	1.04	1.0	0.96	0.91	0.87	0.82
PVC cables	70	—	1.22	1.17	1.12	1.06	1.0	0.94	0.87	0.79	0.71
Mass-impreg. cables: Belted cables 6/10 kV	65	35	1.25	1.20	1.13	1.07	1.0	0.93	0.85	0.76	0.65
Single-core, three-core single lead sheathed and H-type cables 12/20 kV	65	35	1,25	1,20	1,13	1,07	1,0	0,93	0,85	0,76	0,65
18/30 kV	60	30	1,29	1,22	1,15	1,08	1,0	0,91	0,82	0,71	0,58

Table 13-52

Conversion factors for grouping in air[1)], single-core cables in three-phase systems (as per DIN VDE 0276-1000)

1	*2*	*3*	*4*	*5*
Installation in flat formation Spacing = cable diameter *d*	Number of troughs/ racks vertical	Number of systems[2)] horizontal 1	2	3
Laid on the floor 	1	0.92	0.89	0.88
Unperforated cable troughs[3)] 	1	0.92	0.89	0.88
	2	0.87	0.84	0.83
	3	0.84	0.82	0.81
	6	0.82	0.80	0.79
Perforated cable troughs[3)] 	1	1.00	0.93	0.90
	2	0.97	0.89	0.85
	3	0.96	0.88	0.82
	6	0.94	0.85	0.80
Cable racks[4)] (cable gratings) 	1	1.00	0.97	0.96
	2	0.97	0.94	0.93
	3	0.96	0.93	0.92
	6	0.94	0.91	0.90
On racks or on the wall or on perforated cable troughs in vertical configuration 	Number of troughs horizontal	Number of systems vertical 1	2	3
	1	0.94	0.91	0.89
	2	0.94	0.90	0.86

1) If the air temperature is increased by the heat loss of the cables in small buildings or because of high grouping, the conversion factors for different air temperatures in Table 13-51 must also be used.

2) Factors as per DIN VDE 0255 (VDE 0255)

3) A cable trough is a continuous surface with raised edges but no cover. A cable trough is considered perforated if it is perforated over at least 30 % of the entire surface area.

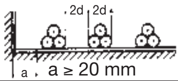
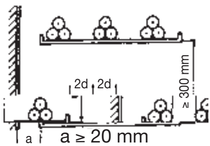
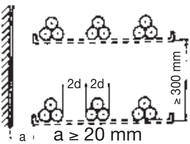
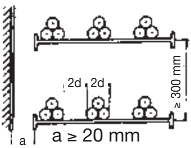
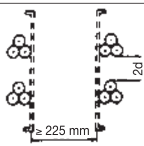
4) A cable rack is a support structure in which the supporting area is no more than 10% of the total area of the structure.

When cables with metal sheathing or shielding are laid flat, the increased sheathing or shielding losses act against the reduced mutual heating when the spacing is increased. For this reason no information on reduction-free configurations can be given.

(continued)

Table 13-52 (continued)

Conversion factors for grouping in air[1], single-core cables in three-phase systems (as per DIN VDE 0276-1000)

6		7	8	9	10
Installation in trefoil formation Spacing = 2 · cable diameter *d*		Number of troughs/ racks vertical	Number of systems[2] horizontal 1	2	3
Laid on the floor		1	0.98	0.96	0.94
Unperforated cable troughs[3]		1	0.98	0.96	0.94
		2	0.95	0.91	0.87
		3	0.94	0.90	0.85
		6	0.93	0.88	0.82
Perforated cable troughs[3]		1	1.00	0.98	0.96
		2	0.97	0.93	0.89
		3	0.96	0.92	0.85
		6	0.95	0.90	0.83
Cable racks[4] (cable gratings)		1	1.00	1.00	1.00
		2	0.97	0.95	0.93
		3	0.96	0.94	0.90
		6	0.95	0.93	0.87
On racks or on the wall or on perforated cable troughs in vertical configuration		Number of troughs horizontal	Number of systems vertical 1	2	3
		1	1.00	0.91	0.89
		2	1.00	0.90	0.86

1) If the air temperature is increased by the heat loss of the cables in small buildings or because of high grouping, the conversion factors for different air temperatures in Table 13-51 must also be used.

2) Factors as in CENELEC Report R064.001 re HD 384,5.523:1991.

3) A cable trough is a continuous surface with raised edges but no cover. A cable trough is considered perforated if the perforations cover at least 30 % of the entire surface area.

4) A cable rack is a support structure in which the supporting area is no more than 10 % of the total area of the structure.

Load reduction is not required when laying in bundles where the spacing of adjacent systems is at least four times the cable diameter, as long as the ambient temperature is not increased by the heat loss (see footnote 1).

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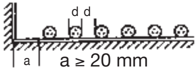
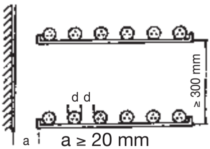
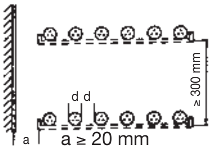
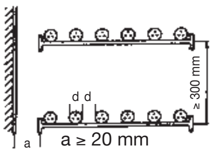
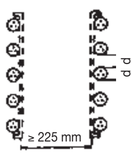
Table 13-53

Conversion factors for grouping in air[1]), multicore cables and single-core DC cables (as per DIN VDE 0276-1000)

1		2	3	4	5	6	7
Installation Spacing = cable diameter *d*		Number of troughs/ racks vertical	Number of cables horizontal[4])				
			1	2	3	4	6
Laid on the floor		1	0.97	0.96	0.94	0.93	0.90
Unperforated cable troughs[2])		1	0.97	0.96	0.94	0.93	0.90
		2	0.97	0.95	0.92	0.90	0.86
		3	0.97	0.94	0.91	0.89	0.84
		6	0.97	0.93	0.90	0.88	0.83
Perforated cable troughs[2])		1	1.00	1.00	0.98	0.95	0.91
		2	1.00	0.99	0.96	0.92	0.87
		3	1.00	0.98	0.95	0.91	0.85
		6	1.00	0.97	0.94	0.90	0.84
Cable racks[3]) (cable gratings)		1	1.00	1.00	1.00	1.00	1.00
		2	1.00	0.99	0.98	0.97	0.96
		3	1.00	0.98	0.97	0.96	0.93
		6	1.00	0.97	0.96	0.94	0.91
On racks or on the wall or on perforated cable troughs in vertical configuration		Number of troughs horizontal	Number of systems vertical				
			1	2	3	4	6
		1	1.00	0.91	0.89	0.88	0.87
		2	1.00	0.91	0.88	0.87	0.85

1) If the air temperature is increased by the heat loss of the cables in small buildings or because of high grouping, the conversion factors for different air temperatures in Table 13-51 must also be used.

2) A cable trough is a continuous surface with raised edges but no cover. A cable trough is considered perforated if it is perforated over at least 30 % of the entire surface area.

3) A cable rack is a support structure in which the supporting area is no more than 10 % of the total area of the structure.

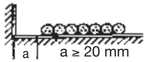
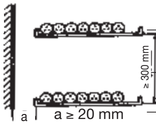
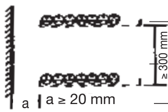
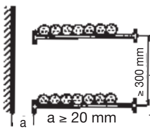
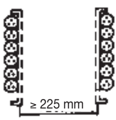
4) Factors as in CENELEC Report R064.001 re HD 384.5.523:1991.

Load reduction is not required where the horizontal or vertical spacing of adjacent cables is at least twice the cable diameter, as long as the ambient temperature is not increased by the heat loss (see footnote 1).

(continued)

Table 13-53 (continued)

Conversion factors for grouping in air[1], multicore cables and single-core d.c. systems (as per DIN VDE 0276-1000)

8		9	10	11	12	13	14	15
Installation Mutual contact		Number of troughs/racks vertical	Number of cables horizontal[4] 1	2	3	4	6	9
Laid on the floor		1	0.97	0.85	0.78	0.75	0.71	0.68
Unperforated cable troughs[2]		1	0.97	0.85	0.78	0.75	0.71	0.68
		2	0.97	0.84	0.76	0.73	0.68	0.63
		3	0.97	0.83	0.75	0.72	0.66	0.61
		6	0.97	0.81	0.73	0.69	0.63	0.58
Perforated cable troughs[2]		1	1.00	0.88	0.82	0.79	0.76	0.73
		2	1.00	0.87	0.80	0.77	0.73	0.68
		3	1.00	0.86	0.79	0.76	0.71	0.66
		6	1.00	0.84	0.77	0.73	0.68	0.64
Cable racks[3] (cable gratings)		1	1.00	0.87	0.82	0.80	0.79	0.78
		2	1.00	0.86	0.80	0.78	0.76	0.73
		3	1.00	0.85	0.79	0.76	0.73	0.70
		6	1.00	0.83	0.76	0.73	0.69	0.66
Perforated cable troughs vertical configuration		Number of troughs horizontal	Number of cables vertical 1	2	3	4	6	9
		1	1.00	0.88	0.82	0.78	0.73	0.72
		2	1.00	0.88	0.81	0.76	0.71	0.70
On racks or on the wall in vertical configuration			Number of cables vertical 1	2	3	4	6	9
			0.95	0.78	0.73	0.72	0.68	0.66

[1] If the air temperature is increased by the heat loss of the cables in small buildings or because of high grouping, the conversion factors for different air temperatures in Table 13-51 must also be used.

[2] A cable trough is a continuous surface with raised edges but no cover. A cable trough is considered perforated if it is perforated over at least 30 % of the entire surface area.

[3] A cable rack is a support structure in which the supporting area is no more than 10 % of the total area of the structure.

[4] Factors as in CENELEC Report R064.001 re HD 384,5.523:1991.

Load reduction is not required where the horizontal or vertical spacing of adjacent systems is at least twice the cable diameter, so long as the ambient temperatures are not increased by the heat loss (see footnote 1).

Table 13-54

Conversion factors f_1, cables laid in ground
All cables (except PVC cables for 6/10 kV) (as per DIN VDE 0276-1000)

1	*2*	*3*					*4*					*5*					*6*
Permissible operating temperature	Soil temperature	Specific thermal resistance of soil K · m/W															
		0.7					1.0					1.5					2.5
		Load factor					Load factor					Load factor					Load factor
°C	°C	0.50	0.60	0.70	0.85	1.00	0.50	0.60	0.70	0.85	1.00	0.50	0.60	0.70	0.85	1.00	0.5 to 1.00
90	5	1.24	1.21	1.18	1.13	1.07	1.11	1.09	1.07	1.03	1.00	0.99	0.98	0.97	0.96	0.94	0.89
	10	1.23	1.19	1.16	1.11	1.05	1.09	1.07	1.05	1.01	0.98	0.97	0.96	0.95	0.93	0.91	0.86
	15	1.21	1.17	1.14	1.08	1.03	1.07	1.05	1.02	0.99	0.95	0.95	0.93	0.92	0.91	0.89	0.84
	20	1.19	1.15	1.12	1.06	1.00	1.05	1.02	1.00	0.96	0.93	0.92	0.91	0.90	0.88	0.86	0.81
	25						1.02	1.00	0.98	0.94	0.90	0.90	0.88	0.87	0.85	0.84	0.78
	30								0.95	0.91	0.88	0.87	0.86	0.84	0.83	0.81	0.75
	35													0.82	0.80	0.78	0.72
	40																0.68
80	5	1.27	1.23	1.20	1.14	1.08	1.12	1.10	1.07	1.04	1.00	0.99	0.98	0.97	0.95	0.93	0.88
	10	1.25	1.21	1.17	1.12	1.06	1.10	1.07	1.05	1.01	0.97	0.97	0.95	0.94	0.92	0.91	0.85
	15	1.23	1.19	1.15	1.09	1.03	1.07	1.05	1.03	0.99	0.95	0.94	0.93	0.92	0.90	0.88	0.82
	20	1.20	1.17	1.13	1.07	1.01	1.05	1.03	1.00	0.96	0.92	0.91	0.90	0.89	0.87	0.85	0.78
	25						1.03	1.00	0.97	0.93	0.89	0.88	0.87	0.86	0.84	0.82	0.75
	30								0.95	0.91	0.86	0.85	0.84	0.83	0.81	0.78	0.72
	35													0.80	0.77	0.75	0.68
	40																0.64
70	5	1.29	1.26	1.22	1.15	1.09	1.13	1.11	1.08	1.04	1.00	0.99	0.98	0.97	0.95	0.93	0.86
	10	1.27	1.23	1.19	1.13	1.06	1.11	1.08	1.06	1.01	0.97	0.96	0.95	0.94	0.92	0.89	0.83
	15	1.25	1.21	1.17	1.10	1.03	1.08	1.06	1.03	0.99	0.94	0.93	0.92	0.91	0.88	0.86	0.79
	20	1.23	1.18	1.14	1.08	1.01	1.06	1.03	1.00	0.96	0.91	0.90	0.89	0.87	0.85	0.83	0.76
	25						1.03	1.00	0.97	0.93	0.88	0.87	0.85	0.84	0.82	0.79	0.72
	30								0.94	0.89	0.85	0.84	0.82	0.80	0.78	0.76	0.68
	35													0.77	0.74	0.72	0.63
	40																0.59

The conversion factor f_1 must always be used with the conversion factor f_2.
(continued)

Table 13-54 (continued)

1	*2*	*3*					*4*					*5*					*6*
Permissible operating temperature	Soil temperature	Specific thermal resistance of soil K · m/W															
		0.7					1.0					1.5					2.5
		Load factor					Load factor					Load factor					Load factor
°C	°C	0.50	0.60	0.70	0.85	1.00	0.50	0.60	0.70	0.85	1.00	0.50	0.60	0.70	0.85	1.00	0.5 to 1.00
65	5	1.31	1.27	1.23	1.16	1.09	1.14	1.11	1.09	1.04	1.00	0.99	0.98	0.96	0.94	0.92	0 85
	10	1.29	1.24	1.20	1.14	1.06	1.11	1.09	1.06	1.02	0.97	0.96	0.95	0.93	0.91	0.89	0.82
	15	1.26	1.22	1.18	1.11	1.04	1.09	1.06	1.03	0.98	0.94	0.93	0.91	0.90	0.88	0.85	0.78
	20	1.24	1.20	1.15	1.08	1.01	1.06	1.03	1.00	0.95	0.90	0.90	0.88	0.86	0.84	0.82	0.74
	25						1.03	1.00	0.97	0.92	0.87	0.86	0.84	0.83	0.80	0.78	0.70
	30								0.94	0.89	0.83	0.82	0.81	0.79	0.77	0.74	0.65
	35													0.75	0.72	0.70	0.60
	40																0.55
60	5	1.33	1.28	1.24	1.17	1.10	1.15	1.12	1.09	1.05	1.00	0.99	0.98	0.96	0.94	0.92	0.84
	10	1.30	1.26	1.21	1.14	1.07	1.12	1.09	1.06	1.02	0.97	0.96	0.94	0.93	0.90	0.88	0.80
	15	1.28	1.23	1.19	1.12	1.04	1.09	1.06	1.03	0.98	0.93	0.92	0.91	0.89	0.87	0.84	0.76
	20	1.25	1.21	1.16	1.09	1.01	1.06	1.03	1.00	0.95	0.90	0.89	0.87	0.86	0.83	0.80	0.72
	25						1.03	1.00	0.97	0.92	0.86	0.85	0.83	0.82	0.79	0.76	0.67
	30								0.93	0.88	0.82	0.81	0.79	0.78	0.75	0.72	0.62
	35													0.73	0.70	0.67	0.57
	40																0.51

With mass-impregnated cables, increasing the current rating at temperatures below 20 °C is subject to conditions. The conversion factor f_1 must be applied only together with conversion factor f_2.

Table 13-55

Conversion factors f_1, cables laid in ground, PVC cables for 6/10 kV (as per DIN VDE 0276-1000)

1	*2*	*3*	*4*	*5*					*6*					*7*					*8*
Number of three-phase systems		Number of three-phase cables	Soil temperature °C	Specific thermal resistance of soil K · m/W 0.7					1.0					1.5					2.5
				Load factor 0.50	0.60	0.70	0.85	1.00	Load factor 0.50	0.60	0.70	0.85	1.00	Load factor 0.50	0.60	0.70	0.85	1.00	Load factor 0.5 to 1.0
1	1	1	5	1.31	1.27	1.23	1.16	1.09	1.14	1.12	1.09	1.05	1.00	0.99	0.98	0.96	0.94	0.92	0.85
			10	1.29	1.25	1.21	1.14	1.07	1.12	1.09	1.06	1.02	0.97	0.96	0.95	0.93	0.91	0.89	0.81
			15	1.27	1.22	1.18	1.11	1.04	1.09	1.06	1.03	0.98	0.94	0.93	0.91	0.90	0.87	0.85	0.77
			20	1.24	1.20	1.15	1.08	1.01	1.06	1.03	1.00	0.95	0.90	0.89	0.88	0.86	0.84	0.81	0.73
			25						1.03	1.00	0.97	0.92	0.87	0.85	0.84	0.83	0.80	0.77	0.69
			30								0.94	0.89	0.83	0.82	0.80	0.79	0.76	0.73	0.64
			35													0.75	0.72	0.70	0.59
			40																0.54
4	3	3	5	1.29	1.24	1.20	1.13	1.06	1.11	1.08	1.05	1.01	0.96	0.95	0.94	0.93	0.90	0.88	0.81
			10	1.26	1.22	1.17	1.11	1.03	1.08	1.05	1.03	0.98	0.93	0.92	0.91	0.89	0.87	0.84	0.77
			15	1.24	1.19	1.15	1.08	1.00	1.05	1.03	0.99	0.95	0.90	0.89	0.87	0.86	0.83	0.81	0.73
			20	1.21	1.17	1.12	1.05	0.97	1.03	0.99	0.96	0.91	0.86	0.85	0.84	0.82	0.79	0.77	0.68
			25						0.99	0.96	0.93	0.88	0.83	0.82	0.80	0.78	0.76	0.73	0.64
			30								0.90	0.84	0.79	0.78	0.76	0.74	0.71	0.68	0.59
			35													0.70	0.67	0.64	0.53
			40																0.47
10	5	6	5	1.26	1.21	1.17	1.10	1.03	1.08	1.05	1.02	0.97	0.93	0.92	0.90	0.89	0.86	0.84	0.76
			10	1.23	1.19	1.14	1.07	1.00	1.05	1.02	0.99	0.94	0.89	0.88	0.87	0.85	0.83	0.80	0.72
			15	1.21	1.16	1.12	1.04	0.96	1.02	0.99	0.96	0.91	0.86	0.85	0.83	0.81	0.79	0.76	0.68
			20	1.18	1.14	1.09	1.01	0.93	0.99	0.96	0.93	0.87	0.82	0.81	0.79	0.77	0.75	0.72	0.63
			25						0.96	0.93	0.89	0.84	0.78	0.77	0.75	0.73	0.70	0.68	0.58
			30								0.86	0.80	0.74	0.73	0.71	0.69	0.66	0.63	0.52
			35													0.64	0.61	0.58	0.46
			40																0.38

Conversion factor f_1 must be applied only together with conversion factor f_2.

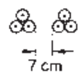
(continued)

Table 13-55 (continued)

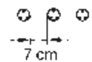
1	2	3	4	5					6					7					8
Number of three-phase systems		Number of three-phase cables	Soil temperature °C	Specific thermal resistance of soil K · m/W 0.7					1.0					1.5					2.5
				Load factor					Load factor					Load factor					Load factor
				0.50	0.60	0.70	0.85	1.00	0.50	0.60	0.70	0.85	1.00	0.50	0.60	0.70	0.85	1.00	0.5 to 1.0
—	8	10	5	1.23	1.19	1.14	1.07 .	0.99	1.05	1.02	0.99	0.94	0.89	0.88	0.86	0.85	0.82	0.80	0.72
			10	1.21	1.16	1.11	1.04	0.96	1.02	0.99	0.96	0.91	0.85	0.84	0.83	0.81	0.78	0.76	0 67
			15	1.18	1.13	1.09	1.01	0.93	0.99	0.96	0.92	0.87	0.82	0.81	0.79	0.77	0.74	0.72	0.63
			20	1.15	1.11	1.06	0.98	0.90	0.96	0.92	0.89	0.84	0.78	0.77	0.75	0.73	0.70	0.67	0.57
			25						0.92	0.89	0.85	0.80	0.74	0.73	0.71	0.69	0.66	0.63	0.52
			30								0.82	0.76	0.70	0.68	0.66	0.64	0 61	0.57	0.45
			35													0.60	0.56	0.52	0.38
			40																0.29
—	10	—	5	1.22	1.17	1.13	1.05	0.98	1.03	1.00	0.97	0.92	0.87	0.86	0.84	0.83	0.80	0.78	0.69
			10	1.19	1.15	1.10	1.02	0.94	1.00	0.97	0.94	0.89	0.83	0.82	0.81	0.79	0.76	0.73	0.65
			15	1.17	1.12	1.07	0.99	0.91	0.97	0.94	0.90	0.85	0.79	0.78	0.77	0.75	0.72	0.69	0.60
			20	1.14	1.09	1.04	0.96	0.88	0.94	0.90	0.87	0.81	0.76	0.74	0.73	0.71	0.68	0.65	0.54
			25						0.90	0.87	0.83	0.78	0.71	0.70	0.68	0.66	0.63	0.60	0.48
			30								0.79	0.73	0.67	0.66	0.63	0.61	0.58	0.54	0.41
			35													0.56	0.52	0.48	0.33
			40																0.22

Arrangement of three-phase systems in column 1

Arrangement of three-phase systems in column 2

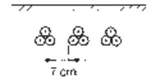


Arrangement of three-phase cables in column 3



Conversion factor f_1 must be applied only together with conversion factor f_2.

Table 13-56



Conversion factor f_2, cables laid in ground
Single-core cables in three phase systems, trefoil formation (as per DIN VDE 0276-1000)

1	2	3					4					5					6				
Type	Number of systems	Specific thermal resistance of soil in K · m/W																			
		0.7					1.0					1.5					2.5				
XLPE cables 0.6/1 kV 6/10 kV 12/20 kV 18/30 kV		load factor					load factor					load factor					load factor				
		0.5	0.6	0.7	0.85	1.00	0.5	0.6	0.7	0.85	1.00	0.5	0.6	0.7	0.85	1.00	0.5	0.6	0.7	0.85	1.00
	1	1.09	1.04	0.99	0.93	0.87	1.11	1.05	1.00	0.93	0.87	1.13	1.07	1.01	0.94	0.87	1.17	1.09	1.03	0.94	0.87
	2	0.97	0.90	0.84	0.77	0.71	0.98	0.91	0.85	0.77	0.71	1.00	0.92	0.86	0.77	0.71	1.02	0.94	0.87	0.78	0.71
	3	0.88	0.80	0.74	0.67	0.61	0.89	0.82	0.75	0.67	0.61	0.90	0.82	0.76	0.68	0.61	0.92	0.83	0.76	0.68	0.61
	4	0.83	0.75	0.69	0.62	0.56	0.84	0.76	0.70	0.62	0.56	0.85	0.77	0.70	0.62	0.56	0.86	0.78	0.71	0.63	0.56
	5	0.79	0.71	0.65	0.58	0.52	0.80	0.72	0.66	0.58	0.52	0.80	0.73	0.66	0.58	0.52	0.82	0.73	0.67	0.59	0.52
	6	0.76	0.68	0.62	0.55	0.50	0.77	0.69	0.63	0.55	0.50	0.77	0.70	0.63	0.56	0.50	0.78	0.70	0.64	0.56	0.50
	8	0.72	0.64	0.58	0.51	0.46	0.72	0.65	0.59	0.52	0.46	0.73	0.65	0.59	0.52	0.46	0.74	0.66	0.59	0.52	0.46
	10	0.69	0.61	0.56	0.49	0.44	0.69	0.62	0.56	0.49	0.44	0.70	0.62	0.56	0.49	0.44	0.70	0.63	0.57	0.49	0.44
PVC cables 0.6/1 kV 3.6/6 kV 6/10 kV		load factor					load factor					load factor					load factor				
		0.5	0.6	0.7	0.85	1.00	0.5	0.6	0.7	0.85	1.00	0.5	0.6	0.7	0.85	1.00	0.5	0.6	0.7	0.85	1.00
	1	1.01	1.02	0.99	0.93	0.87	1.04	1.05	1.00	0.93	0.87	1.07	1.06	1.01	0.94	0.87	1.11	1.08	1.01	0.94	0.87
	2	0.94	0.89	0.84	0.77	0.71	0.97	0.91	0.85	0.77	0.71	0.99	0.92	0.86	0.77	0.71	1.01	0.93	0.87	0.78	0.71
	3	0.86	0.79	0.74	0.67	0.61	0.89	0.81	0.75	0.67	0.61	0.90	0.83	0.76	0.68	0.61	0.91	0.83	0.77	0.68	0.61
	4	0.82	0.75	0.69	0.62	0.56	0.84	0.76	0.70	0.62	0.56	0.85	0.77	0.71	0.62	0.56	0.86	0.78	0.71	0.63	0.56
	5	0.78	0.71	0.65	0.58	0.52	0.80	0.72	0.66	0.58	0.52	0.80	0.73	0.66	0.58	0.52	0.81	0.73	0.67	0.59	0.52
	6	0.75	0.68	0.62	0.55	0.50	0.77	0.69	0.63	0.55	0.50	0.77	0.70	0.64	0.56	0.50	0.78	0.70	0.64	0.56	0.50
	8	0.71	0.64	0.58	0.51	0.46	0.72	0.65	0.59	0.52	0.46	0.73	0.65	0.59	0.52	0.46	0.73	0.66	0.60	0.52	0.46
	10	0.68	0.61	0.55	0.49	0.44	0.69	0.62	0.56	0.49	0.44	0.69	0.62	0.56	0.49	0.44	0.70	0.63	0.57	0.49	0.44

The conversion factor f_2 must be applied only together with conversion factor f_1.

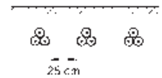
Table 13-56 (continued)

1	*2*	*3*					*4*					*5*					*6*				
Type	Number of systems	Specific thermal resistance of soil in K · m/W																			
		0.7					1.0					1.5					2.5				
		load factor					load factor					load factor					load factor				
		0.5	0.6	0.7	0.85	1.00	0.5	0.6	0.7	0.85	1.00	0.5	0.6	0.7	0.85	1.00	0.5	0.6	0.7	0.85	1.00
	1	0.94	0.95	0.97	0.93	0.87	0.99	0.99	1.00	0.93	0.87	1.06	1.04	1.01	0.94	0.87	1.15	1.08	1.02	0.94	0.87
	2	0.88	0.88	0.84	0.77	0.71	0.93	0.91	0.85	0.77	0.71	0.97	0.92	0.86	0.77	0.71	1.01	0.93	0.87	0.78	0.71
	3	0.84	0.79	0.74	0.67	0.61	0.87	0.81	0.75	0.67	0.61	0.90	0.82	0.76	0.68	0.61	0.91	0.83	0.76	0.68	0.61
	4	0.82	0.74	0.69	0.62	0.56	0.84	0.76	0.70	0.62	0.56	0.85	0.77	0.71	0.62	0.56	0.86	0.78	0.71	0.63	0.56
	5	0.78	0.70	0.65	0.58	0.52	0.79	0.72	0.65	0.58	0.52	0.80	0.73	0.66	0.58	0.52	0.81	0.73	0.67	0.59	0.52
	6	0.75	0.68	0.62	0.55	0.50	0.76	0.69	0.63	0.55	0.50	0.77	0.70	0.63	0.56	0.50	0.78	0.70	0.64	0.56	0.50
	8	0.71	0.64	0.58	0.51	0.46	0.72	0.64	0.58	0.52	0.46	0.72	0.65	0.59	0.52	0.46	0.73	0.66	0.59	0.52	0.46
	10	0.68	0.61	0.55	0.49	0.44	0.69	0.61	0.56	0.49	0.44	0.69	0.62	0.56	0.49	0.44	0.70	0.62	0.56	0.49	0.44

The conversion factor f_2 must be applied only together with conversion factor f_1.

Table 13-57

Conversion factor f_2, cables laid in ground
Single-core cables in three phase systems, trefoil formation (as per DIN VDE 0276-1000)



1	2	3					4					5					6				
Type	Number of systems	Specific thermal resistance of soil in K · m/W																			
		0.7					1.0					1.5					2.5				
XLPE cables 0.6/1 kV 6/10 kV 12/20 kV 18/30 kV		load factor					load factor					load factor					load factor				
		0.5	0.6	0.7	0.85	1.00	0.5	0.6	0.7	0.85	1.00	0.5	0.6	0.7	0.85	1.00	0.5	0.6	0.7	0.85	1.00
	1	1.09	1.04	0.99	0.93	0.87	1.11	1.05	1.00	0.93	0.87	1.13	1.07	1.01	0.94	0.87	1.17	1.09	1.03	0.94	0.87
	2	1.01	0.94	0.89	0.82	0.75	1.02	0.95	0.89	0.82	0.75	1.04	0.97	0.90	0.82	0.75	1.06	0.98	0.91	0.83	0.75
	3	0.94	0.87	0.81	0.74	0.67	0.95	0.88	0.82	0.74	0.67	0.97	0.89	0.82	0.74	0.67	0.99	0.90	0.83	0.74	0.67
	4	0.91	0.84	0.78	0.70	0.64	0.92	0.84	0.78	0.70	0.64	0.93	0.85	0.79	0.70	0.64	0.95	0.86	0.79	0.71	0.64
	5	0.88	0.80	0.74	0.67	0.60	0.89	0.81	0.75	0.67	0.60	0.90	0.82	0.75	0.67	0.60	0.91	0.83	0.76	0.67	0.60
	6	0.86	0.79	0.72	0.65	0.59	0.87	0.79	0.73	0.65	0.59	0.88	0.80	0.73	0.65	0.59	0.89	0.81	0.74	0.65	0.59
	8	0.83	0.76	0.70	0.62	0.56	0.84	0.76	0.70	0.62	0.56	0.85	0.77	0.70	0.62	0.56	0.86	0.78	0.71	0.62	0.56
	10	0.81	0.74	0.68	0.60	0.54	0.82	0.74	0.68	0.60	0.54	0.83	0.75	0.68	0.61	0.54	0.84	0.76	0.69	0.61	0.54
PVC cables 0.6/1 kV 3.6/6 kV 6/10 kV		load factor					load factor					load factor					load factor				
		0.5	0.6	0.7	0.85	1.00	0.5	0.6	0.7	0.85	1.00	0.5	0.6	0.7	0.85	1.00	0.5	0.6	0.7	0.85	1.00
	1	1.01	1.02	0.99	0.93	0.87	1.04	1.05	1.00	0.93	0.87	1.07	1.06	1.01	0.94	0.87	1.11	1.08	1.01	0.94	0.87
	2	0.97	0.95	0.89	0.82	0.75	1.00	0.96	0.90	0.82	0.75	1.03	0.97	0.91	0.82	0.75	1.06	0.98	0.92	0.83	0.75
	3	0.94	0.88	0.82	0.74	0.67	0.97	0.88	0.82	0.74	0.67	0.97	0.89	0.83	0.74	0.67	0.98	0.90	0.84	0.74	0.67
	4	0.91	0.84	0.78	0.70	0.64	0.92	0.85	0.79	0.70	0.64	0.93	0.86	0.79	0.70	0.64	0.95	0.87	0.80	0.71	0.64
	5	0.88	0.81	0.75	0.67	0.60	0.89	0.82	0.76	0.67	0.60	0.90	0.82	0.76	0.67	0.60	0.91	0.83	0.77	0.67	0.60
	6	0.86	0.79	0.73	0.65	0.59	0.87	0.80	0.74	0.65	0.59	0.88	0.81	0.74	0.65	0.59	0.89	0.81	0.75	0.65	0.59
	8	0.83	0.76	0.70	0.62	0.56	0.84	0.77	0.71	0.62	0.56	0.85	0.78	0.71	0.62	0.56	0.86	0.78	0.72	0.62	0.56
	10	0.82	0.75	0.69	0.60	0.54	0.82	0.75	0.69	0.60	0.54	0.83	0.76	0.69	0.61	0.54	0.84	0.76	0.70	0.61	0.54

The conversion factor f_2 must be applied only together with conversion factor f_1.

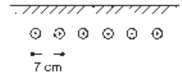
(continued)

Table 13-57 (continued)

1	*2*	*3*					*4*					*5*					*6*				
Type	Number of systems	Specific thermal resistance of soil in K · m/W																			
		0.7					1.0					1.5					2.5				
		load factor					load factor					load factor					load factor				
		0.5	0.6	0.7	0.85	1.00	0.5	0.6	0.7	0.85	1.00	0.5	0.6	0.7	0.85	1.00	0.5	0.6	0.7	0.85	1.00
Mass-impregnated cables	1	0.94	0.95	0.97	0.93	0.87	0.99	0.99	1.00	0.93	0.87	1.06	1.04	1.01	0.94	0.87	1.15	1.08	1.02	0.94	0.87
0.6/1 kV	2	0.90	0.91	0.88	0.82	0.75	0.95	0.94	0.89	0.82	0.75	1.00	0.96	0.89	0.82	0.75	1.05	0.97	0.90	0.83	0.75
3.6/6 kV	3	0.87	0.86	0.80	0.74	0.67	0.91	0.87	0.81	0.74	0.67	0.95	0.88	0.81	0.74	0.67	0.97	0.89	0.82	0.74	0.67
6/10 kV	4	0.86	0.82	0.76	0.70	0.64	0.89	0.83	0.77	0.70	0.64	0.91	0.83	0.77	0.70	0.64	0.92	0.84	0.78	0.71	0.64
12/10 kV	5	0.84	0.79	0.73	0.67	0.60	0.86	0.79	0.73	0.67	0.60	0.87	0.80	0.73	0.67	0.60	0.89	0.81	0.74	0.67	0.60
18/30 kV	6	0.83	0.77	0.71	0.65	0.59	0.84	0.77	0.71	0.65	0.59	0.85	0.78	0.71	0.65	0.59	0.86	0.78	0.72	0.65	0.59
	8	0.80	0.73	0.67	0.62	0.56	0.81	0.74	0.68	0.62	0.56	0.82	0.74	0.68	0.62	0.56	0.83	0.75	0.68	0.62	0.56
	10	0.78	0.71	0.65	0.60	0.54	0.79	0.71	0.65	0.60	0.54	0.80	0.72	0.66	0.61	0.54	0.81	0.73	0.66	0.61	0.54

The conversion factor f_2 must be applied only together with conversion factor f_1.

Table 13-58



Conversion factor f_2, cables laid in ground
Single-core cables in three phase systems, flat formation (as per DIN VDE 0276-1000)

1	2	3					4					5					6				
Type	Number of systems	Specific thermal resistance of soil in K · m/W																			
		0.7					1.0					1.5					2.5				
		load factor					load factor					load factor					load factor				
		0.5	0.6	0.7	0.85	1.00	0.5	0.6	0.7	0.85	1.00	0.5	0.6	0.7	0.85	1.00	0.5	0.6	0.7	0.85	1.00
XLPE cables 0.6/1 kV 6/10 kV 12/20 kV 18/30 kV	1	1.08	1.05	0.99	0.91	0.85	1.13	1.07	1.00	0.92	0.85	1.18	1.09	1.01	0.92	0.85	1.19	1.11	1.03	0.93	0.85
	2	1.01	0.93	0.86	0.77	0.71	1.03	0.94	0.87	0.78	0.71	1.05	0.95	0.88	0.78	0.71	1.06	0.96	0.88	0.79	0.71
	3	0.92	0.84	0.77	0.69	0.62	0.93	0.85	0.77	0.69	0.62	0.95	0.86	0.78	0.69	0.62	0.96	0.86	0.79	0.69	0.62
	4	0.88	0.80	0.73	0.65	0.58	0.89	0.80	0.73	0.65	0.58	0.90	0.81	0.74	0.65	0.58	0.91	0.82	0.74	0.65	0.58
	5	0.84	0.76	0.69	0.61	0.55	0.85	0.77	0.70	0.61	0.55	0.87	0.78	0.70	0.62	0.55	0.87	0.78	0.71	0.62	0.55
	6	0.82	0.74	0.67	0.59	0.53	0.83	0.75	0.68	0.60	0.53	0.84	0.75	0.68	0.60	0.53	0.85	0.76	0.69	0.60	0.53
	8	0.79	0.71	0.64	0.57	0.51	0.80	0.71	0.65	0.57	0.51	0.81	0.72	0.65	0.57	0.51	0.81	0.72	0.65	0.57	0.51
	10	0.77	0.69	0.62	0.55	0.49	0.78	0.69	0.63	0.55	0.49	0.78	0.70	0.63	0.55	0.49	0.79	0.70	0.63	0.55	0.49
		load factor					load factor					load factor					load factor				
		0.5	0.6	0.7	0.85	1.00	0.5	0.6	0.7	0.85	1.00	0.5	0.6	0.7	0.85	1.00	0.5	0.6	0.7	0.85	1.00
PVC cables 0.6/1 kV 3.6/6 kV 6/10 kV	1	0.96	0.97	0.98	0.91	0.85	1.01	1.01	1.00	0.92	0.85	1.07	1.05	1.01	0.92	0.85	1.16	1.10	1.02	0.93	0.85
	2	0 92	0.89	0.86	0.77	0.71	0.96	0.94	0.87	0.78	0.71	1.00	0.95	0.88	0.78	0.71	1.05	0.97	0.89	0.79	0.71
	3	0.88	0.84	0.77	0.69	0.62	0.91	0.85	0.78	0.69	0.62	0.95	0.86	0.79	0.69	0.62	0.96	0.87	0.79	0.69	0.62
	4	0. 86	0.80	0.73	0.65	0.58	0.89	0.81	0.74	0.65	0.58	0.90	0.82	0.74	0.65	0.58	0.91	0.82	0.75	0.65	0.58
	5	0.84	0.76	0.70	0.61	0.55	0.85	0.77	0.70	0.61	0.55	0.87	0.78	0.71	0.62	0.55	0.87	0.79	0.71	0.62	0.55
	6	0.82	0.74	0.68	0.59	0.53	0.83	0.75	0.68	0.60	0.53	0.83	0.76	0.69	0.60	0.53	0.85	0.76	0.69	0.60	0.53
	8	0.79	0.71	0.65	0.57	0.51	0.80	0.72	0.65	0.57	0.51	0.81	0.72	0.65	0.57	0.51	0.81	0.73	0.66	0.57	0.51
	10	0.77	0.69	0.63	0.55	0.49	0.78	0.70	0.63	0.55	0.49	0.79	0.70	0.63	0.55	0.49	0.79	0.71	0.64	0.55	0.49

The conversion factor f_2 must be applied only together with conversion factor f_1.

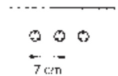
(continued)

Table 13-58 (continued)

1	*2*	*3*					*4*					*5*					*6*				
Type	Number of systems	Specific thermal resistance of soil in K · m/W																			
		0.7					1.0					1.5					2.5				
		load factor					load factor					load factor					load factor				
		0.5	0.6	0.7	0.85	1.00	0.5	0.6	0.7	0.85	1.00	0.5	0.6	0.7	0.85	1.00	0.5	0.6	0.7	0.85	1.00
Mass-impregnated cables 0.6/1 kV 3.6/6 kV 6/10 kV 12/10 kV 18/30 kV	1	0.93	0.94	0.95	0.91	0.85	1.00	1.00	1.00	0.92	0.85	1.09	1.06	1.01	0.92	0.85	1.19	1.10	1.03	0.93	0.85
	2	0.89	0.89	0.86	0.77	0.71	0.95	0.93	0.87	0.78	0.71	1.01	0.95	0.88	0.78	0.71	1.05	0.97	0.89	0.79	0.71
	3	0.86	0.84	0.77	0.69	0.62	0.90	0.85	0.78	0.69	0.62	0.95	0.86	0.79	0.69	0.62	0.96	0.87	0.79	0.69	0.62
	4	0. 84	0.80	0.73	0.65	0.58	0.88	0.81	0.74	0.65	0.58	0.91	0.82	0.74	0.65	0.58	0.91	0.82	0.75	0.65	0.58
	5	0.82	0.77	0.70	0.61	0.55	0.86	0.77	0.70	0.61	0.55	0.87	0.78	0.71	0.62	0.55	0.87	0.79	0.71	0.62	0.55
	6	0.81	0.74	0.68	0.59	0.53	0.83	0.75	0.68	0.60	0.53	0.85	0.76	0.69	0.60	0.53	0.85	0.76	0.69	0.60	0.53
	8	0.78	0.71	0.65	0.57	0.51	0.80	0.72	0.65	0.57	0.51	0.81	0.73	0.66	0.57	0.51	0.82	0.73	0.66	0.57	0.51
	10	0.77	0.69	0.63	0.55	0.49	0.78	0.70	0.63	0.55	0.49	0.79	0.70	0.64	0.55	0.49	0.79	0.71	0.64	0.55	0.49

The conversion factor f_2 must be applied only together with conversion factor f_1.

Table 13-59



Conversion factor f_2, cables laid in ground
Three-core cables in three-phase systems (as per DIN VDE 0276-1000)

1	2	3					4					5					6				
Type	Number of systems	Specific thermal resistance of soil in K · m/W																			
		0.7					1.0					1.5					2.5				
		load factor					load factor					load factor					load factor				
XLPE cables[1)]		0.5	0.6	0.7	0.85	1.00	0.5	0.6	0.7	0.85	1.00	0.5	0.6	0.7	0.85	1.00	0.5	0.6	0.7	0.85	1.00
0.6/1 kV																					
6/10 kV	1	1.02	1.03	0.99	0.94	0.89	1.06	1.05	1.00	0.94	0.89	1.09	1.06	1.01	0.94	0.89	1.11	1.07	1.02	0.95	0.89
PVC cables[1)]	2	0.95	0.89	0.84	0.77	0.72	0.98	0.91	0.85	0.78	0.72	0.99	0.92	0.86	0.78	0.72	1.01	0.94	0.87	0.79	0.72
0.6/1 kV with	3	0.86	0.80	0.74	0.68	0.62	0.89	0.81	0.75	0.68	0.62	0.90	0.83	0.77	0.69	0.62	0.92	0.84	0.77	0.69	0.62
$S_n \geq 35\ mm^2$	4	0.82	0.75	0.69	0.63	0.57	0.84	0.76	0.70	0.63	0.57	0.85	0.78	0.71	0.63	0.57	0.86	0.78	0.72	0.64	0.57
	5	0.78	0.71	0.65	0.59	0.53	0.80	0.72	0.66	0.59	0.53	0.81	0.73	0.67	0.59	0.53	0.82	0.74	0.67	0.60	0.53
	6	0.75	0.68	0.63	0.56	0.51	0.77	0.69	0.63	0.56	0.51	0.78	0.70	0.64	0.57	0.51	0.79	0.71	0.65	0.57	0.51
	8	0.71	0.64	0.59	0.52	0.47	0.72	0.65	0.59	0.52	0.47	0.73	0.66	0.60	0.52	0.47	0.74	0.66	0.60	0.53	0.47
	10	0.68	0.61	0.56	0.49	0.44	0.69	0.62	0.56	0.50	0.44	0.70	0.63	0.57	0.50	0.44	0.71	0.63	0.57	0.50	0.44
		load factor					load factor					load factor					load factor				
PVC cables[1)]		0.5	0.6	0.7	0.85	1.00	0.5	0.6	0.7	0.85	1.00	0.5	0.6	0.7	0.85	1.00	0.5	0.6	0.7	0.85	1.00
0.6/1 kV with																					
$S_n < 35\ mm^2$	1	0.91	0.92	0.94	0.94	0.89	0.98	0.99	1.00	0.94	0.89	1.04	1.03	1.01	0.94	0.89	1.13	1.07	1.02	0.95	0.89
3.6/6 kV	2	0.86	0.87	0.85	0.77	0.72	0.91	0.90	0.86	0.78	0.72	0.97	0.93	0.87	0.78	0.72	1.01	0.94	0.88	0.79	0.72
	3	0.82	0.80	0.75	0.68	0.62	0.86	0.82	0.76	0.68	0.62	0.91	0.84	0.77	0.69	0.62	0.92	0.84	0.78	0.69	0.62
	4	0.80	0.76	0.70	0.63	0.57	0.84	0.77	0.71	0.63	0.57	0.86	0.78	0.72	0.63	0.57	0.87	0.79	0.73	0.64	0.57
	5	0.78	0.72	0.66	0.59	0.53	0.81	0.73	0.67	0.59	0.53	0.81	0.74	0.68	0.59	0.53	0.82	0.75	0.68	0.60	0.53
	6	0.76	0.69	0.64	0.56	0.51	0.77	0.70	0.64	0.56	0.51	0.78	0.71	0.65	0.57	0.51	0.79	0.72	0.65	0.57	0.51
	8	0.72	0.65	0.59	0.52	0.47	0.73	0.66	0.60	0.52	0.47	0.74	0.67	0.61	0.52	0.47	0.75	0.67	0.61	0.53	0.47
	10	0.69	0.62	0.57	0.49	0.44	0.70	0.63	0.57	0.50	0.44	0.71	0.64	0.58	0.50	0.44	0.71	0.64	0.58	0.50	0.44

The conversion factor f_2 must be applied only together with conversion factor f_1.

(continued)

1) In direct-current systems, these factors are also valid for single-core cables for 0.6/1 kV.

Table 13-59 (continued)

1	*2*	*3*					*4*					*5*					*6*				
Type	Number of systems	Specific thermal resistance of soil in K · m/W																			
		0.7					1.0					1.5					2.5				
Mass-impregnated cables		load factor					load factor					load factor					load factor				
		0.5	0.6	0.7	0.85	1.00	0.5	0.6	0.7	0.85	1.00	0.5	0.6	0.7	0.85	1.00	0.5	0.6	0.7	0.85	1.00
Belted cables	1	0.94	0.95	0.97	0.94	0.89	1.00	1.00	1.00	0.94	0.89	1.06	1.05	1.01	0.94	0.89	1.13	1.07	1.02	0.95	0.89
0.6/1 kV 3.6/6 kv	2	0.89	0.89	0.85	0.77	0.72	0.94	0.92	0.86	0.78	0.72	0.99	0.93	0.87	0.78	0.72	1.01	0.94	0.88	0.79	0.72
Single lead	3	0.84	0.81	0.76	0.68	0.62	0.89	0.83	0.77	0.68	0.62	0.91	0.84	0.78	0.69	0.62	0.92	0.85	0.79	0.69	0.62
sheathed (SL)	4	0.82	0.77	0.71	0.63	0.57	0.85	0.78	0.72	0.63	0.57	0.86	0.79	0.73	0.63	0.57	0.87	0.80	0.73	0.64	0.57
cables 3.6/6 kV	5	0.80	0.73	0.67	0.59	0.53	0.81	0.74	0.68	0.59	0.53	0.82	0.75	0.69	0.59	0.53	0.83	0.76	0.69	0.60	0.53
6/10 kV	6	0.77	0.70	0.65	0.56	0.51	0.79	0.71	0.65	0.56	0.51	0.79	0.72	0.66	0.57	0.51	0.80	0.73	0.66	0.57	0.51
	8	0.73	0.66	0.61	0.52	0.47	0.74	0.67	0.61	0.52	0.47	0.75	0.68	0.62	0.52	0.47	0.75	0.68	0.62	0.53	0.47
	10	0.70	0.63	0.58	0.49	0.44	0.71	0.64	0.58	0.50	0.44	0.72	0.65	0.59	0.50	0.44	0.72	0.65	0.59	0.50	0.44
PVC cables 6/10 kV		load factor					load factor					load factor					load factor				
		0.5	0.6	0.7	0.85	1.00	0.5	0.6	0.7	0.85	1.00	0.5	0.6	0.7	0.85	1.00	0.5	0.6	0.7	0.85	1.00
Mass-impregnated cables	1	0.90	0.91	0.93	0.96	0.91	0.98	0.99	1.00	0.96	0.91	1.05	1.04	1.03	0.97	0.91	1.14	1.09	1.04	0.97	0.91
Belted cables 6/10 kV	2	0.85	0.85	0.85	0.81	0.76	0.93	0.92	0.89	0.82	0.76	0.98	0.95	0.90	0.82	0.76	1.03	0.96	0.90	0.82	0.76
H cables	3	0.80	0.79	0.78	0.72	0.66	0.87	0.86	0.80	0.72	0.66	0.93	0.86	0.80	0. 73	0.66	0.95	0.87	0.81	0.73	0.66
6/10 kV 12/20 kV	4	0.77	0.77	0.74	0.67	0.61	0.85	0.81	0.75	0.67	0.61	0.89	0.82	0.75	0.68	0.61	0.90	0.82	0.76	0.68	0.61
18/30 kV	5	0.75	0.75	0.70	0.63	0.57	0.84	0.77	0.71	0.63	0.57	0.85	0.77	0.71	0.63	0.57	0.86	0.78	0.72	0.64	0.57
Single lead	6	0.74	0.73	0.67	0.60	0.55	0.81	0.74	0.68	0.60	0.55	0.82	0.74	0.68	0.61	0.55	0.83	0.75	0.69	0.61	0.55
sheathead (SL) cables	8	0.73	0.69	0.63	0.56	0.51	0.77	0.70	0.64	0.56	0.51	0.77	0.70	0.64	0.57	0.51	0.78	0.71	0.64	0.57	0.51
12/20 kV 18/30 kV	10	0.71	0.66	0.60	0.53	0.48	0.74	0.67	0.61	0.54	0.48	0.74	0.67	0.61	0.54	0.48	0.75	0.67	0.61	0.54	0.48

The conversion factor f_2 must be applied only together with conversion factor f_1.

13.2.3 Selection and protection

Protection against overload (DIN VDE 0100-430)

If overloading of the circuits, e.g. socket outlets, motors, is anticipated, the overload protection system must meet the following conditions:

$I_b \leq I_n \leq I_z$ (1)
$I_2 \leq 1.45 \cdot I_z$ (2)

Here:

I_b Prospective operating current of circuit

I_z Current rating of wire or cable

I_n Rated current of protection system
Note, with adjustable protective devices I_n is the set value

I_2 The current that trips the protection system under the conditions specified for the device (conventional tripping current I_2)

(This trip value is also designated by other symbols in some equipment regulations.)

The rated current I_n may equal the current-carrying capacity I_z when overload protection equipment is used, to which $I_2 \leq 1.45\ I_n$ applies. This property is included in miniature circuit-breakers (IEC 60898-1), circuit-breakers (IEC 60947-2 (DIN VDE 0636-201).

The current-carrying capacity of cables depending on the varying laying and operating conditions can be found in the tables in Section 13.2.2. For fixed installation of plastic-insulated cables and lines in buildings, Table 13-60 gives the permissible current-carrying capacity and also the rated current magnitudes of the protection devices suitable for overload protection.

Protection in the event of short circuit (DIN VDE 0100-430 and Supplement 5 to DIN VDE 0100)

The same types of protection devices as for overload protection come under consideration for protection of cables in the event of short circuit.

To protect in case of short circuit, the breaking capacity of the protection device must be at least equal to the greatest current in the event of a galvanic short circuit at the installation site. However, a lower breaking capacity is permissible if the device is backed up by another which has the necessary capacity. In this case, the characteristics of the two devices must be coordinated so that the downstream device and the protected cable cannot be damaged (energy throughput, weld resistance, dynamic strength of current paths).

The prerequisite for effective protection in the event of a short circuit is that the fault current reaches the trip value of the short-circuit protection device. This means that the resistance of the cable, i.e. its length, must not exceed a specified limit value. The upstream loop impedance between the power source and the protection device must be taken into account here.

The tables 13-61 and 13-62 can be used to determine the maximum lengths of PVC-insulated conductors ensuring the permitted break times t in the event of short circuits, for a variety of protective devices required only to respond to short circuits.

Examples of the permissible maximum lengths for short-circuit protection with fuses are given in Tables 13-61 and 13-62. There are additional tables on this subject in Supplement 5 to DIN VDE 0100.

The permissible break time t for short circuits lasting up to 5 s can be approximately determined with the following equation.

$$t = \left(\frac{k \cdot S}{I}\right)^2$$

- t permissible break time after fault in s
- S conductor cross-section in mm^2
- I current on dead short-circuit in A
- k constant, with values (see Tables 5-3 and 5-4) of 115 for PVC-insulated copper conductor, 76 for PVC-insulated aluminium conductor, 141 for rubber-insulated copper conductor, 87 for rubber-insulated aluminium conductor, 115 for soft solder joints in copper conductor.

If the permissible break times are very short (< 0.1 s), the product $k^2 \cdot S^2$ obtained from the equation must be greater than the value $I^2 \cdot t$ stated by the manufacturer of the current-limiting device.

These protection devices, depending on the performance data, can provide both overload and short-circuit protection. However, there are devices such as contactors with overcurrent tripping or backup fuses that are not suitable for both functions.

Protection with direct contact

The same conditions as with protection of cables and lines against overload by short circuit currents also apply for protection with indirect contact (see also Section 5.1.2). The protection device must disconnect the protected component of an installation from the system within the period defined in the standard (0.1 s, 0.2 s, 0.4 s or 5 s) to prevent excessively high touch voltages from occurring. If in the event of a double fault the IT-System network is tripped by a protection device with time/current characteristic, a minimum fault current must also be ensured in this case. This requires a maximum length for the cables and lines in question.

Voltage drop (DIN VDE 0100-520 (VDE 0100 Part 520))

A constant service voltage is essential for proper functioning of much equipment. For this reason, cables and lines must be rated to ensure that the permissible voltage drop is not exceeded (see also Section 2.4 and 6.1.6). This case also requires maximum values for the lengths of cables and lines, based on the expected load current.

Note

There may be different maximum values for cable and line lengths when selecting the protection devices for the three different cases. In general, the limit value must be calculated separately for all three criteria and the lowest value of the current circuit must be taken (Supplement 5 to DIN VDE 0100).

Table 13-60 Current-carrying capacity I_z in A of cables and lines for permanent installation in buildings (DIN VDE 0298-4) Assignment of rated currents of overload protection devices I_n in A, whose tripping current I_2 must be $I_2 \leq 1.45\ I_n$.

Method of laying	A1		A2		B1		B2		C	
	Laying in insulated walls				Laying in conduits				Laying on a Wall	
	Single-core non-sheathed cables in electricial ducts or conduits in a thermally insulated wall		Multicore or multicore sheathed interior lines in electrical ducts or conduits in a thermally insulated wall		Single-core non-sheathed in electricial ducts or conduits on a wall		Multicore or multicore sheathed interior lines in electrical ducts or conduits on a wall		Single-core or multicore cables or single-core or multicore sheathed interior lines	
Number of loaded conductors	2	3	2	3	2	3	2	3	2	3
Nominal cross-section, mm²	Current carrying capacity A									
Copper 1.5	15.5	13.5	15.5	13.0	17.5	15.5	16.5	15.0	19.5	17.5
2.5	19.5	18.0	18.5	17.5	24	21	23	20	27	24
4	26	24	25	23	32	28	30	27	36	32
6	34	31	32	29	41	36	38	34	46	41
10	46	42	43	39	57	50	52	46	63	57
16	61	56	57	52	76	68	69	62	85	76
25	80	73	75	68	101	89	90	80	112	96
35	99	89	92	83	125	110	111	99	138	119
50	119	108	110	99	151	134	133	118	168	144
70	151	138	139	125	192	171	168	149	213	184
95	182	164	167	150	232	207	201	179	258	223
120	210	188	192	172	269	239	232	206	299	259

Method of laying	D[2]		E		F			G	
	Laying in the ground		Laying exposed in air						
	Multicore cables in electrical ducts or conduits or cable vaults in the ground		Multicore cables at a distance of a least 0.3 x diameter *D* from the wall		Single-core cables at a distance of at least 1 x diameter *D* from the wall				
					with contact			at distance *D*	
Number of loaded conductors	2	3	2	3	2		3		
Nominal cross section, mm²	Current carrying capacity A								
Copper 1.5	18.5	15.5	22	18.5	–	–	–	–	–
2.5	25	21	30	25	–	–	–	–	–
4	32	27	40	34	–	–	–	–	–
6	40	34	51	43	–	–	–	–	–
10	54	45	70	60	–	–	–	–	–
16	69	59	94	80	–	–	–	–	–
25	88	76	119	101	131	114	110	146	130
35	106	91	148	126	162	145	137	181	162
50	126	108	180	153	196	174	167	219	197
70	156	133	232	196	251	225	216	281	254
95	184	161	282	238	304	275	264	341	311
120	209	183	328	276	352	321	308	396	362

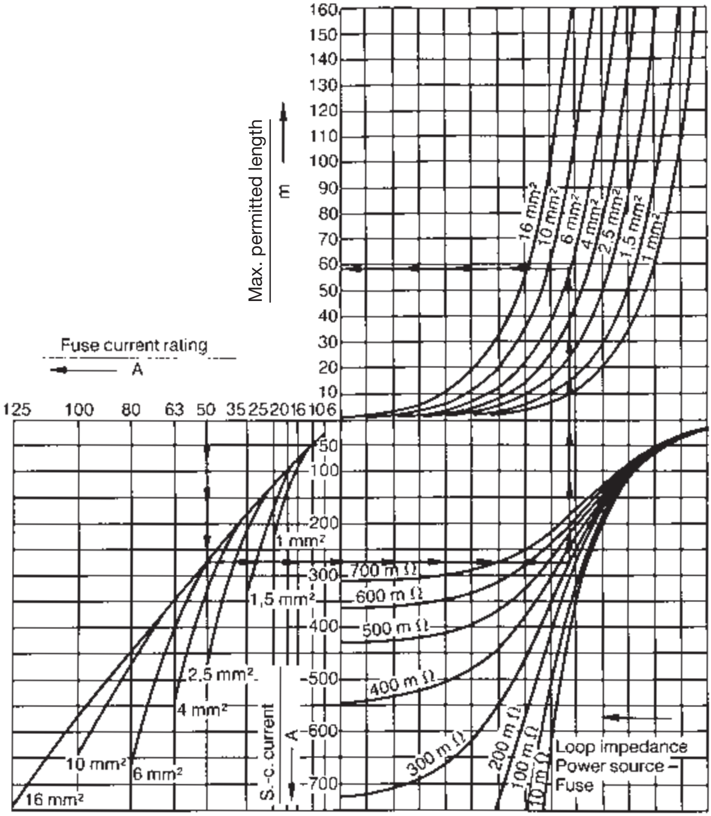
1) See Table 13-65.

2) Miniature circuit-breakers and fuses are not available in all cases with the rated currents given here. If necessary, the next lowest standard quantity must be used.

Fig. 13-9 (DIN 57100-430 from 1981-06)
Nomogram for determining max. permissible wire or cable lengths with single-phase short circuits in 380/220 V networks for fuses to DIN VDE 0636 responding only to short-circuit currents, and PVC-insulated wires up to 16 mm² Cu (to DIN VDE 100-430).

Example:

Fuse current rating	50 A
Wire cross-section	6 mm²
Loop impedance	300 mΩ
Max. permitted length	58 m



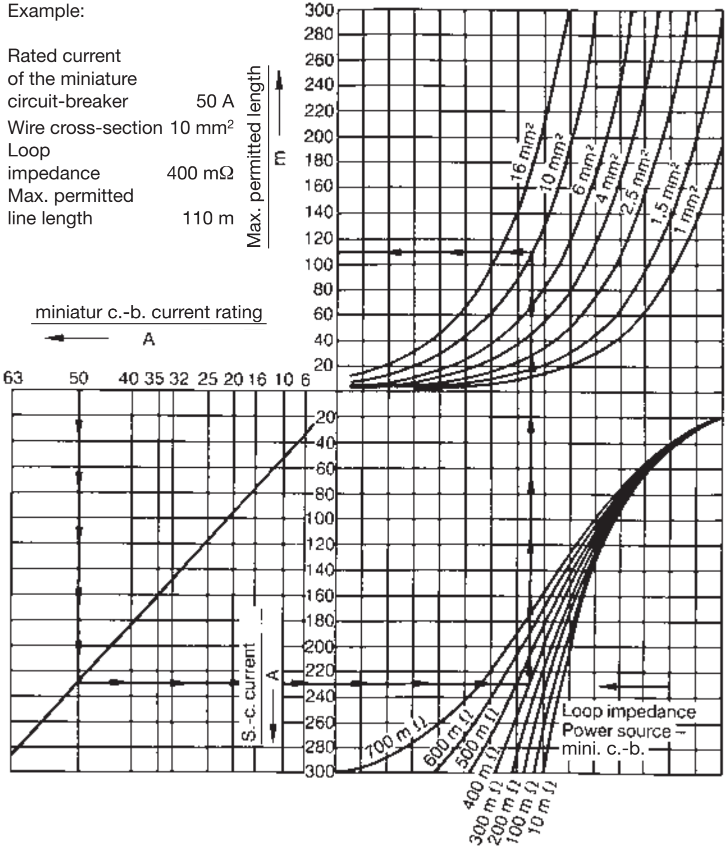
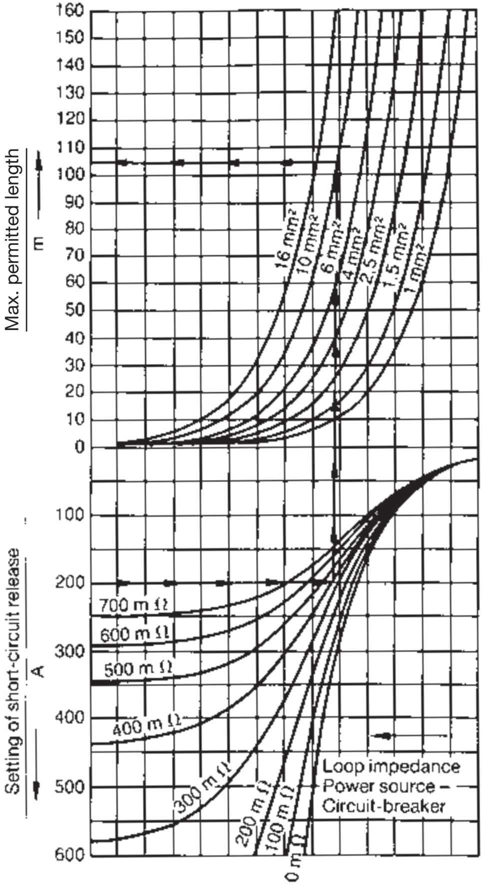


Fig. 13-10a (DIN 57100-430 from 1981-06)

Nomogram for determining max. permissible wire or cable lengths with single-phase short circuits in 380/220 V networks for miniatur circuit-breaker to DIN VDE 0641 responding only to short circuits, and PVC-insulated wires up to 16 mm² Cu (to DIN VDE0100-430).



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Example:	
Setting of short-circuit release	200 A
Wire cross-section	10 mm^2
Loop impedance	400 mΩ
Max. permitted line length	105 m
(to DIN VDE 0100-430)	

Fig. 13- 10b (DIN 57100-430 from 1981-06)

Nomogram for determining max. permissible wire or cable lengths with single-phase short circuits in 380/220 V networks for circuit-breakers to IEC 60947-1 responding only to short circuits, and PVC-insulated wires up to 16 mm^2 Cu.

Table 13-61

Maximum permissible cable and line lengths
Copper conductor, insulation PVC or rubber (as in Supplement 5 to VDE 0100)
Fuse, duty class gG as per IEC 60 269-1
Nominal voltage of the installation: 400 Volt, 50 Hz
Tripping after 5 s or after the permissible short-circuit temperature is reached

Conductor nominal cross-section	Rated current of protection device	Minimum short-circuit current	Loop impedance before the protection device mΩ								
			10	50	100	200	300	400	500	600	700
			Maximum permissible length l_{max}								
mm²	A	A	m	m	m	m	m	m	m	m	m
1.5	6	27	270	269	267	264	261	258	255	252	249
	10	47	155	154	152	149	146	143	140	137	134
	16	65	112	111	109	106	103	100	97	94	91
	20	126	58	57	55	52	49	46	43	40	36
	25	135	54	53	51	48	45	42	39	36	32
2.5	10	47	253	251	249	244	239	234	229	224	219
	16	65	183	181	178	173	169	164	159	154	148
	20	85	139	138	135	130	125	120	115	110	105
	25	110	108	106	103	98	93	88	93	78	73
	32	165	72	70	67	63	57	52	47	42	36
4	16	65	297	294	290	282	274	266	258	250	241
	20	85	227	224	220	212	204	196	187	179	171
	25	110	175	172	168	160	152	144	135	127	118
	32	150	128	125	121	113	105	96	88	79	71
	40	190	101	98	94	86	77	69	60	51	42
	50	280	68	65	61	53	45	36	27	18	8
6	20	85	342	337	331	319	307	294	282	270	257
	25	110	264	259	253	241	229	216	204	191	178
	32	150	193	188	182	170	158	145	132	119	106
	40	190	152	147	141	129	116	104	91	77	64
	50	260	111	106	100	87	75	62	48	35	20
	63	330	87	82	76	64	57	38	24	10	0
10	25	110	441	433	423	403	382	361	340	319	298
	32	150	323	315	305	284	264	242	221	199	178
	40	190	255	246	236	216	195	173	152	130	107
	50	260	185	177	167	146	125	103	81	58	34
	63	320	150	142	132	111	89	67	44	20	0
	80	440	108	100	90	69	46	23	0	0	0
16	32	150	512	499	483	450	417	384	350	315	280
	40	190	404	391	374	341	308	274	240	205	169
	50	260	294	281	265	231	198	163	127	91	54
	63	320	238	225	209	175	141	106	69	32	0
	80	440	172	159	143	109	73	37	0	0	0
	100	580	130	117	100	65	29	0	0	0	0

Table 13-62

Maximum permissible cable and line lengths
Copper conductor, insulation PVC, XLPE or EPR (as in Supplement 5 to VDE 0100)
Fuse, duty class gG as per IEC 60 269-1
Nominal voltage of the installation: 400 Volt, 50 Hz
Tripping after 5 s or after the permissible short-circuit temperature is reached

Conductor nominal cross-section	Rated current of protection device	Minimum short-circuit current	Loop impedance before the protection device in mΩ				
			10	50	100	200	300
			Maximum permissible length l_{max}				
mm²	A	A	m	m	m	m	m
25	63	320	374	354	328	275	221
	80	440	271	250	224	170	115
	100	580	204	183	157	102	46
	125	750	157	136	109	54	0
	160	930	125	104	77	21	0
35	80	440	372	343	307	233	157
	100	580	280	251	215	140	52
	125	750	215	186	149	73	0
	160	930	172	143	106	28	0
	200	1350	116	87	49	0	0
	250	1600	97	67	29	0	0
50	100	580	376	337	288	187	83
	125	750	289	249	200	97	0
	160	930	231	191	141	38	0
	200	1350	156	116	65	0	0
	250	1600	130	90	39	0	0
70	125	750	408	352	281	136	0
	160	930	326	270	199	53	0
	200	1350	220	164	92	0	0
	250	1600	184	127	54	0	0
	315	2200	130	73	0	0	0
95	160	930	438	361	265	70	0
	200	1350	296	219	122	0	0
	250	1600	246	169	72	0	0
	315	2200	174	97	0	0	0
	400	2750	135	58	0	0	0
120	200	1350	362	267	148	0	0
	250	1600	302	207	88	0	0
	315	2200	213	118	0	0	0
	400	2750	165	70	0	0	0
150	200	1350	426	314	174	0	0
	250	1600	355	243	103	0	0
	315	2200	250	139	0	0	0
	400	2750	195	83	0	0	0
	500	3900	129	17	0	0	0

13.2.4 Installation of cables and wires

When installing cables and wires, one must make sure that throughout their anticipated useful life their performance and reliability are not diminished by such factors as:

– Grouping, external heat sources (which reduce current-carrying capacity)
– Mechanical, thermal and chemical action
– Nature of soil (laying in sand or stone-free ground)
– Earth movement, vibration, tremors
– Dynamic stressing due to fault currents
– Leakage currents and corrosion

When pulling cables, the maximum tensile forces in Table 13-63 (always referred to the conductor's total nominal cross-section area; shielding or concentric conductors are disregarded) must not be exceeded. The same maximum tensile forces are applicable when pulling three single-core cables simultaneously with a single cable grip. In the case of three factory-stranded single-core cables, the forces are valid for three cables, but for only two cables in the case of three non-stranded single-core cables. The bending radii to be observed are shown in Table 13-64.

Single-core cables in trefoil formation can be fixed in the same way as multi-core cables, when run through conduits of steel they must be contained in the same tube. With single-core cables or wires in AC or three-phase systems, clips of plastic or non-magnetic metal must be used so that the fixing system does not create a closed conductive loop.

Commonly used methods of laying wires are described in DIN VDE 0298-4, see Table 13-65.

Cables and wires must be arranged or marked so as to be clearly identifiable at any later date.

While pulling cables insulated or sheathed with PVC, the cable temperature must not drop below a limit of – 5 °C; whereas for XLPE cables (with PE sheath) a limit of – 20 °C is allowed. The lowest admissible cable temperature when pulling paper insulated mass cables is + 5 °C.

If outside temperatures are lower, it is advisable to store the cables in a heated area (e. g. 24 h at 20 °C) or warm them as necessary before laying.

The coding of insulated and bare conductors according to IEC 60446 is shown in Table 13-66.

For further guidelines on the laying of cables and wires, see Sections 6.1.7 and 15.4.2, also DIN VDE 0298-1 and 0298-3.

Table 13-63

Calculation of max. permitted pulling forces

1 Pulling method	2 Cable type	3 Formula	4 Factor
With pulling eye on conductors	All cable types	$P = \sigma \cdot A$	$\sigma = 50\ N/mm^2$ (Cu conductor) $\sigma = 30\ N/mm^2$ (Al conductor)
With cable grip	Plastic-insulated cable, without metal sheath and without armouring (e. g. NYY, NYSY, NYSEY, N2XSY, etc.)	$P = \sigma \cdot A$	$\sigma = 50\ N/mm^2$ (Cu conductor) $\sigma = 30\ N/mm^2$ (Al conductor)
	All wire-armoured cables (e. g. NYFGY, NAYFGY etc.)	$P = K \cdot d^2$	$K = 9\ N/mm^2$
	Cable without armour for tensile stresses:		
	Single-core cables (e. g. NKBA, NYKY, NKLEY etc.)	$P = K \cdot d^2$	$K = 3\ N/mm^2$
	Three-core SL cables (e. g. NEKEBA, NAEKEBA etc.)	$P = K \cdot d^2$	$K = 1\ N/mm^2$

A = conductor cross section (mm^2)
d = cable diameter (mm)

Table 13-64

Minimum bending radii

Cable	Paper-insulated cable		Plastic-insulated cable	
	With lead sheath	With smooth Al sheath	$U_0 = 0.6$ kV	$U_0 > 0.6$ kV
Single-core	25 × *d*	30 × *d*	15 × *d*	15 × *d*[1)]
Multicore	15 × *d*	25 × *d*	12 × *d*	15 × *d*
Many-core			12 × d	

d = Cable diameter (mm)

1) For stranded cables: diameter over laid-up conductor

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Table 13-65

Methods of cable laying to DIN VDE 0298 Part 4

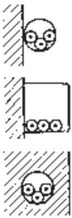
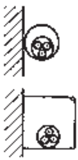
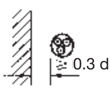
A		Laying in insulated walls (including floor) – single-core non-sheathed cables in electrical ducts or conduits (including closed floor ducts) – multicore lines and single-core sheathed wires in electrical ducts or conduits – multicore lines and single-core sheathed wires in walls
B 1		Laying on walls or under plaster – single-core non-sheathed cables in electrical ducts or conduits on the wall (including ventilated floor ducts) – single-core non-sheathed cables, single-core sheathed cables, multicore lines in electrical conduits in walls (including ceiling)
B 2		Laying on walls – multicore non-sheathed cables in electrical ducts or conduits on the wall or floor
C		Direct laying – multicore lines and single-core sheathed cables on the wall or on the floor (including open or ventilated ducts) – multicore lines in walls (including ceilings)
E		Laying exposed in air, i.e. thermal dissipation is ensured without hindrance – where the lines are installed > 0.3 d from the wall (d = external diameter of the line) – with lines installed side by side spaced at a minimum of twice the line diameter, – with lines installed above one another with a vertical spacing of a minimum of twice the line diameter

Table 13-66

Alphanumeric codes and symbols in relation to colour coding of insulated and bare conductors (to IEC 60446)

Conductor designation		Coding Alpha-numeric	Symbol	Colour
AC network	phase 1	L 1		[1]
	phase 2	L 2		[1]
	phase 3	L 3		[1]
	neutral	N		Light blue[4]
DC network	positive	L +	+	[1]
	negative	L –	–	[1]
	middle	M		Light blue[4]
Protective conductor		PE		Green/ yellow[3]
Neutral conductor with protective function		PEN		Green/ yellow[3]
Earth		E		[1] [2]

[1] Colour code not specified.
[2] Earth wires must be coded green/yellow if connecting protective conductor to earth.
[3] This colour code must not be used for any other conductor.
[4] If there is no neutral conductor, the light blue conductor in multi-core wires and cables may be used for other purposes apart from the protective conductor.

Table 13-67

Letter code for designation of some distinct colours (IEC 60757)

Colour	Lettercode
Black	BK
Brown	BN
Red	RD
Orange	OG
Yellow	YE
Green	GN
Blue (including light blue)	BU
Violet (purple)	VT
Grey (slate)	GY
White	WH
Pink	PK
Gold	GD
Turquoise	TQ
Silver	SR
Green-and-yellow	GNYE

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13.2.5 Cables for control, instrument transformers and auxiliary supply in high-voltage switchgear installations

Certain preferred types of cable are used for electrically connecting spatially separated system components. Their selection must take account of the following technical requirements:

- Number of cores according to function,
- Cross-section of cores according to required power rating, cable length and permitted voltage drop and also ambient circumstances,
- Earthing conditions,
- Protection against transient overvoltages,
- Protection against mechanical damage.

Preferred cable type[1)]	Transmission function
NYY	control, signalling, current and voltage transformers and auxiliary voltage supply. They are used where no special protection against mechanical damage is required. There is no option for reducing transient overvoltages. The yellow-green conductor must be earthed at both ends with the shortest possible connection.
YBY	control, signalling, current and voltage transformers and auxiliary voltage supply. They are used where enhanced protection against mechanical damage is required. This type of cable is preferred in switchgear installations manufactured for export. There are limited options for reducing transient overvoltages. The yellow-green conductor and also the galvanized steel cable sheath must be earthed at both ends with the shortest possible connection.
NYCY	control, signalling, current and voltage transformers and auxiliary voltage supply. There are limited options for reducing transient overvoltages. The concentric copper conductor must be earthed at both ends with the shortest possible connection.
YCY	control, signalling, current and voltage transformers and auxiliary voltage supply. Braided shield with 80% coverage. Preferred use where reducing transient overvoltages is essential, e.g. connections for electronic equipment. The concentric copper conductor must be earthed with the shortest possible connection (preferably through the glands). There is only limited mechanical protection.

1) to DIN VDE 0271

Table 13-67 a to d lists the preferred cables used in high-voltage switching installations, including core coding and the principal mechanical data. The cables marked with an asterisk (*) are usually not available ex-stock, but have technical and economic advantages in the switchgear field. Minimum production lengths and early ordering are points to remember with these cables.

For high and extra-high-voltage switching stations and also extensive systems, cross sections and voltage drops should be verified by calculation; this requirement applies particularly to current transformer circuits and control circuits, see Sections 2.4 and 6.1.6.

Table 13-68

Preferred control and auxiliary supply cables 0.6 / 1 kV for high-voltage switching stations

Core number and cross-section	Core coding NYY-J Number	Coloured*	Mech. data External diameter mm[1)]	Weight kg/km[1)]	Functions Control Inter-locking position indic. etc.	Current trans-former	Voltage trans-former	Infeed AC/DC (Power supply)
7 × 1,5	1-6	GNYE	15	360	●			
14 × 1,5	1-13	GNYE	20	620	●			
19 × 1,5	1-18	GNYE	22	760	●			
24 × 1,5	1-23	GNYE	24	950	●			
4 × 2,5		GNYE/BN/ BK/GY	14	320				●
5 × 4		GNYE/BU/ BN/BK/GY	18	550				●

1) Typical values

Core number and cross-section	Core coding NYYO Number	Coloured*	Mech. data NYY-O External diameter mm[1)]	Weight kg/km[1)]	Functions Control Inter-locking position indic. etc.	Current trans-former	Voltage trans-former	Infeed AC/DC (Power supply)
4 × 4		BU/BN/ BK/GY	17	480				DC
4 × 6		BU/BN/ BK/GY	18	590				DC
4 × 10		BU/BN/ BK/GY	20	790				DC
4 × 16		BU/BN/ BK/GY	22	1 110				DC
1 × 50		BK	16	630				Batterie
1 × 95		BK	19	1 150				Batterie
1 × 120		BK	21	1 350				Batterie

(continued)

Table 13-68 (continued)

Core number and cross-section	Core coding YBY NYCY Number	Coloured*	Mech. data YBY NYCY External diameter mm[1)]	Weight kg/km[1)]	Functions Control Inter-locking position indic. etc.	Current trans-former	Voltage trans-former	Infeed AC/DC (Power supply)
7 × 1,5/2,5	1-6		17	420	●			
14 × 1,5/2,5	1-13		21	660	●			
19 × 1,5/4	1-18		23	820	●			
24 × 1,5/6	1-23		26	1 100	●			
7 × 2,5/2,5	1-6		18	530			●	
4 × 4/4		BU/BN BK/GY	18	525		●		
7 × 4/4	1-7		20	730		●		
4 × 6/6		BU/BN BK/GY	19	650		●		
7 × 6/6	1-7		22	950			●	●

Core number and Cross-section	Core coding YBY-J/O Number	Coloured*	Mech. Data YBY-J/O External diameter mm[1)]	Weight kg/km[1)]	Functions Battery installation			
5 × 2,5		GNYE/BK BU/BN/GY	17	480			●	●
7 × 2,5	1-7		18	560	●		●	
14 × 2,5	1-14		22	800	●			
24 × 2,5	1-24		28	1 230	●			●
5 × 4		GNYE/BK BU/BN/GY	19	640		●	●	●
5 × 6		GNYE/BK BU/BN/GY	21	750		●	●	●
5 × 10		GNYE/BK BU/BN/GY	23	1 150		●	●	●
5 × 16		GNYE/BK BU/BN/GY	25	1 410		●	●	●

● Preferred variation

1) Typical values

* in general not available from stock

The listed cable types can also be replaced by a halogen-free design (Type NHX...) if required.

13.2.6 Telecommunications cables

With centralized network management, all the remotely controlled and monitored switching facilities produce measurements and signals which are converted by telecontrol systems and transmitted to the dispatching centre. As a rule, all the transmitted measurements are gathered centrally in a marshalling cubicle and sent via cable links to the telecontrol system. Multipair telecommunication cables of type J-Y(ST)Y 0.8 are preferred for this purpose

For technical data, types and dimensions of these cables see Tables 13-69 and 13-70.

These cables can be used for telecontrol, measurement and signalling, and also for telephony, but not for power transmission. In accordance with VDE 0800 Part 1, they can be used in dry and humid areas, and also outdoors if permanently installed.

They are protected against external electrical interference by a static shield of plastic-coated metal foil. Inside the cable there is also a bare solid copper screening wire in contact with the static shield throughout its length.

This wire has a diameter of 0.4 mm for up to 10 pairs, and 0.6 mm for more than 10 pairs.

The screening wire must be connected to earth at one end of the cable. The individual cores are colour-coded and laid up in pairs. The individual pairs/wires are identified by coding the cores from the outside inwards, see next page.

Coding of cores

2-pair cables are coded as follows:

1st pair (tracer pair)	Core a = red / Core b = black
2nd pair	Core a = white / Core b = yellow

and for all other cables

1st pair (tracer pair)	Core a = red / Core b = blue
2nd pair	Core a = white / Core b = yellow
3rd pair	Core a = white / Core b = green
4th pair	Core a = white / Core b = brown
5th pair	Core a = white / Core b = black

and this sequence then repeats.

Table 13-69

Telecommunications cables. Technical data

Conductor diameter				mm	0.6	0.8
Loop resistance	at 20 °C		max.	Ω/km	130	73.2
Insulation resistance			min.	MΩ · km	100	100
Effective capacitance	at 800 HZ		max.	nF/km	120[1]	120[1]
Line attenuation (planning guideline)	at 800 HZ			dB/km	1.74	1.13
Capacitive coupling	at 800 HZ	k_1	max.	pF/100 m	300[2]	
		$k_{9\ldots12}$	max.	pF/100 m	100[3]	
Test voltage	Wire/wire			U_{eff} V	800	
	Wire/shield			U_{eff} V	800	
Service voltage	(peak value)		max.	V	300	
Permitted temperature range	when laying			°C	– 5 to + 50	
	before and after laying			°C	– 30 to + 70	
Permitted bending radius				min.	7.5 × Cable diameter	

1) For cables with two pairs, the values can be 20 % higher
2) 20 % of the value – but at least 1 value – may be up to 500 pF
3) 10 % of the value – but at least 4 values (related) – may be up to 300 pF

Table 13-70

Telecommunications cables. Types J-Y(St)Y – Dimensions

Number of pairs	Wire dia. mm	Wall thickness of outer sheath mm	Outside dia. approx. mm	Weight approx. kg/km
2	2 x 0.6	1 0	5.0	37
4	2 x 0.6	1.0	6.4	53
6	2 x 0.6	1.0	7.4	74
10	2 x 0.6	1.0	8.6	102
16	2 x 0.6	1.2	10.6	158
20	2 x 0.6	1.2	10.9	176
24	2 x 0.6	1.2	11.7	205
30	2 x 0.6	1.2	13.2	260
40	2 x 0.6	1.2	14.7	330
50	2 x 0.6	1.4	16.1	400
60	2 x 0.6	1.4	17.4	470
80	2 x 0.6	1.6	20.4	668
100	2 x 0.6	1.6	22.2	805
2	2 x 0.8	1.0	6.4	58
4	2 x 0.8	1.0	8.7	91
6	2 x 0.8	1.2	10.4	134
10	2 x 0.8	1.2	12.8	198
16	2 x 0.8	1.2	15.1	294
20	2 x 0.8	1.2	16.5	349
24	2 x 0.8	1.4	18.2	424
30	2 x 0.8	1.4	20.0	512
40	2 x 0.8	1.4	22.5	657
50	2 x 0.8	1.6	25.3	826
60	2 x 0.8	1.6	27.3	968
80	2 x 0.8	1.8	31.3	1285
100	2 x 0.8	2.0	34.9	1597

13.2.7 Data of standard VDE, British and US cables

The outside diameters and weights of certain selected cables are given in Tables 13-71 to 13-74.

Tables 13-75 and 13-76 compare the principal cross-sections according to AWG, SWG and VDE standards. The conversion of circular mils and square inches into square millimetres is shown in Table 13-77.

Table 13-71

Outside diameters in mm and weights (typical) in kg/km of single-core cables, bracket data = shield cross-section in mm²

Core no. and cross-section mm²	NYY 0.6/1 kV mm kg/km	N2XSY 6/10 kV mm kg/km	NA2XSY 6/10 kV mm kg/km	N2XSY 12/20 kV mm kg/km	NA2XSY 12/20 kV mm kg/km	N2XSY 18/30 kV mm kg/km	NA2XSY 18/30 kV mm kg/km
1 × 25	13	—	—	—	—	—	—
	380	—	—	—	—	—	—
1 × 35 (16)	14	22	25	26	—	—	—
	470	790	690	930	—	—	—
1 × 50 (16)	15	23	26	27	30	32	36
	630	940	760	1 090	860	1 280	1 100
1 × 70 (16)	17	24	27	29	32	34	37
	840	1 160	870	1 350	950	1 590	1 250
1 × 95 (16)	19	26	29	30	33	36	39
	1 110	1 430	950	1 600	1 070	1 890	1 380
1 × 120 (16)	21	28	30	32	35	37	40
	1 350	1 670	1 050	1 870	1 180	2 150	1 510
1 × 150 (25)	23	29	32	33	37	39	42
	1 650	2050	1 230	2 250	1 380	2 570	1 770
1 × 185 (25)	24	31	34	35	38	41	44
	2 010	2 400	1 380	2 670	1 520	2 930	1 930
1 × 240 (25)	27	33	37	37	41	43	46
	2 570	2 950	1 520	3 200	1 740	3 550	2 270
1 × 300 (25)	30	36	39	40	43	46	49
	3 250	3 650	1 830	3 900	1 960	4 250	2 530
1 × 400 (35)	33	39	42	43	46	49	51
	4 030	4 550	2 240	4 800	2 390	5 200	2 950
1 × 500 (35)	37	42	45	47	49	52	55
	5 120	5 700	2 500	6 000	2 810	6 400	3 350

Table 13-72 Outside diameters in mm and weights (typical) in kg/km of three-core cables, bracket data = shield cross-section in mm²

Core no. and cross-section	NYY 0.6/1 kV Outside dia. kg/km	NYCY 0.6/1 kV Outside dia. kg/km	NYCWY 0.6/1 kV Outside dia. kg/km	NYFY 3.6/6 kV Outside dia. kg/km	NYSEY 6/10 kV Outside dia. kg/km
3 × 1.5 (1.5)	13	14	—	—	—
	240	270	—	—	—
3 × 2.5 (2.5)	14	15	—	—	—
	290	330	—	—	—
3 × 4 (4)	15	16	—	—	—
	390	435	—	—	—

Continued on next page

Table 13-72 (continued)

Outside diameters in mm and weights (typical) in kg/km of three-core cables, bracket data = shield cross-section in mm²

Core no. and cross-section mm²	NYY 0.6/1 kV mm kg/km	NYCY 0.6/1 kV mm kg/km	NYCWY 0.6/1 kV mm kg/km
3 × 6 (6)	17	18	—
	480	550	—
3 × 10	18	—	20
	650	—	770
3 × 16	21	—	22
	870	—	1 050
3 × 25 (16)	24	—	26
	1 320	—	1 510
3 × 35 (16)	25	—	27
	1 325	—	1 800
3 × 50 (16)	28	—	—
	1 780	—	—
3 × 50 (25)	31	—	32
	2 140	—	2 350
3 × 70 (16)	31	—	—
	2 480	—	—
3 × 70 (35)	34	—	35
	2 910	—	3 100
3 × 95 (16)	35	—	—
	3 320	—	—
3 × 95 (50)	38	—	39
	3 900	—	4 200
3 × 120 (16)	39	—	—
	4 070	_	—
3 × 120 (70)	42	—	43
	4 900	—	5 300
3 × 150 (25)	42	—	—
	4 950	—	—
3 × 150 (70)	46	—	47
	4 750	—	6 500
3 × 185 (95)	52	—	51
	7 350	—	7 710
3 × 240 (120)	57	—	55
	10 000	—	9 700

Table 13-73

Outside diameters in mm and weights (typical) in kg/km of 3$^1/_2$, 4- and 5-core cables, bracket data = shield cross-section in mm^2

Core no. and cross-section mm^2	NYY 0.6/1 kV mm kg/km
3 × 25 (16)	27 1 570
3 × 35 (16)	27 1 600
3 × 50 (25)	31 2 140
3 × 70 (35)	34 2 910
3 × 95 (50)	38 3 900
3 × 120 (70)	42 4 900
3 × 150 (70)	46 5 750
3 × 185 (95)	52 7 350
3 × 240 (120)	57 9 400
3 × 300 (150)	64 11 950

Core no. and cross-section mm^2	NYY 0.6/1 kV mm kg/km	NYCWY 0.6/1 kV mm kg/km	NYCY 0.6/1 kV mm kg/km
4 × 1.5	14 270	— —	15 310
4 × 2.5	15 330	— —	16 380
4 × 4	17 450	— —	18 530
4 × 6	18 570	— —	19 670
4 × 10 (10)	20 780	21 900	
4 × 16 (16)	22 1 070	24 1 250	
4 × 25 (16)	27 1 640	28 1 690	
4 × 35 (16)	28 1 800	30 2 200	
4 × 50 (25)	31 2 400	35 3 050	
4 × 70 (35)	35 3 300	39 4 050	
4 × 95 (50)	40 4 400	44 5 350	
4 × 120 (70)	44 5 400	48 6 850	
4 × 150 (70)	49 6 650	53 8 250	

Core no. and cross-section mm^2	NYY 0.6/1 kV mm kg/km
5 × 1.5	15 310
5 × 2.5	16 330
5 × 4	18 520
5 × 6	20 670
5 × 10	22 920
5 × 16	24 1 290
5 × 25	27 1 890

Table 13-74

Outside diameters in mm and weights (typical) in kg/km of multi-core cables

Core no.	NYY-J 0.6/1 kV 1.5 mm² mm kg/km	2.5 mm² mm kg/km	YBY-J 0.6/1 kV 2.5 mm² mm kg/km	NYCY 0.6/1 kV 1.5/1.5 mm² mm kg/km	2.5/2.5 mm² mm kg/km
5 ×	15	16	17	—	—
	310	390	480	—	—
7 ×	16	17	18	17	18
	370	470	560	420	520
10 ×	19	20	—	20	21
	510	650	—	560	720
12 ×	19	21	—	20	22
	550	720	—	610	790
14 ×	20	21	22	21	—
	610	640	800	660	—
16 ×	21	22	—	—	24
	670	860	—	—	960
19 ×	22	24	—	23	26
	750	990	—	820	1 120
21 ×	21	24	—	—	—
	670	920	—	—	—
24 ×	23	26	28	26	28
	750	1 030	1 230	1 040	1 370
30 ×	25	27	—	—	—
	890	1 230	—	—	—
40 ×	28	31	30	—	—
	1 150	1 590	1 440	—	—

Table 13-75

Cross-sections of electrical conductors.
Comparison between AWG and VDE standards

VDE	American Wire Gauge (AWG)						
			Cross-sections			Diameter[1)]	
mm²	AWG		mm²	sq. in.	cir. mils	mm	inches
150	000 000	= 6/0	170.50	0.2641	336 400	14.73	0.5800
120	00 000	= 5/0	135.35	0.2094	266 773	13.12	0.5165
95	0 000	= 4/0	107.21	0.1662	211 600	11.68	0.4600
—	000	= 3/0	85.01	0.1318	167 772	10.40	0.4096
70	00	= 2/0	67.43	0.1045	133 079	9.27	0.3648
50	0	= 1/0	53.52	0.0829	105 625	8.25	0.3249
—	1		42.41	0.0657	83 694	7.35	0.2893
35	2		33.62	0.0521	66 358	6.54	0.2576

Continued on next page

13

Table 13-75 (continued)

Cross-sections of electrical conductors.
Comparison between AWG and VDE standards

VDE		American Wire Gauge (AWG)				
			Cross-sections		Diameter[1)]	
mm²	AWG	mm²	sq. in.	cir. mils	mm	inches
25	3	26.66	0.0413	52 624	5.83	0.2294
—	4	21.15	0.0328	41 738	5.19	0.2043
16	5	16.77	0.0260	33 088	4.62	0.1819
—	6	13.30	0.0206	26 244	4.11	0.1620
10	7	10.55	0.0163	20 822	3.66	0.1443
—	8	8.37	0.0130	16 512	3.26	0.1285
6	9	6.63	0.0103	13 087	2.91	0.1144
—	10	5.26	0.0081	10 384	2.59	0.1019
4	11	4.17	0.0065	8 226	2.30	0.0907
—	12	3.31	0.0051	6 529	2.05	0.0808
2.5	13	2.63	0.0041	5 184	1.83	0.0720
—	14	2.08	0.0032	4 109	1.63	0.0641
1.5	15	1.65	0.0026	3 260	1.45	0.0571
—	16	1.31	0.0020	2 581	1.29	0.0508
1	17	1.04	0.0016	2 052	1.15	0.0452
0.75	18	0.82	0.0013	1 624	1.02	0.0403
—	19	0.65	0.0010	1 289	0.91	0.0359
0.50	20	0.52	0.0008	1 024	0.81	0.0320

1) Single solid conductor

Table 13-76

Cross-sections of electrical conductors.
Comparison between SWG and VDE standards

VDE		British Standard Wire Gauge (SWG)				
			Cross-sections		Diameter[1)]	
mm²	SWG	mm²	sq. in.	cir. mils	mm	inches
120	7/0	126.67	0.1963	250 000	12.70	0.500
95	6/0	109.09	0.1691	215 298	11.78	0.464
95	5/0	94.57	0.1465	186 634	10.97	0.432
—	4/0	81.07	0.1256	160 000	10.16	0.400
70	3/0	70.17	0.1087	138 480	9.45	0.372
—	2/0	61.36	0.0951	121 094	8.84	0.348
50	0	53.20	0.0824	104 990	8.23	0.324
—	1	45.60	0.0707	90 000	7.62	0.300
35	2	38.59	0.0598	76 157	7.01	0.276
—	3	32.18	0.0499	63 507	6.40	0.252
—	4	27.27	0.0423	53 817	5.89	0.232
25	5	22.78	0.0353	46 965	5.39	0.212
—	6	18.68	0.0290	36 865	4.88	0.192

1) Single solid conductor

Continued on next page

Table 13-76 (continued)

Cross-sections of electrical conductors.
Comparison between SWG and VDE standards

VDE	British Standard Wire Gauge (SWG)					
		Cross-sections			Diameter[1)]	
mm²	SWG	mm²	sq. in.	cir. mils	mm	inches
16	7	15.69	0.0243	30 964	4.47	0.176
16	8	12.97	0.0201	25 596	4.06	0.160
—	9	10.51	0.0162	20 742	3.66	0.144
10	10	8.30	0.0130	16 380	3.25	0.128
—	11	6.82	0.0110	13 459	2.95	0.116
6	12	5.48	0.0085	10 815	2.64	0.104
—	13	4.29	0.0065	8 466	2.34	0.092
4	14	3.24	0.0050	6 394	2.03	0.080
—	15	2.63	0.0041	5 190	1.83	0.072
2.5	16	2.08	0.0038	4 105	1.63	0.064
—	17	1.59	0.0025	3 138	1.42	0.056
1.5	18	1.17	0.0018	2 309	1.22	0.048
1	19	0.81	0.0013	1 599	1.02	0.040
0.75	20	0.66	0.0010	1 303	0.91	0.036
—	21	0.52	0.0008	1 026	0.81	0.032

[1)] Single solid conductor

Table 13-77

Conversion of circular mils into square millimetres and square inches

MCM	sq. in.	mm²	MCM	sq. in.	mm²
50	0.0393	25.3	550	0.4320	279.8
100	0.0785	50.7	600	0.4712	304.0
150	0.1178	76.0	650	0.5105	329.4
200	0.1571	101.3	700	0.5498	354.7
250	0.1063	126.7	750	0.5890	380.0
300	0.2356	152.0	800	0.6283	406.3
350	0.2749	177.3	850	0.6676	430.7
400	0.3142	202.7	900	0.7069	456.0
450	0.3534	228.0	950	0.7461	481.4
500	0.3927	253.4	1 000	0.7854	506.7

1 circular mil (MCM) is the cross-section area of a wire of 1 mil diameter.

Conversion formulae:			
	1 mil	$= 10^{-3}$ inch	= 0.0254 mm diameter
	1 CM	$= 10^{-3}$ MCM	$= 0.0005067$ mm²
	1 MCM	= 1000 CM	= 0.5067 mm²
	1 mm	= 39.4 mils	
	1 mm²	= 1973.5 Circ mils	
	1 inch	= 1000 mils	= 25.4 mm
	1 inch²	= 1273200 circ mils	= 645.16 mm²

13.2.8 Power cable accessories for medium voltage and high-voltage

Definitions, standards

Power cable accessories, are fittings for the termination or jointing of power cables, in either open or enclosed form. The design and construction of the cable accessories is determined by the service voltage, type of cable and place of installation. Further information is given in DIN VDE 0278, IEC 61238-1 and also in DIN VDE 0291-1 and 0291-2.

The following definitions are laid down in DIN VDE 0289-6.

Sealing end is a fitting designed to terminate and seal the end of a cable and to provide suitable means for connecting the cable conductor to an electrical machine, switchgear component or an overhead line. The sealing end commences where the cable construction is modified by the fitting of sealing end components. It ends at the point of connection to the apparatus or at any intermediate component connecting a number of sealing ends together.

Jointing box is a fitting designed to connect two or more cables together. Over the length of the joint the fitting fulfills all the functions of the original cable. The span of the joint starts and ends where the construction of the cable is modified or changed by the fitting of joint components. A distinction is made between straight-through, transition and branch jointing boxes.

Plug-in or screw-in cable termination is a fitting which provides a shielded and sealed connection between a cable and electrical equipment. This fitting consists of two components, a plug connection fitted to the cable end and a receptacle permanently attached to the equipment. Depending on the type of fitting, the connection of the conductors is made either by plugging or screwing the two components together. The insulating components are of matching conical form. The connection or disconnection of either type of termination may only be made when the cable is dead. The surfaces of the insulating cones form an interface within the dielectric material. Depending on

Fig. 13-11 shows an example of a shielded plug-in cable termination using the protruding cone system.

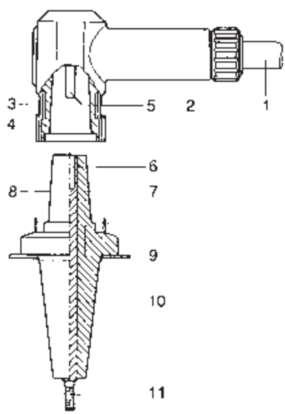


Fig. 13-11

Plug-in cable termination – components of a plug-in unit of the protruding cone type:

1 Cable, 2 Cable plug fitting, 3 Metallic enclosing, 4 Insulating cone, 5 Contact pin, 6 Contact socket (5 + 6 provide the connection between the conductors), 7 Insulating cone, 8 Protruding cone surface, 9 Apparatus enclosure, 10 Apparatus bushing, 11 Terminal bolt whether the fixed part has an external conical protrusion or an internal conical recess, the fitting is said to be of the *protruding or inside cone type*.

Required attributes of sealing ends and junction boxes:

– lasting and dependable connection of cable conductors one with another or with an item of electrical equipment.

  Methods of connection: crimping, clamping, bolting and plugging (multi-contacts)

– electrical field control within the fitting

  At voltages of 12 kV and above, cables are manufactured with a semiconductive layer (insulation screen) over the insulation. In order to achieve the additional insulation required within the fitting, this conducting layer must be cut back for a certain distance. The electrical field at this point must be controlled if inadmissibly high field strengths are to be avoided (Fig. 13-12). Three methods of field control are available.

  – geometric field control
  – resistive field control
  – refractive field control

  The most common method used is geometric field control (Fig. 13-13) which is also used in high-voltage equipment. A stress cone (deflector) fitted at the point of discontinuity enlarges the field cross-section, distorting the field and reducing the field stress within the fitting. In the case of resistive (ohmic) control, the exposed insulation within the fitting is covered for part of its length with a conducting material having a non-linear characteristic. The capacitive discharge currents flowing through the voltage-dependent resistance ensure an even distribution of voltage and field strength.

  Refractive field control is similar to the resistive method but the resistive layer is replaced by a layer of material having a higher dielectric constant than the cable insulation. The change in dielectric characteristic causes the field lines to be distorted (broken), providing control of the electrical field.

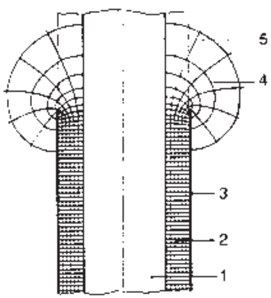


Fig. 13-12

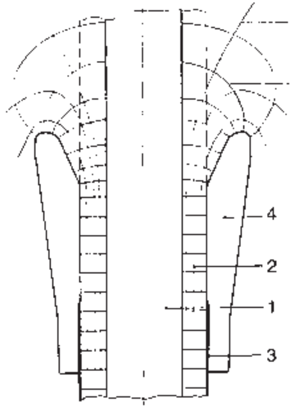
Distribution of electrical field (uncontrolled) at the end of the conducting sheath in the insulation of medium-voltage cables:

1 Conductor, 2 Insulation, 3 Insulation screen, 4 Field lines, 5 Lines of equipotential

Fig. 13-13

Geometric field control:

1 Conductor, 2 Insulation, 3 Outer conducting layer, 4 Stress cone (deflector), 5 Field lines, 6 Lines of equipotential



– establish an adequate level of insulation within the fitting

  The internal insulation must be such that even after thermal (load changes) and dynamic (short-circuit) cycling stresses it remains free of cavities and fully in contact with the cable insulation (free from corona discharges) and meets all test voltage requirements (DIN VDE 0278-629-1).

– maintain a reliable level of insulation external to the fitting

  The external insulation must be capable of withstanding all environmental influences (e.g. UV radiation, ozone, chemically aggressive pollutants) and, like the internal insulation, be resistant to aging. Resistance to tracking and creepage currents is of particular importance in sealing end design.

– resistance to mechanical stresses

  Cable fittings must be designed to accommodate all thermal (material expansion) and dynamic influences (movement due to short-circuit forces) which may arise, and remain fully functional. Where increased stresses due to short-circuits are expected, additional measures (e.g. phase supports, heavier clamps) must be taken to exclude or limit the influence on cables or equipment components.

– easy to install, maintenance-free

  To minimize installation time and reduce the risk of erection mistakes, the fittings are designed so that a considerable degree of pre-assembly can be performed in the factory and site work limited to a few non-critical operations. The materials used should reduce maintenance (e.g. cleaning and the consequent expensive down time) to a minimum, or eliminate it completely.

Additional requirements for transition joint boxes

– separation of insulating media

  Design measures must ensure that impregnating liquid from a paper-insulated cable cannot come in contact with plastic-insulated cable.

– regeneration of impregnated paper-insulated cables

  As the paper-insulated cable is thermally and mechanically stressed during the making of a joint, the fitting should provide a reservoir of impregnating oil to ensure that the cable can regenerate.

Additional requirements for enclosed cable terminations

– earthed external surfaces, touch-proof

– greater immunity to environmental influences, e.g. watertight

– simple, repetitive making and breaking of the connection.

Choice of material, design features and installation methods are examined on the basis of a number of fittings in common use.

Design and construction of medium-voltage accessories

For medium-voltage equipment, silicone rubber has become the most widely used material for sealing ends, cable joints and enclosed terminations. The techniques used are described on the basis of selected examples. Only with transition joints are designs still in use in which, as well as push-on techniques, a stress cone of impregnated crepe paper is manually manufactured on site, analogous to the dielectric of paper-insulated cables. Table 13-77 lists the most commonly used fittings for voltages from 12 to 36 kV, showing their general construction (outlines) and main dimensions.

Silicone rubber possesses a number of decisive advantages in comparison with other insulating materials available for push-on cable fittings. It is also being increasingly used in high-voltage equipment. The long-term flexibility and a low modulus of elasticity of the material mean that it can be readily assembled without the use of tools: it adapts readily and lastingly to the shape of the insulating material over which it is fitted (e.g. phase conductor insulation, epoxy components). Silicone rubber is water-repellent, and free of chemically active carbon. The result is sealing ends with external insulating surfaces which are essentially maintenance-free.

The *multirange indoor end seal designed for push-on installation* of silicone rubber is suitable for usage under severe indoor conditions because of its exterior shape (see Fig. 13-14).

The elasticity of silicone rubber allows up to five cable cross-sections to be covered with one size insulating body. To prevent moisture from entering the cable, after compressing the cable lug a sealing hose is slid over the cable end to the corresponding upper section of the insulating body. The electrical field at the edge of the outer field limit of the cable is controlled by a deflector embedded in the insulating body (field control funnel). How to fit the end seals to the cross-section area and insulation rating is stamped on the insulating body. The insulating body is slid onto the prepared cable end with the aid of a lubricant.

Special tools (sheath cutter and stripping tool) have been developed for preparing modern XLPE cables with polyethylene (PE) outer sheath and fix bonded insulation screen, reducing the task to a few simple, time-saving operations.

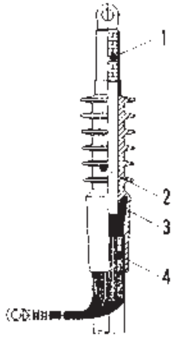


Fig. 13-14

24 kV push-on indoor-type cable sealing end of silicone rubber: 1 Crimped cable lug, 2 Insulator, 3 Deflector, 4 Wire screen

Multirange techniques are also in use with straight joints. Fig. 13-15a shows the design of a 24 kV joint of silicone rubber, which like the multirange end seals can also handle up to five conductor cross-sections with one joint size. In this case, the electrical field is controlled refractively with a continuous internal stress control layer followed by the insulation layers. At the end there is a conductive tube, which forms the outer screening of the joint with the woven copper band installed at the construction site. All three layers are extruded together in one process. A heat-shrink tube is used as external protection for the straight joint; as an alternative it can be protected by wrapping it with a special corrosion protection coating.
This multirange joint not only covers several cross-sections but it is also possible to use centric screwed connectors instead of compression connectors, so long as they are fitted with a snap-off head. These screwed connectors can also be used for several cross sections.

For connections between paper insulated mass-impregnated cables and XLPE cables, the previously customary "wet” jointing boxes are now increasingly being replaced by "dry” joints. The wet transition joints, either in classical design with oil-impregnated insulating paper or in the modern variant with a number of prefabricated insulating parts, have integrated impregnation material reservoirs and can help to overcome problems arising from ageing when joints are fitted to paper-insulated cables. The increasing pressure on costs of materials and assembly work and the fact that fewer and fewer technicians are familiar with the installation of paper-insulated cable fittings have led to this change in technology.

In the dry transition joint, the individual coupling consists in principle of a plastic cable joint, with which the mass-impregnated cable is, so to speak, made into a plastic-insulated cable by an oil-tight wrap of self-sealing silicone tape (figure 13-15b). As the protective joints formerly used in the laying of three core separately lead-sheathed cable have in most cases been replaced by shrink-on separators on the three core cables, there is no further need for the complex and potentially hazardous handling of hot insulating and filling compounds (figure 13-15c).

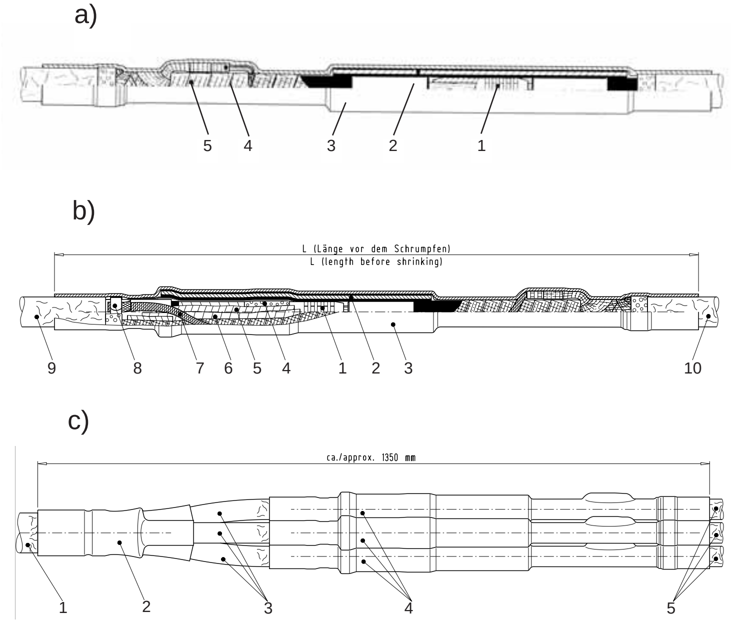


Fig. 13-15

a) 24 kV multirange straight joint type SEV 24 for connection of single core XLPE cables: 1 Connector, 2 Insulator, 3 Shrink tube, 4 Screen connection, 5 Woven copper strip
b) Transition joint type SEVü 24 for connection of single core XLPE cables to single core mass-impregnated cables
c) Transition joint type AM/SEVü 24 for connection of single core XLPE cables to three core separately lead-sheathed cables

Cables are connected to metal-enclosed switchgear and in some cases to the high voltage side of distribution transformers by means of enclosed cable termination systems. A distinction is made here between the inner cone and outer cone systems. The interface between the cable termination and the switchgear or transformer consists of a cone-shaped bushing which, in the inner cone system, projects into the installation, and in the outer cone system protrudes from it. In order to ensure compatibility, the contour dimensions of these bushings are specified in European standards EN 50180 and EN 50181.

In the inner cone system (figure 13-16a), the insulating part of silicone rubber is inserted into the bushing. The pressure required for dielectric strength at the face between the insulating part and the socket is maintained by a pressure spring, which also absorbs the increase in volume of the insulating part when the load changes. The inner cone system is notable for its compact design, even when transmitting currents up to 1250 A.

In the outer cone system, the insulating part is plugged onto the bushing. In this case, the insulating material's own elasticity provides for the necessary pressure at the joint face. The insulating part has a conductive coating on the surface which makes the sealing end shockproof. If metal shockproofing is required, the sealing end can also be fitted with a metal casing.

The SET 24 plug-in sealing end (figure 13-16b) is designed as a multirange device, i.e. one size can cover cross-sections of 95-240 mm^2, and with an appropriate field control adapter even 25 – 240 mm^2 at 24 kV (presupposing suitable cable lugs, e.g. screw-type cable lugs).

Tests for medium-voltage fittings

The requirements for fittings are specified in the regulations DIN VDE 0278-628 (test procedure), DIN VDE 0278-629-1 (testing requirements for cable fittings for extruded plastic-insulated cables) and DIN VDE 0278-629-2 (testing requirements for cable fittings for cables with impregnated paper insulation).

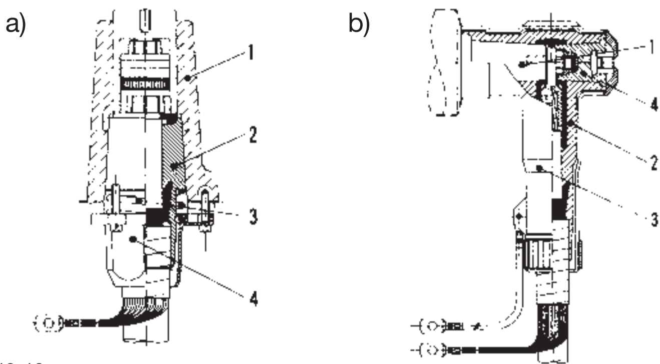


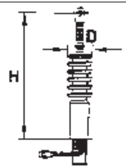
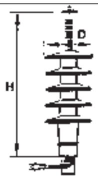
Fig. 13-16

a) Inside cone connector 24 kV made of silicone rubber type SEIK23: 1 Inside cone bushing, 2 Insulating body, 3 Compression spring, 4 Metal housing

b) Protruding cone T-shaped connector 24 kV type SEHDT23.1: 1 Protruding cone bushing, 2 Insulating body, 3 Metal housing, 4 Sealing piece

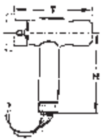
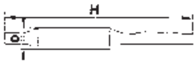
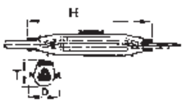
Table 13-78

Construction (outlines and main dimensions) of the most common fittings (sealing ends, through- and transition joints) for 12 – 36 kV cables

Cable cross-section	mm^2	35			150			240			500		
Main dimensions	mm	H	D	T	H	D	T	H	D	T	H	D	T
	Indoor sealing end for XLPE single-core cable												
	12 kV	270	35	—	295	54	—	310	54	—	330	46	—
	24 kV	270	50	—	295	54	—	310	54	—	340	69	—
	36 kV	320	77	—	350	77	—	360	83	—	385	105	—
	Outdoor sealing end for XLPE single-core cable												
	12 kV	330	120	—	350	92	—	365	92	—	350	120	—
	24 kV	290	105	—	315	110	—	330	110	—	350	120	—
	36 kV	425	133	—	455	138	—	465	144	—	485	151	—
	Plug-in elbow sealing end for XLPE single- core cable												
	12 kV	245	61	109	254	74	109	—	—	—	—	—	—
	24 kV	245	61	109	260	74	130	—	—	—	—	—	—

Continued on next page

Table 13-78 (continued)

Cable cross-section	mm²	35			150			240			500		
Main dimensions mm	mm	H	D	T	H	D	T	H	D	T	H	D	T
	Plug-in T-shaped sealing end for VPE single-core cable												
	12 kV	—	—	—	275	88	190	275	88	190	290	89	280
	24 kV	275	88	190	275	88	190	275	88	190	290	89	280
	36 kV	—	—	—	290	89	280	290	89	280	290	89	280
	Joint box for VPE single-core cable												
	12 kV	1000	—	—	1000	—	—	1000	—	—	—	—	—
	24 kV	1000	—	—	1000	—	—	1000	—	—	—	—	—
	36 kV	1000	—	—	1000	—	—	1200	—	—	—	—	—
	Transition joint for connecting VPE single-core cable with belted or H-type cable												
	12 kV	—	—	—	1000	—	—	1000	—	—	—	—	—
	Transition jointing box for connecting XVPE single-core cable to three-core shielded cable												
	24 kV	—	—	—	1350	—	—	1350	—	—	—	—	—

Structure and function of high voltage fittings

Several different types of fittings are available for high and extra-high voltage cables with XLPE insulation:

- Outdoor sealing ends for installation in outdoor switchgear installations or on overhead line masts at the transition from overhead lines to cables. The sealing ends are available alternatively with porcelain insulators or with composite insulators, i.e. glass fibre reinforced plastic tubes with sheds of silicone rubber fitted over them. A prefabricated and pre-testable field control unit in the form of a slide-on part, for instance of silicone rubber, is used for stress control.

- SF_6 switchgear sealing ends for installation in the sealing end enclosures of SF6 gas-insulated switchgear. The sealing end insulator consists of cast epoxy resin and can be fitted with flanges of various diameters for use in single phase or three-phase encapsulated switchgear. Conventional switchgear sealing ends are filled with an insulating fluid.

There are now compact dry plug-in sealing ends available for installation in SF_6 switchgear for up to the maximum permissible operating voltage of 550 kV. The advantages are a reduction of up to approx. 50 % in overall length, and the opportunity to perform switchgear erection and cable installation separately. The gas-tight cast resin insulator is pre-assembled as a socket with contact at the switchgear works, while the plug-in part of the sealing end with a stress control element of highly elastic silicone rubber and a plug-in high current contact is connected („plugged in“) at site after cable assembly.

The connection dimensions of the interface between the switchgear and cable sealing end are listed as standardized dimensions in IEC TS 60859 for both the conventional („fluid-filled“) and plug-in („dry type“) sealing ends.

- Transformer sealing ends for installation in the sealing end enclosure which is filled with transformer insulating oil. As with the SF_6 sealing end, the insulator here also consists of epoxy resin. Standardization is being sought to bring the interfaces in line with the customary SF_6 sealing ends. Plug-in dry compact sealing ends like those for SF6 switchgear are also available for transformer connection.

- Connecting joints to connect individual lengths of cable together. For single core cable, the joints can be fitted with isolating modules, i.e. the metal jacket or metal screen is interrupted in the joint and led out through separate connecting lines. Joints with isolation are necessary when the so-called cross bonding process is applied. There, the metal jackets or screens are crossed over at certain distances to reduce the active power losses from induced sheath currents.

Various joint designs are available:

- Push-on straight joints with insulating parts in a single piece, e.g. of silicone rubber.

- Solid material joints with single-piece insulating parts of cast resin and stress control parts of silicone rubber. This type of joint was originally developed for the 400 kV voltage level, but is also used for 220 kV and 500 kV.

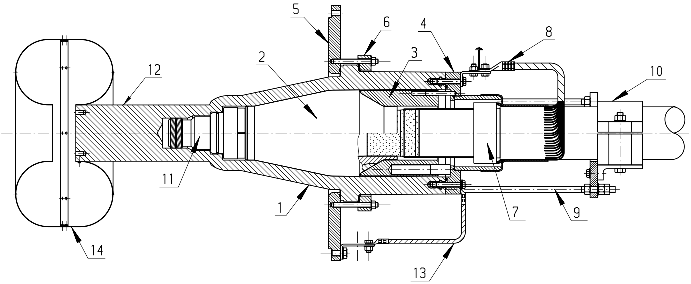


Fig 13-17

Plug-in cable sealing end for GIS and transformers for Um = 245-550 kV (Südkabel GmbH).

Tests on high and extra-high voltage cable fittings

The specifications for testing the properties of fittings for high and extra-high voltage cables with XLPE insulation are included in the relevant test standards for the cables. These can be found in DIN VDE 0276-632 for a maximum permissible operating voltage of 170 kV, and in the international test standard IEC 62067 for higher operating voltages.

13.3 Safe working equipment in switchgear installations

The following implements are required for safe working in indoor and outdoor switching stations:

- Earthing and short-circuiting devices to IEC 61230
- Insertion plates (insulating guard plates) to DIN VDE 0682-552.
- High-voltage detector to IEC 61234-1.
- Fuse tongs for voltages over 1 kV to EN 57681-3.
- Warning signs to DIN 40008 Part 2; they must conform to DIN VDE 0105-100 (VDE 0105 Part 100).

As per EN 50 110-1 (VDE 0105 Part 100), the dead status allowing safe access to any part of the switching installation should be established and secured with the following measures (“5 Safety Rules”):

- Disconnecting
- Securing against reclosing
- Testing for absence of voltage (all poles)
- Earthing and short-circuiting
- Covering or fencing off adjacent live parts

In general, the above sequence must be followed. Reasonable non-conformances can be specified in plant manuals. The following information applies to the measures:

Disconnecting

The equipment used for disconnecting must conform to the isolating distance requirements specified in IEC 60129. Such equipment can be in the form of

- disconnectors,
- switch disconnectors,
- fuse disconnectors,
- fuse-bases,
- draw-out switching devices whose isolating contact configurations meet the isolating distance requirements

The specifications for isolating distances are also met by equipment having air gaps of at least 1.2 times the minimum clearances in Table 1 of DIN VDE 0101, e.g. isolating links or wire loops.

A segregation may be used in place of an isolating distance.

Securing against reclosing

Warning or prohibition signs must be displayed to guard against reclosing. In addition, switchgear mechanisms must be blocked or tripping disabled.

Testing for absence of voltage

The voltage detector specified in IEC 61243-1 is used to detect non-hazardous absence of voltage in air-insulated switchgear installations.

The voltage testers (voltage detectors) to IEC 61243-1 show a clear indication “voltage present” when the line-to-earth voltage of the station component being tested has at least 40 % of the nominal voltage of the voltage detector. To ensure that interference fields do not influence the indication, minimum lengths for the extension part are defined in the above standard.

The detectors fall into three categories:

Voltage detector “for indoors only”
For use indoors with lighting levels of up to 1000 lux.

Voltage detector “not for use in rain, snow, etc.”
Can be used indoors and outdoors, but not in rain, snow, etc.

Voltage detector “for use in rain, snow, etc.”
Can be used indoors and outdoors in all weathers.

The instructions of operating these devices must be strictly followed.

In gas-insulated switch disconnector panels, the test for absence of voltage can be conducted directly at the T-shaped plug-in end seals with voltage detectors.

As per EN 50110-1, the test for absence of voltage of a switchbay can also be indicated with signal lamps if the change in the indication is visible during the disconnection process. The use of a make-proof earthing switch as an option for testing for absence of voltage should not be adopted as the general operational practice.

In gas-insulated switchgear and increasingly also with metal-clad air-insulated switchgear, the absence of voltage is tested with a capacitively coupled low-voltage display device. The coupling capacitors are continuously connected to the high-voltage conductor and are generally integrated into current transformers, resin insulators or bushings. The display devices may be permanently fixed to the installation or connected to the coupling capacitor with plug connectors. With appropriate subcapacitors, this forms a voltage divider connected to earth, to the tap of which the low-voltage display device – measuring against earth – is connected. Depending on the design of the display device, high-resistance, low-resistance and more recently medium-resistance systems are distinguished. IEC 61243-5(currently in draft form) is applicable to this type of testing for absence of voltage.

Earthing and short-circuiting

The earthed and short-circuited condition must be visible from the working position. The ground connection can be made either with an earthing switch incorporated in the switching bay, or with an earthing and short-circuiting device. An earthing truck is a possibility for metal-clad switchgear with draw-out switching devices.

Fig. 13-18 illustrates the earthing of a busbar with earthing truck and earthing cable in a metal-clad panel after the circuit-breaker has been withdrawn.

The lower isolating contact and the cable are earthed and shorted over the permanently installed earthing switch.

In gas-insulated switchgear, the feeder circuits are preferably earthed over the circuit-breaker (in closed position) connected to an earthing switch, which does not have a short-circuit current-making capacity.

The cable can in addition be separately earthed with the cable plug in disconnected position by means of a portable earthing device.

Using the earthing device

Observing the 5 safety rules (EN 50110-1), the earthing cable (Fig. 13-19) is first screwed to the specially marked fixed earthing point. To be safe, the 3 phase conductors are then checked for voltage with the voltage detector. The individual phase conductors are then discharged by touching the feeder lines with the earthing cable. Finally, the earthing cable is placed on the earthing pin of the respective phase conductor, and firmly screwed in place.

The earthing device must be removed again in the reverse order before the earthed feeder is put back in operation.

Earthing devices fittings are also available for direct connecting to the disconnector bolts of switchgear installations with draw-out circuit-breakers.

The earthing and short-circuiting devices are designed to withstand one exposure to the maximum permissible short-circuit stress. Having been fully subjected to this stress, they must be discarded.

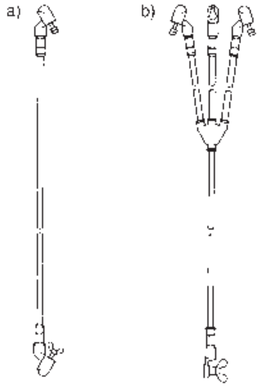


Fig. 13-19

Earthing devices to DIN 57683

a) Earthing and short-circuiting device for 20 and 25 mm dia. spherical fixed points, single-phase, cable cross-section 16 to 150 mm

b) Earthing and short-circuiting device for 20 and 25 mm dia. spherical fixed points, three-phase model, cable cross-section 16 to 150 mm

Covering or fencing off adjacent live parts

Work may be carried out in the vicinity of live parts only if precautions against direct contact (EN 50110-1) have been taken in the form of

- protection by cover or barrier, or
- protection by distance.

Before working on an outgoing feeder with fixed apparatus, a plate is inserted in the open busbar disconnector. This guards against contact with live parts on the busbar side. Provided the cable side is dead (beware of dangerous reverse voltages), work can proceed on the feeder apparatus after attaching the earthing device. Special care is called for in the case of transformers connected in parallel on the low-voltage side.

Work on live parts

A further working method is work on live parts (EN 50 110-1). This work must be performed in accordance with nationally tested procedures. A series of general stipulations , e.g. work procedures, work instructions, organization of workflows and special training, must be observed during the performance of the work.

14 Protection and Control in Substations and Power Networks

14.1 Overview and Tasks

The task of protection and control in substations and in power grids is the provision of all the technical means and facilities necessary for the optimal supervision, protection, control and management of all system components and equipment in high and medium-voltage power systems.

The task of the control system begins with the position indication of the HV circuit-breaker and ends in complex systems for substation automation, network and load management as well as for failure- and time based maintenance. For all these functions the data acquisition at the switch yard and – if applicable - the command execution at the switch yard are part of the network control and management.

Fig. 14-1 provides an overview of the functions and subsystems that make up the control technology in the context of electric power transmission and distribution. The purpose of these secondary systems is to acquire information directly at the high- and medium-voltage apparatus in the substations and to allow their safe on-site operation, including the secure power supply of all their parts.

Modern automation technology provides all the means necessary for processing and compressing information at the actual switchgear locations in order to simplify and secure normal routine operation. This allows more efficient use of existing equipment and quick localization and disconnection of faults in case of troubles, thereby also reducing the load on the communication links and in the network control centers.

Protection devices are required to safeguard the expensive power equipment and transmission lines against overloads and damages. Therefore, they have to switch off very quickly short circuits and earth faults and to isolate very selectively the faulted or endangered parts in the power system. They are thus a major factor in ensuring the stability of the power system.

The purpose of power system control as a subdivision of power system management is to secure the transmission and distribution of power in the more and more complex power systems by providing each control centre with a continually updated and user-friendly overall picture of the entire network.

All important information is transmitted via communication links from the substations to the control centre, where it is instantly evaluated and corrective actions are taken.

The growing amount of data acquired, the increasing communication bandwidth and the performance and memory capacity of modern computers have resulted in replacement of conventional mosaic panels for direct process control by computer based control systems with screen or video based displays. In few cases, conventional mimic panels are still kept for power grid overview.

Load management is directly influencing the system load, e.g. with the help of ripple control communication via the power network. It is selectively disconnecting and re-connecting consumers or consumer groups. On the basis of actual and forecasted load figures it is possible to level out load curves, to make better usage of available power resources, or to buy or sell energy on the market

It would be beyond the scope of this book to describe in detail all the subsystems and components belonging to network control. Therefore, this chapter can only serve as an introduction to the complex tasks, fundamentals, problems and solutions encountered in power network management and its related systems.

Closer attention is given, however, to all components and interfaces which directly concern the switchgear and the switchgear engineer, and which have to be considered in the planning, erection and operation of substations.

Due to the increase of automation functions, the more complex protection concepts and the at least partial integration of the protection into the control system, the overall system of control, monitoring and protection functions is called substation automation system. The terms 'digital' and 'numerical' apply for all microprocessor based devices with identical meaning.

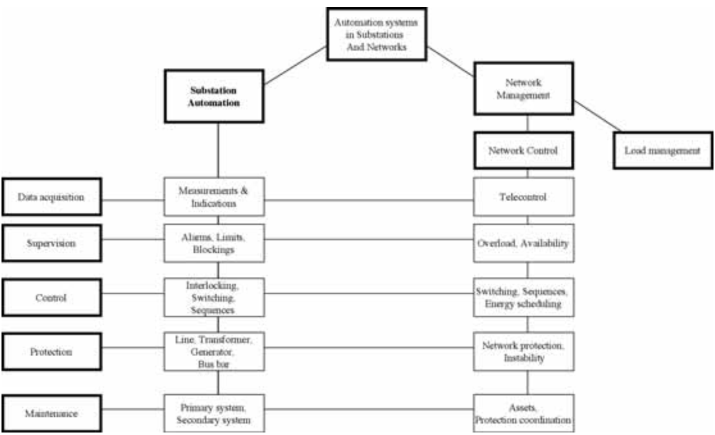


Fig. 14-1

Functions and subsystems of automation in substations and networks

14.2 Protection

Various protection devices in power systems with rated voltages > 1kV are available to protect generators, transformers, cables, busbars and consumers. The purpose of these devices is to detect faults and to switch off and isolate these selectively and quickly from the network as a whole so that the consequences of the fault are limited as much as possible. With today's high fault current levels and highly integrated networks, faults have far-reaching consequences, both direct (damaged equipment) and indirect (loss of production). Protection relays must therefore act very fast with the greatest possible reliability and availability, however also very selectively, to not switch off parts where it is not needed..

Relays can be divided into various categories.

A basic distinction with respect to function is made between switching (contactor) relays and measuring relays.

The relays used for protection purposes, together with supervisory relays, fall into the category of measuring relays and appeared according to their technology first as electromechanical and later as solid-state measuring relays. Today new protection relays are nearly exclusively numerical relays, i.e. based on software running in microprocessors. Therefore, more and more the term protective device is used instead of protection relay. More precisely, there are protection functions which are implemented in devices singly or in combination with other functions. Protection functions supervise dedicated values of the power system or of its components and respond very quickly and selectively if critical limits are exceeded.

There are also protective devices for direct current (DC), but in the context of this chapter, only the protection of circuits with alternating current (AC) is described. Important for measurements in multi-phase systems, common is the three-phase system, is that values may be single-phase or three-phase related. In addition, the sinusoidal voltages and currents are shifted against each other by the so-called phase angle. The sinusoidal values may be also represented as rotating phasors with amplitude and angle facilitating a lot of protection algorithms.

Nearly all protective devices are today integrated in some kind of systems requesting information like start and trip events from the protection function(s) and providing access to these e.g. for changing parameter sets. Numerical relays provide often also disturbance recording and, therefore, disturbance recorder file transfer over a serial link. All this information has to be exchanged over the so-called station bus according to IEC 61850 or one of the older proprietary protocols.

At the output of protective devices, there are switching relays which open e.g. the circuit breaker by closing the trip circuit. These relays act normally also as galvanic separation between power system equipment (primary technology) and the substation automation system including protection (secondary system). It is important that the output (trip) relays are able to switch the applied high currents and to not stick together. Because of their importance for the protection function, they are supervised in most cases.

An alternative not commonly used up to day are electronic components like thyristors for switching the trip circuit.

If not only the values from the instrument transformers but also the trip commands are transmitted serially via the so-called process bus to some breaker electronics integrated e.g. in the drive, then no such switching relays exist anymore. Supported by the communication standard IEC 61850 such solutions will dominate the future, especially since they allow also transmitting current and voltage samples both from non-conventional and conventional instrument transformers.

14.2.1 Protection relays and protection systems

Todays standard protection relays and protection systems are in some few cases still static, but designed to be at least numerically controlled (with microprocessors).

Electromechanical relays are practically never specified in new systems. The relays have to meet the following international specifications if applicable:

- IEC 60255 Electrical relays

This standard covers a broad range of requirements but has to be complemented by the following standards if applicable

- IEC 60068 Environmental testing
- IEC 61000 Electromagnetic compatibility (EMC)
- IEC 60870 Telecontrol Equipment and Systems
- IEC 61850 Communication Networks and System in Substations

14.2.2 Limit protection

Overcurrent and Time-Overcurrent protection

Single- or three-phase currents above a set limit will be detected and switched off after an also set time delay. The tripping time is independent how much the limit has been exceeded. This protection is called Definite Time Lag (DTL) Relay.

The preference in English-speaking countries is an overcurrent relay, which responds

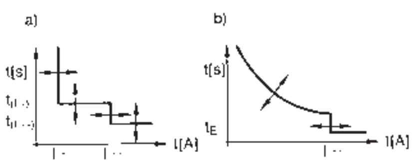


Fig. 14-2

Characteristics of overcurrent protection

a) DTL relays, two-stage
b) IDMT relays with high-current stage
I > Overcurrent stage
I ≫ High-current stage
t_E Opening time

Time-Overcurrent relays are used in radial networks with single infeed. The relays are connected via a current transformer. With a direction-sensing function measuring current and voltage and considering changing phase relations in case of fault, the relay is extended to a directional time-overcurrent protection. Such protective devices are preferably used for parallel lines and for the undervoltage sides of parallel operating transformers.

Overload protection

The temperature conditions at the protected object are simulated with the same time constant in the relays. Any load bias is taken into account by this thermal replica in the relay in accordance with the heating and cooling curves. Alarm signals or trip commands are issued if a set temperature limit is exceeded. The relays are built as secondary relays and operate usually in two or more stages. Overload relays are used for objects that can overheat such as transformers and motors, but less commonly for cables. The quality of this protection depends strongly on the accuracy of the thermal replica.

Frequency protection

If the frequency (f) goes above or below set limits or decays at an unacceptable rate (df/dt), this is detected and results in load shedding or disconnection of network parts (islanding). The deviation from the rated frequency is a good indication for an imbalance between produced and consumed active power (P). If e.g. the frequency decays because of the loss of generating group, a corresponding load has to be shed as soon as possible.

Voltage protection

Voltage deviations are reported, allowing the system load to be reduced as necessary. There are both over- and undervoltages.

Other limit protections

Other protective devices used for dedicated objects in the substation include e.g. interturn-fault, negative sequence, reverse-power protection for generators. Buchholz protection, temperature monitors, oil level indicators, oil and air flow indicators are used for power transformers. Insulation monitoring is special for conductors.

14.2.3 Comparison protection

Differential protection

The currents measured at the beginning and end of the protected object (line, transformer, generator, etc.) are matched in phase angle and magnitude and compared. If a set ratio of difference current to through current is exceeded, the relay issues a trip command.

In numerical relays, all classical components of differential protection like matching transformers, alarm and trip elements and inrush current stabilization are realized by algorithms in the microprocessor. The inrush stabilization prevents e.g. the trip of the transformer differential protection by the third harmonics of the current caused by the magnetization behavior of the transformer.

Differential relays exist as both, transformer and line differential protection. Line differential protection consists of a unit at each end of the line with current acquisition, comparison function and trip output for the local circuit breaker. For maximum precision the devices on both sides are commonly provided pair wise by one manufacturer. In addition, the differential protection needs a communication link for the transmission of data to be compared, i.e. the currents. For the long lines only serial connections are used, e.g. installed as fiber optic cables. The same is valid more and more also for the short links as needed for transformer or generator differential protection. IEC 61850 as standard for communication inside the substation will be the future solution also for lines.

The comparison of AC samples of phasors requires very accurate time synchronization in the range of microseconds of the data acquisition of both sides of the line. This is achieved by a proper "hand-shake” or GPS synchronization.

The differential protection is switching off very fast and selectively the faulted object between the measuring points. For correct protection operation the communication link has to be supervised properly. To cope with the loss of the communication, the differential protection is complemented by a distance or overcurrent protection.

Busbar protection

The busbar in a substation is a node in the power grid. According to Kirchhoff's law the sum of all incoming and outgoing currents has to be zero. The busbar protection acquires and sums up all these currents. If the current exceeds a set value near zero, all connected feeders are tripped. Therefore, the busbar protection represents a multi-leg differential protection.

The busbar is not a simple node but consists of section switches and depending of the number of parallel busbars, of bus couplers. Common are double busbar schemes. Therefore, each feeder bay may be connected alternatively to one of the busbars by busbar isolators. To identify the actual node configuration, a dynamic busbar image (topology) out of the status position of all isolators is created. This allows tripping only the faulted part in case of a busbar fault. Regarding the complexity of data acquisition (e.g. saturation of the current transformers) and the high speed requested to limit damage in the case of high short-circuit powers, static electronic protection systems have been used. Today, only numerical busbar protection systems are newly installed. This allows for compensation of the current transformer behavior. Because of the computation power provided today other functions like breaker failure protection, timed-overcurrent protection, undervoltage protection and phase discrepancy monitoring may be integrated. Very commonly, busbar protection consists of one centralized unit to calculate the current difference and make the trip decision, and one decentralized unit per feeder for data acquisition and trip execution. In the decentralized unit, all line protection functions may be integrated also, at least for back-up protection.

Comparative protection

The variables measured at beginning and end of the protected object are not compared per sample but as averages in a certain time window (e.g. for a half-wave of sinusoidal values) checked for coincidence (phase comparison protection) or for equal signal direction (signal comparison). These protection devices require only low communication bandwidth and are very insensitive to interference. Since not the raw data but calculated data are used this protection is slower than the differential and busbar protection.

14.2.4 Directional protection

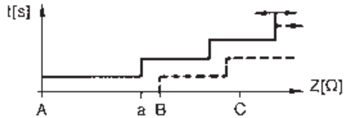
Distance protection

The distance of a fault from the relay is calculated by comparing the fault impedance with the known line impedance. Therefore, voltage and current are measured and a tripping range (protection zone) is assigned. A device for distance protection comprises normally some forward zones and one backward zone. The tripping characteristic is represented in the impedance plane as complex polygons or circles. In accordance with adjustable distance-time parameters the distance protection trips the allocated circuit breaker directly or with some delay as some kind of back-up protection. Distance protection operates selectively and very fast in meshed networks with multiple infeed and need basically no communication. Since some of the protection zones exceed the line end detecting more remote faults, releases or blockings should be communicated also to increase the selectivity by switching off only the faulted line. Known line and fault impedances allow also determining the fault location with reasonable accuracy, facilitating the maintenance of long and not easi§gly accessible lines. IEC 61850 as standard for communication inside the substation will be the future solution also for line protection communication.

The characteristic of a distance protection is shown in Fig. 14-3

Fig. 14-3

Characteristic of a distance protection
A, B, C Substations
Substation A: location of a relay
a = approx. 85 – 90 % of distance between A and B, i.e. of the line length



Directional earth-fault relays

An indication of direction is obtained from the sign of the angular difference between the phasors of neutral current and neutral voltage. The side of the fault is identified by comparing the values measured in the network. Other methods of measurement are possible.

Object protection with directional comparison relays

Are direction protection relays at the boundary of a power grid zone or of a busbar bay comparing all acquired directions, it may be decided if the fault is inside or outside these extended objects. A comprehensive communication network is needed, but with a low bandwidth only because of the limited information to be exchanged. Compared with differential protection, this simple solution is slower because of the time needed for fault direction evaluation, and requires to measure current and voltage at each measuring point.

14.2.5 Autoreclosing

In case of faults on overhead lines the line protection (e.g. time-overcurrent relay or distance relay) interrupts one or all three phases to cut off the power infeed into the fault. Assuming a transient fault the line or the power respectively should be switched on as soon as possible. For this purpose the protection related function autoreclosure is used. This function provides normally a closing sequence of one fast step and two slow ones. If the closing step is successful, the autoreclosure function is reset. If the fault persists, the protection will trip again and the next autoreclosing step is initiated.

An unsuccessful closing sequence ends with a final trip of the breaker. After the first unsuccessful step, tripping and autoreclosing is done normally for all three phases independent from the first step.

Autoreclosing assumes an appropriate communication between the protective device(s) and the autorecloser device e.g. by serial communication according to IEC 61850.

14.2.6 Advantages of numeric relays

The numerical relays mentioned above with up-to-date microprocessors (µP) provide a lot of important benefits:

Analog variables are digitized (A/D conversion) at the input card of the device and preprocessed if applicable. The trip decision is made in the microprocessor and, therefore, allows considering any complex conditions needed by the protection function. The resulting protection is much more adaptive regarding the power system conditions as any previous protection technology.

Parameters determining the behavior of the protective device are loaded and changed from outside via communication interface. Also dynamically self-adapting protection is feasible.

Several protection functions can be combined in a single device and executed in parallel (multi-functional devices). Functions from build-in libraries may be activated or downloaded from external libraries.

Numerical devices have a continuous self-supervision. Details depend on implementation.

Configuration and setting of the devices may be done over communication interface either locally by a laptop or from the remote workplace of the protection engineer. Consistency and plausibility checks support this work.

Opto-coupler inputs allow the potential-free input of external signals.

Serial interfaces support both the integration into substation automation systems and the connection of properly equipped process devices like instrument transformers and switchgear. A manual or automatic transmission of events and disturbance recorder files is possible. The standard for all this serial communication is IEC 61850.

In substation automation systems all events and alarms may be displayed in dedicated lists at the screen of the operator, and archived for later analysis.

Events and disturbance recorder files may be transmitted to a remote, centralized workplace for a comprehensive fault analysis.

Storage facilities for events and disturbance files allow to buffer data so that these are not lost in case of a communication interrupt. They provide also the transmission of data on request only.

Besides protection functions the same numerical device or devices out of the same device family allow performing also control and monitoring functions. In most distribution substations, a single device comprises already all protection and control functions needed in one bay.

14.2.7 Protection schemes

As already indicated above for differential or directional protection, many protection functions or protective devices respectively operate not alone but are integrated in an overall protection scheme. The design and implementation of such schemes is strongly facilitated by the state-of-the-art serial communication system.

In addition to the examples below also breaker failure protection and the inverse blocking of protection in radial power grids belong to such schemes.

Besides the serial communication of protective devices there is also the request for parallel protective devices like for main 1, main 2 and sometimes back-up protection in transmission power grids. Such kind of redundancy is not allowed to be jeopardized by modern communication architecture.

Protection of switchgear, lines and transformers

The basic scheme for protecting switchgear, lines and transformers is shown in Fig.14-4.

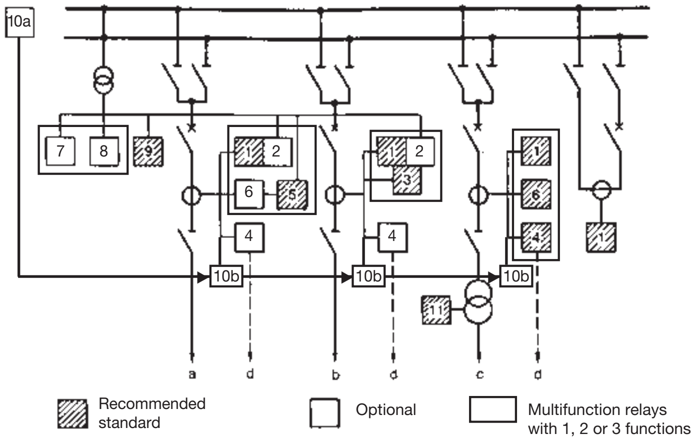


Fig. 14-4

Basic scheme of protection system for switchgear, lines and transformers:
a) Cable, b) Overhead line, c) Transformer, d) Auxiliary line
1 Time-overcurrent protection, 2 Distance protection, 3 Autorecloser, 4 Differential protection, 5 Directional ground-fault protection, 6 Overload protection, 7 Frequency monitoring, 8 Voltage monitoring, 9 Ground-fault indicator monitoring, 10 Busbar protection (10a Central unit, 10b Bay unit), 11 Buchholz protection, transformer temperature monitoring

Generator unit protection

The term generator unit protection is used when the functions of protecting the generator, the main transformer and the auxiliary transformer are combined with those for protecting the generator circuit-breaker or load disconnector.

Today, for generator unit protection almost exclusively numerical relays are used. Important factors influencing the form of the generator unit protection scheme within the overall design of the electrical system are

– whether the generator is switched by a circuit-breaker or a load switch,
– whether the auxiliary transformer has two or three windings,
– the number of auxiliary transformers,
– the method of excitation (solid-state thyristors or rotating rectifiers).

Therefore, the protection scheme is project specific. As an example, Fig. 14-5 shows the single-line diagram for a unit-type arrangement with generator circuit-breaker in a large thermal power plant and the allocated protection scheme. It should be noted that the protection blocks shown are not protective devices but protection functions which may be implemented in some set of numerical devices.

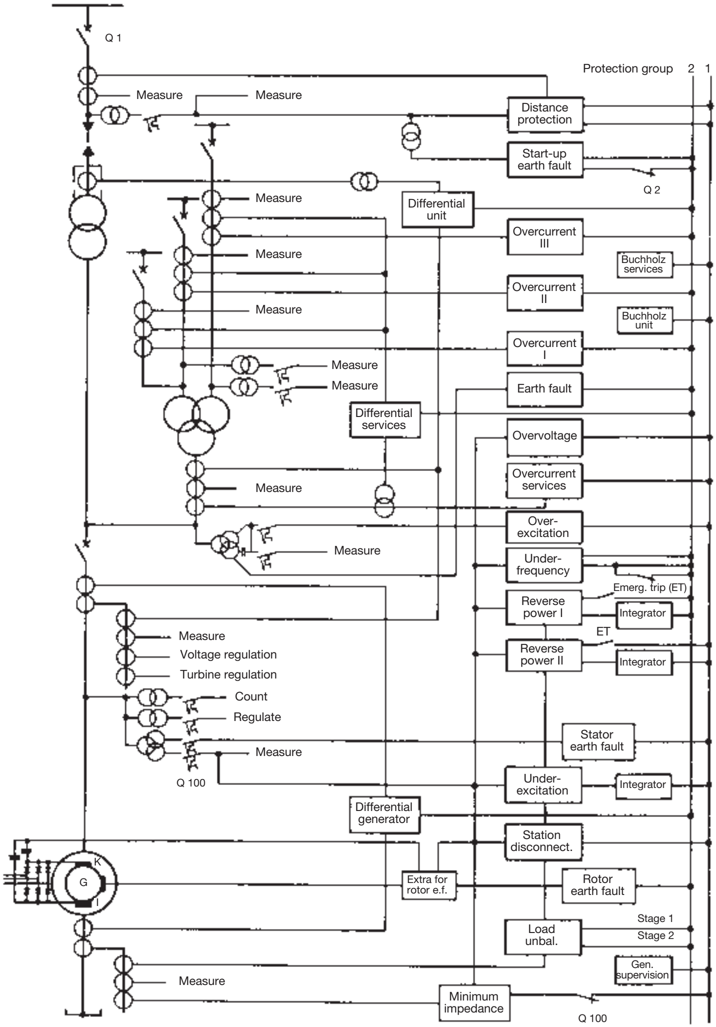


Fig. 14-5
Single-line diagram of generator unit protection system and single line diagram with generator circuit-breaker

The function diagram shows how the individual protective devices are linked to the operating circuits. The allocation of the trip commands of the protection functions to the switching devices (e.g. generator circuit-breaker, magnetic field switch, etc.) and switching functions (e.g. automatic switchover of the auxiliary power) are implemented with programmable logics as part of the numerical devices. Therefore, the tripping scheme may be modified if needed.

To increase the availability of protection, the protection scheme is split into two separate and largely independent groups and the related devices installed in different cubicles. This means also separated power supplies and separated trip logics.

Protection functions which complement or back-up each other have to be carefully distributed over both groups.

Stationary or mobile test equipment allows testing these two groups independently both in case of switch-off or running generators.

14.3 Control, measurement and regulation (secondary systems)

Secondary systems are all those facilities needed to ensure reliable operation of the primary system, e.g. of the HV substation. They cover the functions of controlling, interlocking, signaling, monitoring, measuring, counting, recording and protecting. The power for these auxiliary functions is taken from batteries, so that they continue to work also in the event of network faults. Whereas in the past conventional techniques were used for decentralized control, e.g. from a local panel, this can now be done using computer based substation control techniques, often called 'substation automation', with or without protection.

The interface that this necessitates, is moving ever closer to the process, i.e. to the primary system. How near this interface can be brought to the process depends, for example, on how practical and reliable it is to convert from electromechanical methods to electronic (numerical) techniques, or whether the information to be transmitted can be provided by the process in a form which can be directly processed by the electronics. The communication standard IEC 61850 even defines a serial interface to the process, which provides sampled analog values of voltage and current from the instrument transformers or sensors.

Today, overall network management is undertaken by computer-assisted systems based at regional or supra-regional control centers and load-dispatching stations. The conventional means to connect these to the substation is via remote terminal units (RTU). If however a computer based substation automation system exists, the RTU can be reduced to a protocol converter to the SA system. The trend to use the IEC61850 up to the network control can reduce this even further to a data filtering and concentrating unit.

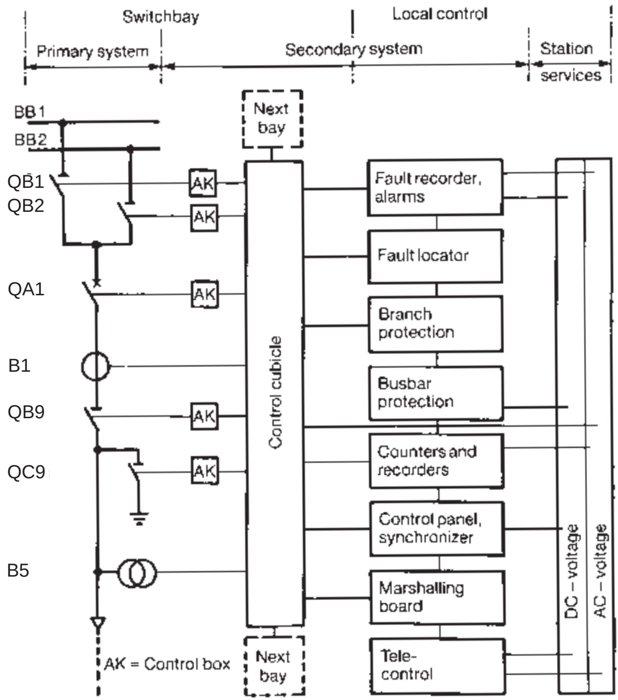


Figure 14-6
gives an overview of the SA functions in HV substations.

14.3.1 DC voltage supply

It is essential that the components of the secondary systems have a secure DC power supply. For HV and EHV installations, this means that the DC power supply must be redundant (see also chapter 6.1.5) so as not to be rendered inoperative by a single fault. Indeed it is advisable to provide two separate infeeds also for the low-voltage three-phase network. If these infeed is not very dependable, a diesel generator should also be provided for emergency. The three-phase loads are connected as symmetrically as possible to the two three-phase busbars formed; the battery rectifiers are also connected here, one to each busbar.

In case of proper selection of the rectifier, the DC output from the rectifier and also the battery can be connected independently to the DC busbars, so giving greater flexibility.

It is best to use 220 V and 110 V for direct control. As these circuits are today also used by the process near IEDs (IED = Intelligent Electronic Device) at bay level, these should operate with the same voltages, thus simplifying the power supply schema. The same requirement is valid for the power supply of communication equipment like Ethernet switches for IEC 61850, at least near to the process. Older remote terminal units may still need 60 V, 48 V and 24 V for remote control and signal circuits.

With the aid of inverters, a secure AC busbar can be created from the DC busbar if necessary. The HMI computers could be industrial PCs with DC power supply. If not, then they need) this secure AC supply like also commercial VDUs (e.g. LCD displays.

The DC network must be carefully planned. The auxiliary circuits must be assigned to each function and bay, so that only one function or one bay is affected by a fault. By this approach, faults in the signal circuit, for example, do not influence the control circuit, and vice versa.

14.3.2 Interlocking

To ensure reliable control, beneath the blocking of switches due to switch inherent reasons, the HV switching devices within each bay and at a higher level within the entire substation are interlocked with respect to each other. The interlocking conditions depend on actual busbar configuration, i.e. from the position of all switches at any given time. The interlocking must in particular prevent an isolator from operating while under load, or to connect power with earth.

For secure interlocking there exist some principle rules. Rules related to the operation philosophy of the utility may be added. If for example a substation with bypass bus shall be interlocked, then you need additional rules for the security of the bypass disconnectors as well as for protection selectivity. These rules can, depending on the switch yard topology, be expressed in substation specific Boolean algebra, or by means of a topology based implementation be directly applied to the switch yard topology and the current switch states. For the following example for a double busbar with one feeder, one bus coupler and one bus earthing switch (see Fig. 14-8) the specifically derived security related rules are listed for better understanding.

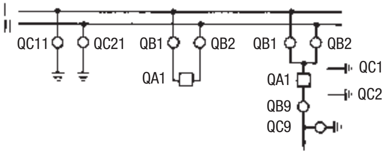


Bild 14-7

Single line diagram of a double busbar substation with one feeder, one bus coupler and one bus earthing switch each

The following conditions must be fulfilled in this case:

1. Disconnectors QB1, QB2 and QB9 can be operated only when breaker Q0A1 is open (protection against switching under load).
2. Breaker Q0A1 cannot be closed with disconnectors QB1, QB2 or QB9 in the intermediate position (intermediate position indication).

3. Disconnectors QB1 and QB2 are mutually interlocked so that only one can be closed at a time.
4. When the bus coupler is closed, the second bus disconnector (QB1 or QB2) belonging to the connected busbar can be closed. One of the two closed disconnectors can afterwards be opened (change of bus connection under load).
5. Disconnectors QB1 and QB2 can be operated only if the related bus earthing switch Q15C11 or Q25C21 is open.
6. Disconnector QB9 can be operated only when earthing switch QC89 is open (taking into account the other end of line, if necessary).
7. Earthing switch Q8C9 can be operated only when disconnector QB9 is open (taking into account the other end of outgoing line if necessary).
8. Disconnectors QB1, QB2 and QB9 can be operated only when maintenance earthing switches Q5C1/Q5C2 are open.
9. Maintenance earthing switches Q5C1/Q5C2 can be operated only when disconnectors QB1, QB2 and QB9 are open.
10. The circuit breaker Q0A1 of the bus coupler can be opened only if not more than one bus bar isolator in each feeder is closed (bus coupler lock-in).
11. One bus earthing switch QC115 or QC251 can be operated if in the respective bus section all bus disconnectors of the corresponding bus system are open.
12. All interlocking conditions remain active if the auxiliary power fails.

For the case that switch positions are wrongly acquired or an interlocking failure prohibits necessary switching, an interlocking release switch can override the interlocking conditions. Switching operations are then within the responsibility of the person authorized. The exact procedures for this situation are defined b the operation philosophy of the utility.

14.3.3 Control

The purpose of a control device in a switchgear installation is to change a defined actual condition into a specified desired condition.

The operating procedures of controlling, interlocking and signaling can be performed either by simple contact-type electromechanical and electromagnetic devices such as discrepancy switches, auxiliary contactors and auxiliary relays, or by contact-less electronic components. Both methods allow single switching operations and programmed switching sequences up to fully automated switching routines.

With conventional control techniques, there are limits regarding automation.

Conventional control techniques are becoming less popular because of the space required, the equipment’s high power consumption, wear due to constant operation, and the fixed wiring, and are more and more replaced by microprocessor based substation automation systems. Today they are used mainly for local control within the switching installation, or emergency operation directly at the switch gear.

General, the devices can be divided into those relating to

– switching apparatus (process level),
– bay (bus bar, branch, feeder) level and
– station level.

The apparatus-related devices are contained in a box on the circuit-breaker or disconnector. The bay related devices are usually in a control cubicle or local relay kiosk. Station related devices are located in central relay kiosks or in the substation control building.

To coordinate the different control hierarchy levels, each level contains a local / remote switch, which allows blocking control from higher levels. This principle is often also extended to the network control level. The local/remote switch at the lowest level close to the process is mostly realized by means of mechanical, key operated switches, while at higher levels like for the station / network control the switching is mostly implemented by software in the appropriate processors.

When setting up the control system concept, it must be considered whether the substation is mostly operated manned or unmanned, or whether it is remotely monitored or controlled. The control modes can be generally defined as follows.

Local control

Here, the controls are close to the switchgear. They are used mainly during commissioning and maintenance, often for emergencies as well. They are located on the apparatus itself or in a bay cubicle, and work independently of higher-level control systems.

Direct control

In this mode, the switchgear is controlled locally from the on-site central control point called station level, where each piece of apparatus has its own control switch, etc. It may utilize the switchgear's control voltage or light-duty relays. Control from the station panel always includes indication of the switchgear's respective operating positions. Today this is mostly replaced by station level computer based HMI.

Select before operate (execute)

This mode is used both for on-site control and in central control rooms. It is arranged in a number of steps, so that from an operator's position one can, for instance, pick first the station, then the bay and finally the item of switchgear before initiating the actual switching operation with the "execute" button.

Both station-level and network control systems nowadays have computer based work places consisting of a key board, mouse or other pointing device, and one or more screens. If necessary certain switching sequences can be predefined. The back indications of switch positions are displayed in the single line diagram on the screen. In very few cases, overview panels in conventional technique are used in parallel to the screens.

Double command blocking

Although within an operating level there may be several work stations, but mostly one command only shall be executed at a moment in time. This can be solved by mutually interlocked operator places. However, even commands from several levels could be executed in parts of the system, which might influence each other e.g. for interlocking. In this case a double command blocking is implemented close to the process, e.g. in the bay controller. If a switch is selected for a command, then it is checked first that no other switch is currently selected or even executing. If this is the case, then the selection is blocked.

Remote control

In this mode, the substation is controlled from regional and central control centers, predominantly via telecontrol link or the communication network of the utility. The interface between station and remote control is the network control gateway providing protocol conversion also.

Control functions include a wide variety of dedicated applications; representative examples are the monitoring of tripping circuits (Fig. 14-8), and the duplication of tripping circuits (Fig. 14-9).

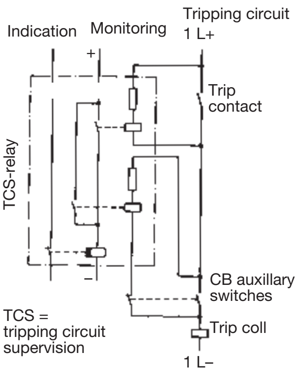


Fig. 14-8

Tripping circuit supervision for a circuit-breaker in closed and open position

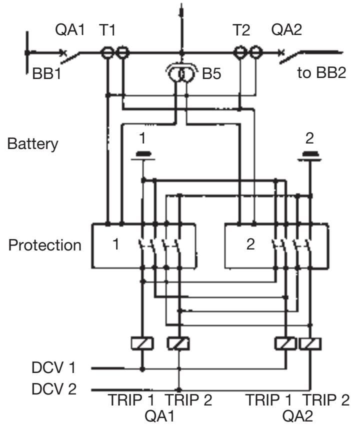


Fig. 14-9

Duplication of tripping circuits with 1½- and 2-breaker arrangement

14.3.4 Indication

Operating personnel must be informed of disturbances and faults, operational conditions and the position of the switchgear.

Switchgear contact positions are indicated by position transmitters, light emitting diodes (LED) or displayed in the single line diagram on a screen. The switchgear positions must not be indicated until the apparatus has reached its final CLOSED or OPEN position; otherwise an intermediate position must be indicated.

Alarms from faults and disturbances may be indicated by optical and acoustic means similar to position changes, but in any case they will be displayed in the event and alarm lists of the operator's workplace and recorded. For more details see Section 14.3.8 Recording and logging.

For the acquisition of binary indications the signalling relays are equipped with potential-free auxiliary contacts, which today means realization with opto-couplers within the computerised bay level devices or process near sensors. Sum indications and sum alarms are calculated within the bay level IEDs as well as in the station computer and in gateways to the control centers.

Alarms are indications, which request actions by the operation personal. Therefore, all alarms have to be acknowledged after observation, latest after appropriate actions. Unacknowledged alarms are kept even if the original alarm state has disappeared. The alarm handling is done normally in the alarm list on the screen of the local or remote operator's place. This allows to group, display selectively and to acknowledge all the alarms.

14.3.5 Measurement

Operating a substation involves measuring, recording and evaluating operational quantities such as currents, voltages, powers, etc. For these tasks, the primary system provides appropriate instrument transformers or sensors both for voltage and current, which are installed at the busbar and/or in feeders . The kind, number and position of instrument transformers depends on the operational requirements as well as on the protection scheme. More details see in Sections 10.5.2 to 10.5.5 on instrument transformer selection.

Voltage transformers in the feeders are useful for measurement and protection. Voltage transformers at the busbar are convenient for synchronizing and measurement purposes; there is then no need for calculation of missing values.

The secondary sides of current and voltage transformers must be earthed to avoid any risk to equipment and personnel from unacceptably high voltages.

Current transformers are not allowed to be operated with open secondary windings, as the high voltages occurring at the secondary terminals are dangerous to personnel and may damage the instrument transformer.

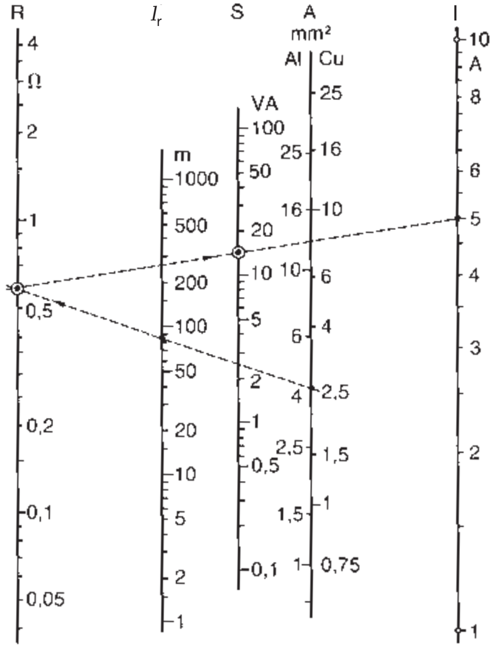
Current transformer circuits must be earthed at one point only. In high-voltage installations this point should be in the feeder control cubicle wherever possible. The standards valid in the particular countries must be observed. One must make sure that the instrument transformer power rating is at least equal to the power consumption of the measuring devices including the connecting lines. The dimensions of these can be determined with help of Fig. 14-10.

See DIN 43700 and 43701 for detailed information on standardized designs and dimensions of control panel instrumentation and measurement ranges.

In case of using serial transmission of sampled values according to IEC 61850 from the instrument transformers or sensors to the measuring and protective devices, all this dimensioning is an internal issue of the instrument transformers and, therefore, not needed anymore for the system design.

Classification of instrument transformers and their principal applications

Electrical measuring instruments have a class coding. The classes are: 0.1; 0.2; 0.5; 1; 1.5; 2.5 and 5. These indicate the measurement or reading error in percent, both in positive and negative direction. They always relate to the high end of the measuring range.



Example:

$A = 2.5\ mm^2, l_r = 85\ m$: then $R \approx 0.6\ \Omega$

$I = 5\ A, R \approx 0.6\ \Omega$: then $S \approx 15\ VA$

Fig. 14-10

Current transformer secondary lines; To determine resistance and power consumption, R = line resistance Ω, l_r = resultant line length m, S = power VA, A = line cross section mm² for Cu and Al, I = sec. transformer current A

Instruments of classes 0.1 to 0.5 are precision instruments, those above are industrial instruments.

For instrument transformers the following standards apply: IEC 61010-1 (VDE 0411 Part 1),IEC 61010-1/A2 (VDE 0411 Part 1/A1) and IEC 60051; DIN 43781 (for recorders) if applicable. . These standards contain the most important definitions, classifications, safety and test requirements and forms of identification.

Measuring transducers

Modern digital bay level IEDs can acquire currents and voltages directly from the primary transformers, and therefore do not need transducers for these electrical quantities. They may also have an interface according to IEC 61850, which supplies easily the measured values for further processing.

Eventually additionally needed transducers in the field of power engineering convert input variables such as current, voltage, power and system frequency into analogue electrical output quantities, usually in the form of impressed direct current, but sometimes also of impressed DC voltage. Preferably these transducers have also a serial interface according to IEC61850 to easily connect them to the substation automation communication system. These values are then easily used by subsequent processing functions and communication systems.

The most important parameters, device properties, designations and tests of transducers for quantities in electrical engineering can be found in the VDE 0411 Part 1 and VDE 0411 Part 1/A1 standards mentioned above in the "Instrumentation" section. The EN 50178 (VDE 0160) and the VDE/VDI Directive 2192 must also be observed.

14.3.6 Synchronizing

Synchronizing is also based on measurement. System components cannot be connected in parallel unless their voltage curves coincide, otherwise the electrical stresses on the equipment become too high. While with DC it is sufficient for the system components that voltage and polarity be the same, with AC voltages the frequency, the voltage and the phase angle must match; with three-phase current this is valid also for the phase sequence.

Digital technology offers the option of feeding the input signals of the primary voltage transformers directly to an automatic synchronization device, which independently releases the closing operation at the right time. This is commonly called synchrocheck, and a standard function in numerical protection relays or control units.

An automatic synchronization device is always recommended for parallel switching of generators with the power grid. This device brings automatically both the rotation speed (frequency) and voltage of the generator into a preset tolerance range using higher and lower commands.

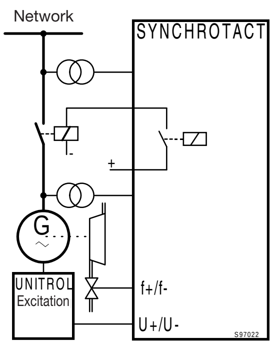
Considering the changing differences in voltage, phase angle, frequency and the mechanical delay of the circuit breaker the paralleling (closing) command is issued such that the breaker contacts touch at precisely the instant of time when the phases are the same.

The SYNCHROTACT® automatic synchronization device in its simplest form is one single channel, which takes care of measurement, voltage and frequency balancing, of monitoring and command issuing with high security against faulty operation.

Fig. 14-15

Automatic synchronizer device.

The synchronizer device issues higher and lower commands to turbine controllers and voltage controllers. When the paralleling conditions are met the circuit-breaker is closed at the exact moment when the phases are the same.



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Depending on system size and safety concept, dual channel solutions are also available. Measuring, microprocessor and command relays in both channels exist independently in the SYNCHROTACT® dual-channel synchronization units. This independence significantly increases security against faulty operation in comparison to the single channel system.

14.3.7 Metering

General

Meters are used for acquiring the amounts of power supplied from the power provider or distributor to the consumer. The selection criteria are shown in Table 14-4.

Meters for billing electricity consumption are in a special category.. In the Federal Republic of Germany, for instance, they have to meet the requirements of the Physikalisch-Technische Bundesanstalt (PTB) to be certified and approved. Similar institutions exist in other countries also.

The voltage drop on the instrument transformer line of billing meters must not exceed 0.1 %.

Table 14-1

Selection criteria and alternatives for electricity meters (counters)

Criterion	Alternatives
Connection	direct or to instrument transformer
Type	electromechanical or electronic
Mounting	surface-mounted housing, live parts fixed
	flush-mounted housing, live parts fixed
	flush-mounted housing, live parts removable
	subrack, live parts on circuit boards
Current	alternating current
	three-phase in 3- and 4-wire systems loaded symmetrically and asymmetrically
Power	active and reactive consumption, incoming and outgoing[1)]
Tariff	single or two-rate tariff[2)]
Accuracy class	0.2, 0.5, 1, 2, 3
Metering system	primary system[3)]
	semi-primary system[4)]
	secondary system[5)]
Special meters	maximum-demand meters[6)]
	pulse meters[7)]
	remote meters

1) Reversal prevention is necessary where the power flow direction changes.
2) Tariff changed with separate timer or ripple control receiver.
3) The ratio of preceding transformers is accounted for in the meter reading.
4) This takes account only of the ratio of preceding voltage or instrument transformers, the readingsmust be multiplied by a constant.
5) This does not take account of the ratio of preceding transformers, the readings must be multiplied by a constant.
6) The maximum rate is calculated from the price per kilowatt-hour (kWh) and per kilowatt (kW).
7) These measure the power throughput and according to the units counted, emit pulses to the connected remote meters, remote summation meters or telecontrol devices.
ASIC measuring chip

Electronic four-quadrant meters

Electronic meters formerly mostly used multipliers, which measure only one energy variable at a time, such as the time-division multiplier or the Hall multiplier. Modern meters use the principle of digital multiplication and integration.

The measured quantities of current and voltage are acquired with metering transformers and digitized using high-precision A/D converters with a sampling frequency such as 2400 Hz, and forwarded to a downstream digital signal processor (DSP). This processor calculates the effective, reactive and apparent power or the corresponding energies and sends energy-proportional pulses to the rate module. The advantages of this process are in the high integration of the measurement functions, the low fault rate, the high measurement stability and the option of performing a full 4-quadrant measurement.

The metered values can also be transferred via serial communication according to IEC61850 from the data acquisition until evaluation (e.g. by a tarif rate processing module). If IEC 61850 is already used for a process bus at the instrument transformer or sensor, there are no limits in voltage losses, distances and location. Pilot installations of such systems use today a separate communication systems. Institutes like the Physikalisch-Technische Bundesanstalt (PTB) investigate how secure against tempering also revenue metering relevant measurands can be transmitted using the communication system of the substation automation system.

Measurand processing

The measured values may also be processed further and the derived values may be calculated like instantaneous values, averages, minimum values, maximum values, etc. Appropriate selection of the sampling frequencies also allow recording the contents of the harmonics within the requested accuracy class.

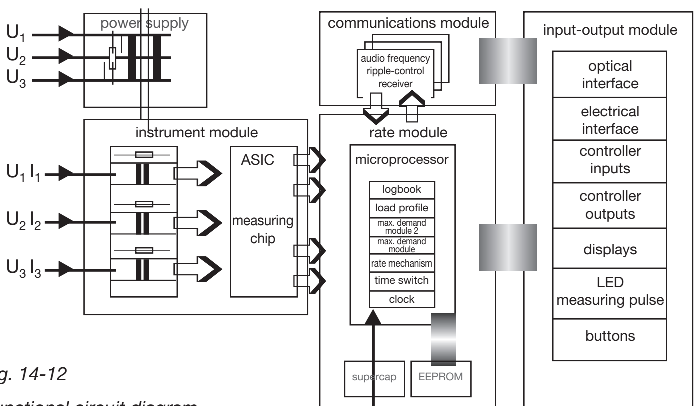

Fig. 14-12

Functional circuit diagram power supply communications module instrument module rate module

The calculated quantities are:
– effective power ...P, with direction also as +P and -P
– reactive power ...as Q1, Q2, Q3, Q4 individually or combined.

The effective power P is derived by multiplying the current and voltage values:

$$p(t) = u(t) * i(t)$$

The reactive power Q can be calculated from the apparent power S and the effective power P applying the vector method as follows:

$$S = Ueff * Ieff$$

$$Q = \sqrt{S^2 - P^2}$$

Because the harmonic contents is taken into account in the two rms values of current (I_{eff}) and voltage (U_{eff}), and, therefore, also in the apparent power S and in the effective power P, the harmonic power is also included in the calculation of the reactive energy Q.

Power supply quality

The quality of the electrical power supply is more and more part of supply contracts. In earlier times it was focussed nearly exclusively on reactive power Q. Today also power availability, harmonics and short time interruptions belong to power qualitiys. This needs calculation of the energy contents of single harmonics, which means further measurement processing and higher frequency range of the measurement chain. These power quality related values can be provided by additional functions in protection or control devices or within dedicated power quality measurement devices. All of these devices should be connected according to the IEC 61850 communication standard.

Standards for metering

The following standards must be taken into account in planning and installing DC and AC power meters:

– DIN 43850	Electrical Meters Technical Specifications
– DIN 43854	Sealed Terminal Cover Screws for Electrical Meters
– DIN 43855	Electrical Meter Labels
– DIN 43856	Electrical Meters, Multi-rate Tariff Switches, Ripple-control Receivers Terminal Marking, Pattern Numbers, Circuit Diagrams
– DIN 43857-1...	Electrical Meters in Insulated Cases to 60 A Limit Current
– DIN 43862	Removable Meter with Fixed Measuring Mechanism, Main Dimensions
– DIN 43863-1	Electrical Meter, Rate Devices, General Requirements
– DIN 43864	Electrical Meter, Current Interface for Impulse Transmission
– DIN 43860	Supplementary Devices as per DIN 43857 Part 2, Fastening Brackets
– DIN 43861-1	Ripple-control Receiver for Installation in Light Poles
– DIN 43861-301	Ripple-control Receiver Transmission Protocol with Data

Backup for Transmission Tasks in Ripple-control Technology

– IEC 60387	Electrical Meter Symbols for AC Meters
– IEC 60521	(VDE 0418 Part 12) AC kWh Meters Class 0.5, 1 and 2
– IEC 60687	(VDE 0418 Part 8) Electronic AC kWh Meters, Class 0.2 S and 0.5 S
– IEC 61036	(VDE 0418 Part 7) Electronic AC kWh Meters, Class 1 & 2
– IEC 61268	(VDE 0418 Part 20) Electronic AC VArh Meters, Class 2 & 3
– DIN VDE 0418-4	(VDE 0418 Part 4) Electrical Meters, Maximum-demand Mechanisms
– DIN VDE 0418-5	(VDE 0418 Part 5) Electrical Meters, Duplicating Meters
– IEC 61037	(VDE 0420 Part 1) Electronic Ripple-control Receivers for Rate and Load Controllers
– IEC 61038	(VDE 0419 Part 1) Time Switches for Rate and Load Controllers
– IEC 61107	Meter Content Transmission, Rate and Load Controller Data transmission for fixed and mobile connections
– IEC 61142	Meter Content Transmission, Data Exchange via Local Bus

First standards for power quality

- IEEE 519:	1992 IEEE Recommended Practices and Requirements for Harmonic Control in Electrical Power Systems
- IEEE 1459	2000 IEEE Trail Use Standard Definitions for the Measurement of Electrical Power Quantities under Sinusoidal, Non-sinusoidal, Balanced or Unbalanced Conditions
- IEC 61000-4-7	Electromagnetic Compatibility (EMC) – part 4: Testing and measurement techniques – Section 7: General guide on harmonics and interharmonics measurements and instrumentation for power supply systems and equipment connected thereto.

14.3.8 Recording and logging

Event recorders

Logging and archiving of events in time order are standard substation automation functions, often called SER or SOE for 'Sequence Of Event Recording'. In rare cases, e.g. if special requirements for high accuracy or independency exists, stand alone recorders or loggers are used. The time stamp resolution is normally 1 ms. Events coming with this time interval are then shown in correct time order. The list of events is normally shown as text protocol with time stamp at the screen of the operator's work place and may be printed. Time stamped events come from state change of binary signals, or from limit crossings of analog signals. This is a base functionality of computerized substation automation systems.

In distributed systems an accurate time synchronization between the (bay level) devices is needed, e.g. according to IEC 61850 class T1, meaning ± 1 ms accuracy. To receive this accuracy within the power network across different substations, normally a radio master clock is used within any substation, receiving the time signal either from satellite (GPS, globally applicable) or from ground-based senders like DCF77 in Germany.

Disturbance recorders

As well as recording routine measurements, in case of a fault it is also important being able to reconstruct the time sequence of all signals and events related with this fault. This is accomplished by means of disturbance recorders. They register the variation in time of currents and of voltages and binary changes (e.g. breaker state) shortly before and after the fault. In this way, it is possible to analyze faults, determine their causes and avoid them in the future as far as possible. Disturbance recorder functions serving also the supervision of protection functions are nowadays integrated into the numerical protection devices. If higher accuracies for the analogue values or their sampling are needed, additionally dedicated devices can be installed either permanently, or for some investigation time. These separate devices are very often also combined with event recorders.

To compare the recordings from different feeders or even substations, the disturbance recorders need to be time synchronized also.

Fault locators

The availability of transmission lines is particularly important in HV and EHV networks: it can be improved by fast finding of the fault location and clearing the fault.. The on-line determination of fault distance is based on the comparison of impedance measurements with and without the fault.. Measurements of the fault impedance have to be done very fast as the time available is only from the fault's occurrence until its isolation. Many numerical distance protection devices can supply this fault location as an additional function. The distance of the fault may be read out directly at the device, and/or transferred by the communication system to station level or even network level.

There exist evaluation programs for disturbance recorder data, which can also supply the fault location from the disturbance record. This location can be more accurate as evaluated by the protection device, if either a dedicated device with higher sampling rate or measuring accuracy is taken, or if different disturbance records, e.g. from the two ends of the same line, are combined.

14.3.9 Automatic switching control

An automatics for dedicated switching sequences executes switching or power re-routing operations under clearly defined operational conditions without action of the operator. Controlled by measuring relays, its task is to restore a fault-free supply (load restauration).

The auxiliary power supply systems of substations can include automatic transfer facilities which e.g. in case of an infeed failure quickly close couplers , connect standby transformers or start emergency diesel generators.

The auxiliary power supply systems of thermal power plants include high-speed transfer systems to ensure a secure power supply to the motors for the boiler ancillaries. If the power supply is interrupted, the high-speed switchover function switches the important loads like the mentioned high-voltage motors to a standby network as quickly as possible and without impact on the operation of the plant (see also Section 15.2).

This functionality is also used by industry, especially by the chemical industry, where it is essential that processes continue without interruption.

The 15 kV systems of the German Federal Railway include automatic line testers so that the trains can keep running. A fault on the contact wire (earth fault) first trips the circuit-breaker in the substation, but the control system immediately closes it again. Only if it trips again is the line finally disconnected.

It has to be considered that during any power failure synchronous motors work as continuously slowing down generators. Therefore it is essential that before any reclosure of power the voltage curves have to be checked by the synchrocheck function.

Auto-Reclosing

In overhead line networks, automatic reclosing plays an important part in maintaining the power supply. Experience shows that faults in these networks are often only transitory and can be cleared if the breaker opens for a brief interval during which the arc can extinguish and the insulating distance reseal before it automatically closes again. The timing of a successful reclosing operation is shown in Fig. 14-14. As well as single fast reclosure, there is multiple shot slow reclosure, which must be accompanied by checks on the synchronizing conditions. Fast reclosure can be performed one- or three-phase, depending on type of fault and network conditions, with break times of 0.2 s to 2 s. Slow reclosure is normally only three-phase, with break times up to several minutes. For further details, see Sections 14.2.1 and 10.4.5.

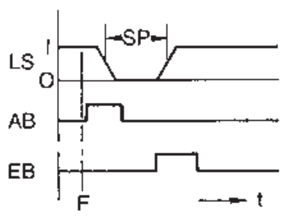

Fig. 14-19

Simplified time diagram of successful reclosure:
AB OPEN command, EB CLOSE command, LS Circuit-breaker, I Close, O Open, SP Dead interval, F Onset of fault

14

Automatic feeder-switching sequences

Switching sequences executed locally can ease the load on operating personnel and the telecontrol facilities, e.g. one can preprogram all the switching steps needed to connect a feeder or to change the busbars, and start the sequences either locally, or remotely, even from the network control center. Such switching sequences can easily be implemented in substation automation systems. Bay level sequences can be implemented on bay level devices, while station level sequences are typically implemented on station level controllers, because this is easier to configure and to maintain.

Modern RTUs offer also the possibility to program and execute such sequences.

14.3.10 Transformer control and voltage regulation

An important function to operate power transformers is to change the transformation ratio. This function serves to adapt the voltage in case of load fluctuations, to distribute load, to adjust active and reactive currents in interconnected systems and to control the voltage for electric furnaces and rectifiers.

To maintain the defined voltages on the consumer side, the transformer's high-voltage winding is provided with taps (main and control windings) which are connected in different orders according to the load. The respective winding sections are selected by means of off-load or on-load tap changers.

Off-load tap changers

Off-load tap changers are used in networks with low fluctuation in load. This tap changer covers a band of ± 5 % of the operating voltage to be guaranteed. The taps are changed off-load in 2 x 2 stages each of 2.5 %. This is normally done manually close to the transformer.

On-load tap changers

On-load tap changers are used in networks with frequent load fluctuations in short time. The control range is + 16 % max. of the operating voltage to be guaranteed in a total of 2 x 16 stages each of 1%. The tap changer operates while the windings are under voltage and load. For this operation the tap changer has a drive with power storage (e.g. spring) which is charged with help of an electric motor.

Tap changer control

1. Local control
   The tap changer can be operated directly at the transformers with the help of a crank handle (emergency operation). Electrical local control by pushbuttons is also possible. In this case, each switching step from one tap to another requires a separate command. The tap changer is designed so that a single command cannot execute more than one step change. Today, the electric local control is mostly replaced by an automatic voltage controller having a manual control mode also.

2. Station control / remote control
   Remote control is possible from the station level or from the network control center. The same control authority principles are applied as for controlling a breaker. If an automatic voltage controller exists, it is controlled by voltage set points.

3. Parallel tap changer control
   Where several transformers are connected in parallel, the taps must have an interlocking system which is active only in parallel operation. The interlocking has to

prevent different tap positions on the paralleled transformers giving rise to an excessive reactive current which could damage the transformers.

The interlocking system operates via otherwise inactive contacts which are allocated to the operating mechanisms of the tap changers.

If in parallel operation the tap positions become different (fault), an alarm is send to the station level.

Today mostly the transformers are equipped with automatic voltage regulation, see Fig. 14-14, and the tap interlocking system is not needed anymore. In parallel operation, however, a function is necessary, which individually corrects the taps to minimize the reactive current circulating between the transformers. This function allows to operate transformers with differently set taps or minor inherent impedance differences in parallel. Principally however, parallel transformers should be as similar as possible.

The controller of only one transformer, the "master" transformer, should be active when running in parallel. This master controller, defined by some selection means determines then the tap settings of all the transformers connected in parallel.

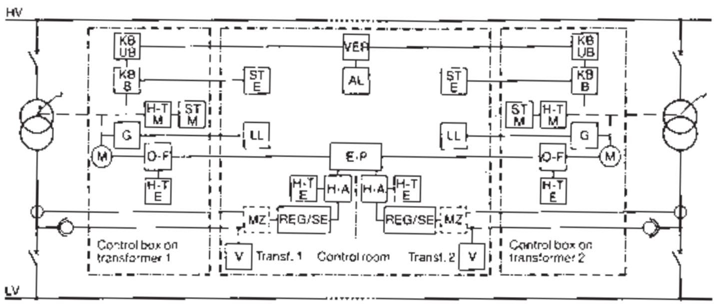

Fig. 14-14

Basic diagram of local / station / automatic parallel tap changer control

H-T M	*higher-lower, mechanical*
ST M	*selected tapping shown, mechanical*
O-F	*selector switch local-remote*
H-T E	*higher-lower, electrical*
M	*drive motor*
KB B	*contact strip, active*
KB UB	*contact strip, inactive*
ST E	*selected tapping shown, electrical*
V	*voltmeter*
G	*contact transmittler*
LL	*running light*
MZ	*measurement unit*
REG/SE	*automatic voltage regulator and setpoint adjuster*
H-A	*selector switch, manual-auto*
E-P	*selector switch single parallel and master selector*
VER	*tapping interlock*
AL	*tapping discrepancy alarm*

4. *Automatic control*

The following summarizes the migration from conventional to numerical technology from the view point of the automatic transformer control.

Voltage regulation by means of tap changers is – as already mentioned above – mostly done automatically. The appropriate numerical device contains in its software all necessary functions like voltage regulation, set point adjustment, load-dependent set point adaptation, and for long lines compensation of the appearing voltage drop. The following operation modes are considered:

– parallel busbar operation,
– parallel network operation,
– networks with widely varying active and reactive power components.

The automatic voltage control system is connected to voltage and current transformers at the voltage level that needs to be held constant. A switching into manual tap changer control mode is possible.

14.3.11 Station control rooms

The equipment in the control room of the substation provides control and supervision of the complete substation at one point. Besides technical performance, the design must also take into account ergonomic aspects such as clear arrangement, ease of access, proper lighting, freedom from glare, acoustic properties, climate and comfort.

In case of computerized distributed substation automation systems the control room essentially contains a station computer (single or redundant) with one or two, seldom up to four screens with key board, mouse, and a printer. The requested substation-proof industrial PC and the station level components of the communication system can be comfortably put into a cubicle beneath or even below the operator's desk. If stations are normally manned, there may be several operator work stations and separate screens with overview pictures.

Especially in the highly industrialized countries the substations are mostly unmanned, and, therefore the control room shrinks to a PC based operator's work place and a gateway to the network control center.

14.4 Substation control with microprocessors

14.4.1 Outline

Substation automation systems using microprocessors and serial data communication perform all the functions of the secondary systems in transformer and switching substations as described above, i.e.

switchgear control, interlocking, measurement, automatic feedback control, indication, signaling, protection (feeders and busbar) and operational metering etc., today with exception of revenue metering (see section 14.3.7).

But computer-aided systems offer more:

process diagnostics, functions for the automation of autonomous substations, facilitation of the general task of power system management by preprocessing.

Essential feature of this new technology is its self-diagnostic capability, which has operational and maintenance benefits for the user, even if he decides against the other new possibilities available.

Summarizing, the new technology offers
– fast fault recognition
– simple physical system structure
– high operational safety,

resulting in a significant improvement of substation availability.

14.4.2 Microprocessor and conventional secondary systems compared

With conventional secondary systems, the various functions considered in section 14.3 are performed by separate devices (discrete components) which mostly work on hardwired and analogue principles and represent different technologies.
The resulting situation is as follows:

– Each task is performed by devices using different technologies (electromechanical, electronic, solid-state or microprocessor-based).
– These discrete devices may require many different auxiliary voltages and power supply concepts.
– The connections between the devices and with the switchgear require a great deal of wiring or cabling and means of matching.
– The data from the switchyard equipment has to be supplied several times, i.e. dedicated for the inputs of protection, control, interlocking etc., making the supervision of interfaces difficult .
– Checking the performance of the individual devices is accompanied by complex verification of the overall performance.

With the new automation technology for substations, the focus is on the system and its function as a whole.
Numerical methods are employed for process-near functions using programmable modules based on microprocessors.
The distinguishing features of the new automation technology are:

– Use of the same microprocessor-based platform for the implementation of all functions, either single or in many combinations.

- Standardized power supply and common supply concept facilitating the system layout.
- Serial data transfer (bus technique) minimizing wiring.
- Fiber optic cables are used in the substation reducing the cost of established adequate electromagnetic compatibility.
- Multiple use of the data from the switchgear.
- Self-diagnosis with continuous function check reducing the periodic testing of overall system and subsystems.
- No dedicated effort for recording events in the correct time order with a resolution of about 1 ms.
- Reduced space requirements.

Another major innovation of the new approach is the screen based human-machine interface (HMI). While the access interface to conventional secondary technology is focused on switch or mimic control panels with switches, buttons, lamps and analogue instrumentation, access to the new automation systems is usually given by a display at bay level and by screen-based operator places all with a keyboard and a mouse. This is valid both for the station level in the substation and the network control level. Operation is mostly application near and menu-guided, no programming or computer skills are necessary.

14.4.3 Structure of computerized control systems

A substation can be divided broadly into bay (feeder) level parts (feeders, buscouplers, sectionalizers and earthing system) with the following secondary functions allocated if applicable:

- Control, supervision, interlocking
- Transformer control and earthing (Petersen) coil regulation
- Bay-level automatic functions
- Indication acquisition and processing
- Measurement acquisition and processing
- Local (bay) control
- Autonomous bay protection

and a station-level part with substation-wide functions such as:

- Local (station level) control
- Communication links e.g. to the network control center
- Connection to auxiliary systems
- Station level functions like alarm and event handling, and archiving
- Busbar protection.

Therefore, the logical structure of the substation automation system has two hierarchical levels also:

The bay level with the bay units (BU) and the station level with one or more station unit (SU), see Fig. 14-26. If data is already digitized directly within the primary equipment and serially communicated like position indications and commands or trips , then even the third level, the process level, gets physical visible also. Therefore the communication standard IEC 61850 foresees three general kinds of function blocks: process connection (data acquisition & actuation) at process level, operation at station level, and the ‘real’ function e.g. at bay level.

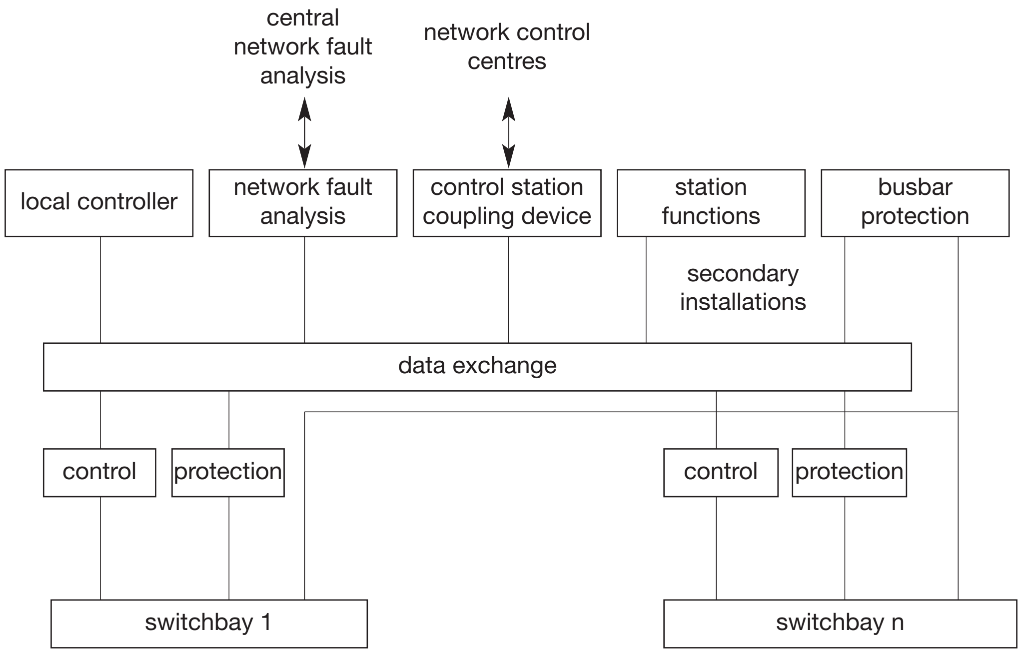

Fig. 14-15
Logical structure of computerized substation control

On the process side of the control system, the bay units are assigned accordingly to the process (bays, feeders). The result is that between every bay and the associated bay unit(s) either a parallel connection, i.e. a direct wiring between bay switchgear and bay unit is established for every data point such as position indicators and encoders for analogue values, or a serial connection , i.e. the data is linked to the bay unit by actuators and sensors over a process bus.

The functions performed in the bay units are basically those, which require data from their associated bay only (e.g. line protection, bay interlocking) and for which short functional loops are preferable.

The functions in the station unit(s), are those which need data from the whole substation (e.g. busbar protection, priority treatment of alarms, indication of busbar voltage), or have a central function (connection to network control center, time receiver, central operator place).

Serial links are used throughout for transferring data between bay and station units.

These serial links are normally busses, which allow all connected IEDs to communicate with all others. The physical connection can be stars, trees or rings. The star can be seen as a shrunken tree, having only the tree root.

The communication standard IEC 61850 introduces a local area network (LAN) , where all connected devices have the same communication rights or roles. Normally the station unit and the gateway to the network control centre are connected to different physical points within the LAN. The exact physical architecture of the communication system depends beneath the requested availability and performance also on the distances between the different connected parts, and the physical environment, inclusive possible electromagnetic interferences.

For large distances and unscreened regions normally optical fibers are used as physical connections (see also 14.4.4). A simplified rule for design and implementation of the physical communication system is: connections within screened cubicles may be electrical; outside cubicles optical fibers have to be used.

The bay units are built up from modular components, possibly as combined bay control and protection units. The number of modules used depends on the required quantity of functions, the desired structure and specified aspects of system quality, such as availability. However, for safety reasons, in the high-voltage area beyond 72 kV the protection components are generally designed to operate independently of the other components of that bay unit.

The self-contained protection devices are all realized today in numerical technology, even from different manufacturers or different device generations. At transmission level the line protection normally is doubled, and requested from different manufacturers to avoid the impact of hidden systematic failures. IEC 61850 allows without problems to integrate protection devices from different manufacturers communication-wise into one system. It replaces thus the IEC 60870-5-103 interface as standard for serial integration of protection devices, which does not support all protection functions in a standardized way and is restricted to master-slave communication with a single master. Therefore, the protection devices can not communicate directly with each other , just if asked by the single master. As pure information interface this might be sufficient, however it does not allow protection concepts with autonomous communication (see 14.2.7), which need a real time communication interface as offered by IEC 61850.

14.4.4 Fibre-optic cables

In modern station control systems, the links between the individual components usually carry information serially. Fibre-optic cables are used for these serial connections, at least outside the cubicles as mentioned above.

Properties and principle

Fibre-optic cables (FOC) are composed of fibers made by glass or plastic having the property of total reflection allowing the transmission of light over long distances.

They have a core with a high refractive index surrounded by a cladding with a low refractive index and a mechanical protective coating (primary coating). The light is conducted by the core subjected to certain boundary conditions. Generally, light-emitting diodes (LEDs) serve as the light source, but laser diodes are also used in special cases. Fig. 14-17 shows an optical transmission link.

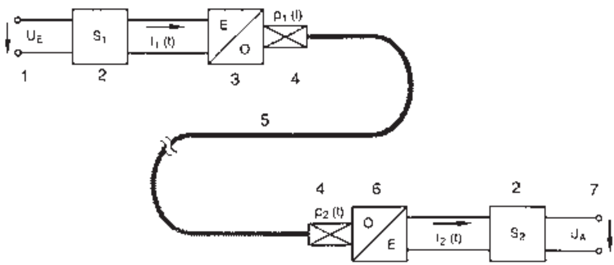

Fig. 14-16

Optical transmission technology with fiber optic cable, 1 Input, 2 Signal conditioning, 3 Electro-optical converter, 4 Connector, 5 Fiber optic cable, 6 Opto-electrical transducer, 7 Output

A very important feature regarding the application of optical cables in substation automation systems is their complete immunity to electromagnetic interference and the absence of any problems with earthing and equipotential bonding.

Other important advantages are their large transmission bandwidth, low signal attenuation (regardless of transmission speed) and ease of handling. Fiber optic cables are thin and flexible, and can be bent to relatively small radii.

Glass fibers differ from plastic fibers mainly in that their attenuation is significantly lower, so the cables can be much longer, normally up to nearly 2000m without any additional measures. Further, they have a longer life-time than plastic fibers. Therefore within switch yards normally glass fibers are used.

Another criterion for optical fiber selection is the way how the light is distributed internally. Within multi-mode fibers the light is distributed in several modes, which then have parallel attenuation. This allows distances up to 2000 m, what is normally sufficient for communication within substations. With mono-mode fibers however distances up to 100 km can be bridges without amplifier in between. It should be noted that also the wave length of the light is important for the reachable distances. Regarding a standardized connection of devices as according to IEC 61850, the fiber optical communication system has to fulfill some common requirements also.

14.4.5 IEC 61850 – the communication standard within electrical substations

Each new substation automation system should use IEC 61850 – mentioned already many times above - as its communication protocol. This only globally recognized communication standard is based on Ethernet, allows direct communication between any of the connected devices, and supports communication within the system hierarchy levels as well as between the hierarchy levels, as well as process near applications. To guarantee real time performance, classical Ethernet busses have not to be used, but only switched Ethernet networks. Further the priority handling and VLAN features as defined in the Ethernet standard have to be supported by the switches. For availability reasons the networks are mostly ring based instead of tree based. The point – point connection between devices can be electrical for short distances within a screened environment, otherwise optical as described already above.

IEC 61850 offers much more than just a communication protocol to connect devices of different manufacturers. Its uniform data model with standardized semantics and the standardized description of substation automation configurations including their functional connection to the switchyard (Substation Configuration description Language) supports uniform maintenance of all secondary devices, provides long life time of engineering data within a system configuration, supports the exchange of engineering data between the engineering tools of different manufacturers, und reduces the effort for engineering and maintenance.

Because of its flexibility and comprehensive features there are further standardization efforts going on to use IEC 61850 also for communication to the network control centre and between protection devices in different substations. Data model extensions for hydro power plants and distributed energy resources are in work also.

A good overview about IEC 61850 is given by the etz-Report 34 "Offene Kommunikation nach IEC 61850 für die Schutz- und Stationsleittechnik", however just in German. A shortened English version can be found in Praxis Profiline, July 2005, IEC 61850, "Basics and user-oriented project-examples for the IEC 61850 series for substation automation".

The parts of the standard are the following:

Common title for all parts: Communication networks and systems in substations

Part 1: Introduction and overview
Part 2: Glossary
Part 3: General requirements
Part 4: System and project management
Part 5: Communication requirements for functions and device models
Part 6: Configuration description language for communication in electrical substations related to IEDs.

Part 7-1: Basic communication structure for substation and feeder equipment – Principles and models
Part 7-2: Basic communication structure for substation and feeder equipment – Abstract communication system interface (ACSI)
Part 7-3: Basic communication structure for substation and feeder equipment – Common data classes
Part 7-4: Basic communication structure for substation and feeder equipment – Compatible logical node classes and data classes
Part 8-1: Specific communication service mapping (SCSM) – Mappings to MMS (ISO/IEC 9506-1 and 9506-2) and to ISO/IEC 8802-3
Part 9-1: Specific communication service mapping (SCSM) – Sampled values over serial unidirectional multidrop point to point link
Part 9-2: Specific communication service mapping (SCSM) – Sampled values over ISO/IEC 8802-3
Part 10: Conformance testing

14.5 Network control and telecontrol

14.5.1 Functions of network control systems

The purpose of network control systems is to operate transmission and distribution networks economically and reliably with the help of data processing and information technology. The principal aim under normal conditions is to minimize overheads and capital costs by optimizing the utilization of the equipment, and, under fault conditions, to secure the supply of power at all points of the network and restore the situation to normal with interruption times kept to a minimum.

This must hold also for the highly dynamic requirements of energy trading in the deregulated market, and must support this.

In order to achieve this, the status of the (usually extensive and closely intermeshed) network regarding topology, voltage and load must be known at all times. Abnormal values must be instantly detected and signaled, and countermeasures taken. As supply systems become ever more complex, this is done at control centers which are fed by telecontrol links with all the information from the substations (switchgear) necessary for appraising the network's status and controlling it.

Initially, all functions were centralized in the control station. However, the increasing volume of information soon resulted in a shortage of processing capacity. The current trend is to decentralize most individual tasks at the point where they occur by implementing intelligent telecontrol stations (RTUs) or, more powerful, substation automation systems and to forward only the compressed information essential for centralized control of the overall network.

The exact tasks to be performed by the network control systems depend on the type and size of the network, on the installed power equipment, and on the operational strategy adopted by the network operator (utility).

In supraregional networks, the electric energy is transported from the power stations to the load centres at voltages of 220 kV and 380 kV, or higher. This transmission network in turn supplies the distribution systems, operating at 110 kV, 60 kV, 20 kV, 10 kV and also other voltages, which carry the electric energy at regional level from the interconnected network to the consumers.

The entire control and supervision of the machinery and equipment in the power plant itself, such as turbines and generators, is the dedicated task of power plant control and, therefore, not considered further here.

The application of network control begins with transmission of the electricity. For this, a load-dispatching centre controls the output of the power plants and the flow of power in the grid to meet the demand at any moment, based on equivalent load curves from previous periods and according to mutual agreements with other electrical utilities and large customers, and together with various other parameters, in order to provide the most economical and secure service.

Network control centers monitor and control the switch position and the loading of switchgear and lines in the transmission and distribution systems. When faults occur, it is possible with the help of the high-speed data processing to obtain immediately an up-to-date picture of the network's general status and the situation at the site of the fault. Based on this all needed actions can be performed in a secure way..

At the lowest distribution level, the supply of all forms of energy, i.e. gas, water, district heat, etc. as well as electricity, may be controlled from one single multi-purpose control center if applicable.

The exact performance required from such a control and management system determines the equipment needed in the control centre. Today this consists almost exclusively of computer systems with distributed functionality, and with color screens displaying the network and its status. Because of the continuous increase of the information to be processed in the control centers, it would no longer be possible for the operators to monitor and control the system without the help of advanced information technology. Process computers take over routine tasks from operators and quickly and safely prepare the data for processing. In addition, control rooms may be equipped also with control panels or large displays with cumulative information for emergency operation.

The different internal data processing and information systems in many utilities are interconnected by company-owned data networks. This offers the option of using operational information from the network control system also for planning tasks, e.g. for network and maintenance planning, and for management decisions. Alternatively, this information can be fetched directly from the substation automation system by means of the IEC 61850 communication protocol, if optical connections with sufficiently high data throughput are available.

Practical experience shows that the design of a new network control system requires close cooperation between operator and supplier so that the individual functional parts of the system, such as data acquisition, transmission and processing, can be ideally matched to each other and to the tasks to be performed.

14.5.2 Telecontrol and telecontrol systems

Along with data processing, telecontrol plays a vital role in central power system management. Its purpose is the economical and reliable transmission of data (such as switching and adjustment commands, signals and measurements) between the decentralized substations and the centralized network control system.

At the transmitting side of a telecontrol system, the relevant information is prepared for transmission, i.e. it is coded and secured with additional redundancy so that errors due to disturbances along the transmission path can be detected at immediately and unwanted outputs are prevented. At the receiving side, the incoming information is decoded, checked and, if free from errors, handed over as a command, signal or measured value to the process modules or to the master computer.

The growing size and complexity of power systems and the increased volume of information has requested an appropriate structuring of the telecontrol network. In case of small control centers with few substations, all substations can still be connected directly to the control center by dedicated telecontrol links, either point-to-point (the control centre communicates only with one substation over each link) or according to the multi-point principle (the control centre interrogates a number of substations one after the other over the same link for new information). For medium or large network management systems with many or distant substations, however, a hierarchically structured telecontrol network is unavoidable because of the usually limited number of available communications channels and also for the relieve of the control center. In this case, the information from several substations, for instance, can be collected, combined and compressed in so-called concentrator stations.

Choosing the most suitable telecontrol system depends on its required functionality and performance. The main criteria are the volume of information and up-to-date time requested. Equally important is the incorporation into the hierarchy of the overall control system.

The most important telecontrol terms can be found in "International electrotechnical dictionary – Chapter 371: Telecontrol" as IEC publication IEC 60050 (371) (1984), incorporated in Germany as IEV 371 (1989), and in the associated change 1 as supplement IEC 60050 (371) dated 1997.

Interesting for this subject is also "Begriffe der Fernwirktechnik", published as ntz-report No. 26 by VDE-Verlag GmbH, Berlin-Offenbach 1991, containing all definitions in English and German.

The IEC's TC 57 has drawn up a number of standards on telecontrol and published them as IEC 60870. The results have been taken over in the European standard EN 60870, and in the German DIN 19244. The important part for telecontrol have been published as IEC 60870-5 (international), EN 60870-5 (European) or the DIN EN 60870-5 (German) standards series under the title "Telecontrol equipment and systems, Part 5 – Transmission protocols". The individual parts describe and define the following subjects:

Part -5-1: Transmission frame formats

Part -5-2: Link transmission procedures

Part -5-3: Structure of application data

Part -5-4: Definition/coding of elements

Part -5-5: Basic application functions

Especially important for telecontrol is the part IEC 60870-5-101 "Companion standard for basic telecontrol tasks"

(1993) or EN 60870-5-101 "Application-based standard for fundamental telecontrol tasks" (1996) is particularly interesting and important for telecontrol. This standard is intended to lead to a unification of the transmission protocols of various manufacturers of telecontrol systems and to make it easier to combine different telecontrol systems in the same network control system. The standard IEC 60870-5-101 is very common in existing or new telecontrol systems.

The usual transmission speeds employed for telecontrol are between 50 and 1200 Bd (baud)1). In large network control systems and in special application cases, e.g. where system protection information with very short reaction time is transmitted, transmission speeds of 2400, 4800, 9600 and even 19200 Bd are also standard if permitted by the available transmission channels.

With the advent of optical fibers for long distances, e.g. integrated into the earthing rope of a line, much higher transmission speeds are possible. In this case the following standards apply: IEC 60870-6 for communication between network control centers, IEC 60870-5-104 and nowadays IEC 61850 for communication from the substation to the network control center. All these protocols are based on the TCP/IP network and transport protocol, so that the telecontrol network can be built with commercially available components for Internet technology. If public networks are used additionally, e.g. as redundant channels, then naturally all the security problems known from the Internet have also to be dealt with.

Even if this higher transmission speed exists, the following tasks for communication gateways and nodes are still relevant:

- information condensing
- data flow reduction by means of information connection
- information distribution to several control centers and substation automation systems
- means for (local) emergency operations.

14.5.3 Transmission techniques

Communications links are required for transmitting the telecontrol signals between the control centers and the various stations of the telecontrol network located normally in substations. The nature and capacity of these links also determine the maximum speed of transmission of the signals.

Audio-frequency (AF) transmission by means of voice-frequency telegraphy (VFT) or modem over the following paths is generally preferred:

- Telecommunication lines or cables with copper wire or fiber-optic conductors,
- PLC links (power-line carrier transmission over high-voltage lines),
- VHF and radio relay links.

Note that links with high bandwidth (64 kBits/s and more) need modulation frequencies and methods far beyond AF.

Direct-current data transmission is also used for short distances (≤ 10 km), in this case usually with only low transmission speeds.

The communication channels are either owned by the system operator (utility) or rented from a telecom company. Typical examples of transmission links belonging to the utility are telecommunication cables in the form of buried or aerial lines running in parallel with high-voltage cables or overhead power lines. Aerial cables are divided into autonomous cables, earth-conductor cables and phase cables.

[1] 1 baud = 1 digital pulse per second

Other examples are multi-channel microwave links, mainly at transmission level and PLC communication using the owned power lines themselves.

If no telecontrol transmission links are owned by the utility, data links can be leased from a telecom company. Note that telecom links (especially current paths) should not be interconnected with utility owned links.. Interfaces between both systems should be carefully designed based on a stringent concept.

With the establishment of communication systems with high bandwidth by the utilities themselves optical fibers will replace more and more all other technologies.

For Germany, the most important provisions and recommendations for the transmission paths are presented together in Volume 1, Chap. 1.1 of the VDEW recommendations. This includes the provisions of VDE 0800 (telecommunications), VDE 0228 (influence by power systems), VDE 0816 and DIN VDE 0818 (for cables), VDE 0850 or EN 60495 and VDE 0851 (for TFH (power line telephony)) and VDE 0888 or EN 187000 (fiber optics for telecommunications).

14.5.4 Technical conditions for telecontrol systems and interfaces with substations

Volume 1 of the manual "Netzleitsysteme in Elektrizitätsversorgungsunternehmen

(EVU)" (Network control systems in electrical utilities) contains recommendations regarding the technical conditions that telecontrol systems have to fulfill. The different interfaces, e.g. to the substations, and the requirements for power supplies are described also.. There exist various international standards concerned with this subject as IEC 60870-1- 1 and IEC 60870-1-3. The following principal conditions for interfacing with the switchgear are also taken from these documents.

Interface secondary system/substation

This interface carries information passing between the secondary system equipment (process interface external or internal to the bay unit of the substation automation system or to the remote terminal unit (RTU) if applicable) and the primary devices in the substation. For the conventional, microprocessor controlled equipment, there are the following 4 kinds of data input/output:

– digital inputs,

– analogue inputs,

– digital outputs,

– analogue outputs.

The classes for noise-voltage limit values and insulation requirements are shown in Tables 14-2 and 14-3. The choice of class depends on the characteristics of the switchgear.

Table 14-2

Noise-voltage limit values and insulation requirements for binary signals

	Transverse voltage	Longitudinal voltage
Operating limits	10 % power frequency volt. peak / peak referred to U_N 0.2 kV H.F. (1) 0.3 kV IMP (1)	 25 V AC 65 V DC 0.3 kV H.F. (1) 0.5 kV IMP (1)
Destruction limits class 1	+ 200 % U_N DC (2) – 125 % U_N DC (2) 200 % U_N A. (2) 0.3 kV H.F. (1) 0.5 kV IMP (1)	 0.5 kV N.F. (1) 0.5 kV H.F. (1) 1.0 kV IMP (1)
Destruction limits class 2 for telecontrol equipment with series EMI barrier	+ 200 % U_N DC (2) – 125 % U_N DC (2) 200 % U_N AC (2) 0.5 kV H.F. (1) 1.0 kV IMP (1)	 0.5 kV N.F. (1) 1.0 kV H.F. (1) 2.5 kV IMP (1)
Destruction limits class 3 for telecontrol equipment connected direct to the switchgear	+ 200 % U_N DC (2) – 125 % U_N DC (2) 200 % U_N AC (2) 1.0 kV H.F. (1) 25 kV IMP (1)	 2.5 kV N.F. (1) 2.5 kV H.F. (1) 5.0 kV IMP (1)
Insulation between inputs and/or outputs and/or earths		(a) min 1 MΩ at 500 V AC (3) (b) min 10 MΩ at 500 V AC (3) (c) min 100 MΩ at 500 V AC (3)

Notes:

(1) N.F. = System frequency (usually 50/60 Hz)
H.F. = Damped high-frequency oscillation, see IEC 60255-4
IMP = High-voltage pulse

(2) The equipment must withstand this voltage for 1 min without harm.

(3) Insulation class (a) is for normal applications. Insulation classes (b) and (c) may be used in special cases.

Table 14-9

Noise-voltage limit values and insulation requirements for analogue signals

	Transverse voltage	Longitudinal voltage
Destruction limits class 1	± 50 mA DC (2) ± 24 V DC (2) 0.2 kV H.F. (1) 0.3 kV IMP (1)	25 V AC 65 V DC 1.0 kV H.F. (1) 2.0 kV IMP (1)
Destruction limits class 2 for telecontrol equipment with series EMI barrier (4)	± 50 mA DC (2) ± 24 V DC (2) 0.5 kV H.F. (1) 1.0 kV IMP (1)	± 0.5 kV DC 0.5 kV N.F. (1) 1.0 kV H.F. (1) 2.0 kV IMP (1)
Insulation between inputs and/or outputs and/or earth		(a) min 1 MΩ at 500 V AC (3) (b) min 10 MΩ at 500 V AC (3) (c) min 100 MΩ at 500 V AC (3)

Notes:

(1) N.F. = System frequency (usually 50/60 Hz)
H.F. = Damped high-frequency oscillation, see IEC 60255-4
IMP = High-voltage pulse

(2) The equipment must withstand this voltage for 1 min without harm.

(3) Insulation class (a) is for normal applications. Insulation classes (b) and (c) may be used in special cases.

(4) The values for class 3 in Table 14-8 apply here if telecontrol equipment is connected direct to control devices at the switchgear.

General conditions for substations

In substations, all the circuit-breakers and disconnectors to be remotely controlled must have a power operating mechanism and, if no process bus interface is existing, a potential-free make and break contact for indicating status. Transformers, arc-suppression and charging-current shunt coils must be provided with additional potential-free contacts to indicate step position and running status. All annunicator relays working together with telecontrol devices must have a potential-free normally open (NO) contact. To detect new changes of state the annunciator contacts must be closed only while the coil is energized. Relays isolating against external interference must be mounted close to the telecontrol equipment. Today the isolation may be performed by opto-couplers only. For measurement, these devices are directly connected to current- and voltage transformers if applicable.

As part of the power equipment, all these interface devices must conform to the relevant IEC standards, for instance IEC 60364, and all interface electronic to IEC 61010.

Commands

Commands to switching devices and transformers or step controlled Petersen coils are transmitted by the appropriate bay units via digital outputs as two-phase pulsed commands of ≤ 220 V DC lasting 100 to 500 ms. Single-phase and one-and-a-half-

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phase output arrangements should be fitted with a switching monitor in the process-close circuit. The operation or running time of all switching devices (breakers, isolators, earthing switches) should to be supervised by the bay control units.

Plunge core are operated by the allocated control units either continuously or stepwise .

With a local/remote switch it must be possible to block commands from remote for any switchyard device e.g. to provide secure maintenance. This blocking has to be possible for any single switching object or for groups of such objects.

Indications

Indications are acquired individually via digital inputs to the allocated device. Normally, these inputs are galvanically separated by means of opto-couplers, whereas the annunciator contacts can be grouped with a common root. For switchgear both positions must be acquired and combined to a double-point indication. These two signals are usually obtained from a changeover contact or a normally closed (NC) and a normally open (NO) contact. Also for isolators that move slowly, the acquisition and transmission of the intermediate position should not be suppressed. by the telecontrol system. Signals indicating trips should, wherever possible, be generated locally in each bay.

The signals can be continuous, of short duration or as transient signals with times of $\geq$ 1 ms. The used signal voltage should principally be the battery voltage of 110 V or 220 V DC, which is compatible with all bay units. For dedicated telecontrol equipment like RTUs, other voltages might be needed.

Measured values

The process interfaces in the digital (numerical) units of substation automation systems take voltages and currents directly from the instrument transformers. Dedicated telecontrol systems might need additional interposing transformers. By the communication system in the substation and the telecontrol gateway all measured data may also be used for remote measuring.

The inputs of bay units or other electronic process interfaces have to be protected properly against overvoltages.

The entire measurement and transmission chain, from switchyard to control centre, should conform at least to accuracy class 1.

Meter readings

If the metering is not already integrated into the secondary system, metered values are fed to the secondary system as counter pulses or coded counter totals. The counting devices (primary coders) usually have 6 decades and BCD coding at the output. For these counters potential-free inputs are required, which is normally provided by opto-couplers at the binary inputs.

Connecting conductors

Only insulated wires and cables have to be used to connect the devices of the secondary system with the switchyard components. Cables with conductors whose insulation is not moisture-proof have to be suitably sealed at the ends if necessary. The wires and cables are best installed in underfloor gulleys or on trays or racks. If no gulley is available, the wiring to the apparatus must be protected by cable channels, cable ducts, or similar. To avoid interference from high-frequency noise created e.g. by switching operations, all relevant cables have to be screened and grounded properly. Earthing wires and cable screens must be connected by low-impedance (also for high frequencies) connectors to rails linked to the protective earth conductor.

Power supply, premises

The devices of the secondary system are usually connected to a secure power supply so that data can still be sent if the power in the power system (switchyard) installation fails. This is generally the 110 V or 220 V station battery, and a secure 220 V AC supply for computers and display screens.

In addition to electrical requirements, the premises in which telecontrol systems are installed and operated must also fulfill certain conditions.

The bay units and process near equipment must fulfill the usual requirements for numerical protection devices. For station level equipment the premises must be dry with room temperature between 0 °C and + 55 °C, in large substations + 5 °C to + 40 °C. Generally the telecontrol equipment and substation automation equipment shall be able to operate without air-conditioning, may be with exception of some station level equipment like station HMI computers.

14.6 Load management and ripple control

Ripple-control techniques enable power suppliers (utilities) to control their sometimes widely dispersed consumers from a central point. The main objective of this technique is load management, i.e. the utility is influencing the consumption of electric energy by connecting and disconnecting suitable objects such as storage heaters, hot water heaters, heat pumps etc.

Fig. 14-17 shows the uncontrolled load pattern between midnight and 3 p.m., the lines representing quarter-hourly averages.

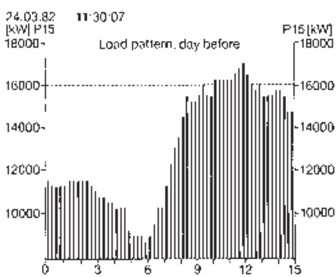

Fig. 14-17

Load pattern between midnight and 3 p.m., shown as quarter-hourly averages

Electric energy consumption throughout the day can be made more even by connecting consumers when load is low- afternoons and at night – and disconnecting them at peak times – mornings, evenings. By these measures, power stations and transmission/distribution networks are loaded more uniformly. Depending on the network management policy, the system, comprising the load management center, ripple-control equipment (transmitter and coupling) and ripple-control receiver can be operated on either the open- or closed-loop principle.

In the first case, the consumers are switched on and off according to a fixed timetable.

In the second case, the allocated computer also measures the effective network load, calculates the trend in order to establish, in relation to a set value, the necessity for connections or disconnections, and chooses the consumers to be affected by any correction required. The system thus functions like a digital feedback circuit.

Although the main objective is load management, the power utilities also use ripple control for other purposes, e.g. tariff control (peak rate, off-peak, special rates, etc.), control of street lighting, neon signs or building illumination, and in special cases also fire and other alarms, and for operating switchgear where there are no telecontrol links.

15 Secondary Installations

15.1 Stand-by power systems

15.1.1 Overview

Stand-by power systems supply power to electrical equipment if the supply from the public distribution system is interrupted by faults or if a direct supply does not seem feasible for technical or business reasons.

The following grouping is based in the different requirements:

– emergency power systems,
– auxiliary power systems,
– frequency converters.

Table 15-1
Application for stand-by power systems

User group		Equipment with secure supply
public and commercial buildings	public assembly areas, shop and office buildings, banks, insurance companies, control centres.	emergency lighting as per DIN VDE0108
public and commercial buildings	high-rise buildings, hotels, government and administration buildings, conference centres, institutions, laboratories.	security, monitoring and power supply systems.
public and commercial buildings	hospitals	as per DIN VDE 0100-710 and 0108, special regulations, AV SV and ZSV network for security, monitoring and power supply systems, operating room lighting.
public and commercial buildings	warehouses and refrigerated storage	cooling units, security systems.
public and commercial buildings	communications centres, data processing centres.	data processing systems, air-conditioning systems.
traffic	airports, air traffic control	control centres, runway, tower and emergency lighting, radio and radar systems, data processing systems, aircraft on-board systems (400 Hz) for ground power.
traffic	railway stations	control centres, emergency lighting, monitoring and signalling systems.
traffic	road tunnels, highway intersections	lighting, ventilation, monitoring and signalling systems

(continued)

Table 15-1 (continued)

Applications of stand-by power systems

User group		Equipment with secure supply
telecommunications and energy transmission	radio systems and telecommunications exchanges, relay stations, energy auxiliary equipment supply substations	telecommunications devices and installations, telecontrol systems, monitoring and power equipment
industry	manufacturing and functional processes	safety, monitoring and power supply installations, process computers, automation.

15.1.2 Stand-by power with generator systems

Generators with diesel engines are preferred for providing stand-by power to consumers for which there is sufficient time for starting a power generator; see ISO 8528.

The generator sets are used to generate power for

- emergency power supply installations that supply the regular consumers in the event of failure of the regular power supply,
- peak load operation to cover daily demand peaks,
- auxiliary supply of cogenerating systems with heat or current-controlled operation,
- installations in continuous operation without an adequate power supply system.

Diesel engines are most frequently used for emergency power systems. Units with an output above 100 kW are normally supplied with turbo charger only. High-speed machines with a rated speed of 1500 min^{-1} are mostly used. As well as better power-to-weight ratio, this allows better adaptation to synchronous generators of the standard type (4-pole design). However,diesel engines with turbo charger do have the disadvantage that they cannot produce their rated output in one stage.

The power generators used may be asynchronous generators (economical) or for installations of higher output, they can be alternators. The most common alternators have a brushless design. A built-in self-excited three-phase stationary-pole exciter with rotating diodes supplies the rotor current. The voltage is regulated in the three-phase exciter field. If fast compensation of the generator voltage is required, self-excited compound generators (constant-voltage generators) are to be preferred. Electronic voltage controllers are equivalent to the compound regulators.

The demands on the power supply of the consumers depend on the application. The operational response of the generator set must be able to meet the consumer's requirements. The following types are classified according to the application:

Type 1, low demands on the voltage and frequency response

Type 2, voltage response generally conforming to that of the public system

Type 3, increased demands on the voltage and frequency response

Type 4, maximum demands on the voltage and frequency response

The sets must be selected depending on the type. When rating the power of the generator, the connected loads of all power consumers must be determined, taking into account the simultaneity factor and the largest consumer that is to be connected. The connected load should be 60%-70% of the rated generator set output to ensure sufficient reserve power for reactive power requirements and switching operations. If 6-pulse three-phase rectifiers are connected as consumers, the output of the set must be adequately rated because of the resulting harmonics (overdimensional). In addition to the intrinsic response of the diesel engine and generator caused by design characteristics, the size and type of the connected consumers have a decisive influence on the required generator power. So with turbocharged diesel engines, a base load already provides better frequency response (turbine pre-acceleration). Rotor damping, type of excitation and overexcitation capacity are the main influences on the maximum voltage dip for the generator.

Typical values for the speed and voltage response are specified in ISO 8528 Parts 1 to 6. Small generators (<10 kVA) are subject to ISO 8528 Part 8.

The machine room should be sufficiently large. Rooms that are too small make operation and maintenance difficult and the ventilation problem is often difficult to solve satisfactorily. The questions regarding setup with proper noise isolation and fuel storage are also important, as is the problem of putting the equipment into place and its accessibility once installed. There must be a 1 m wide space all around the set under all circumstances. The space required is also determined by other installations such as fuel tanks, sound absorbers, closed-circuit cooling, batteries and switching and control equipment; see also Section 4.7 Structural Requirements.

The core of the automatic controller for emergency generator sets is the “ABB neacontic automatic start/stop” with a programmable controller. It controls the following tasks:

“automatic” mode

- all-pole system voltage monitoring
- start command in the event of system fault (preferably time-delayed)
- starting procedure
- repeated start if applicable
- operational monitoring
- control of auxiliary equipment
- monitoring of generator voltage
- switching from network to generator operation (interlocked) or initialization of parallel circuit.
- detection of return of system availability
- delayed automatic return switching of consumers from generator to network operation with and without interrupting power supply.
- aftercooling
- shutdown
- cancellation of the shutdown procedure in the event of another system fault while the set is still running and immediate supply of power.

“manual” mode

- manual operation for startup and shutdown. Interlocked switchover from network and generator mode and back.

“test” mode

- test operation for checking all automatic processes (including transfer of power supply).
- test operation for checking all automatic processes (not including transfer of power supply).
- automatic transfer of power supply if the system fails during test mode operation.

“Off” mode

- all equipment operation blocked, e.g. for maintenance. The power supply to the consumers is not interrupted.

“EMERGENCY OFF” mode

- with mechanically interlocked “OFF” position
- stops in the event of danger to personnel or installation, regardless of the selected mode.

Fault monitoring operates at a higher level than all other operating modes and displays the fault message and shuts down the generator if required.

A generator operating in “automatic” mode can, depending on its size, take over supplying power after 10–15 s. Additional measures such as heating the room, preheating lubricant and coolant, assisted starting, compressed air starting and high-speed excitation can reduce this time to 5–10 s.

The automatic transfer synchronization ensures uninterruptible switchover of the consumers from the generator to the network and from the network to the generator.

Emergency power systems with several generators operating in parallel require an automatic synchronization device for parallel switching. Another option is starting synchronization. This involves several generator sets being simultaneously switched in parallel over busbars during starting. The consumers are separated from the busbars during this process.

The use of equipment for automatic effective and/or reactive power sharing enables the output to be distributed in accordance with the percentage ratio of the load capacity of the individual generator sets.

An additional device (cosφ controller) makes it possible to retain a setpoint for the desired power factor for parallel system operation.

15.1.3 Uninterruptible power supply with stand-by generating sets (rotating UPS installations)

Rotating UPS installations are characterized by a generator running continuously at its rated speed. Its output must be sufficient to supply power to all consumers dependent on an uninterruptible power supply. This also applies for the design of the associated mechanical generator sets.

Rotating UPS installations are classified for the possible override time as follows:

– converter and flywheel for short-term override (about 1 s),
– converter and storage battery for part-time override (to about 30 min.),
– converter and flywheel and coupled diesel machine for long-term override (practically unlimited).

Uninterruptible power systems

The classical design of an uninterruptible power set has the most important components, a diesel engine, an electromagnetic clutch, a flywheel, a three-phase asynchronous motor and a three-phase alternator, installed on a common base frame (Fig. 15-1a).

The asynchronous motor is connected to the public power supply and runs the generator with the flywheel. The consumers that require uninterrupted power are continuously supplied with power from the system through the three-phase converter. The diesel engine is uncoupled and not operating at this time. In the event of a system fault, the asynchronous motor is shut down; at the same time the magnetic clutch is closed and the diesel engine is started by the flywheel.

During the transition from the faulty network to emergency diesel operation, the flywheel alone supplies the driving force for the generator while simultaneously supplying the energy to start the diesel engine. The flywheel start brings the diesel engine to its working speed within 1 . . . 1.2 s. This virtually precludes a failed start.

While in the first standard design described a motor generator supplies the consumers that require protection, in many cases one single electrical machine (reversing machine) is sufficient. It uses the available system voltage to drive the flywheel as a synchronous motor and operates as a diesel generator in the event of a power failure. Fig. 15-1b illustrates the principle of an uninterruptible power system with a synchronous reversing machine.

See Figs. 15-1c) and 15-1d) for other options.

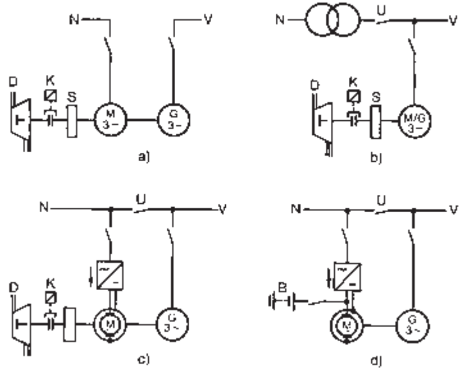

Fig.15-1

Basic design of uninterruptible power sets: a) with induction-synchronous generator set, flywheel and coupled emergency power diesel engine; b) with synchronous reversing machine, flywheel and coupled emergency power diesel engine, c) with direct current three-phase converter, flywheel and coupled emergency power diesel engine, d) with direct current-three-phase converter and storage battery separate from network; N network lead, U clutch, V consumer, S flywheel, B battery, K magnetic clutch,
D emergency power diesel engine

Fast-start power sets

Fast-start power sets are special emergency power systems with flywheels that can be used where short-time interruptions of approximately 250 ms are permissible. Their design is generally similar to the uninterruptible power set with converter set. The difference is that with the uninterruptible power set, the generator supplies power continuously to the consumers while the consumers connected to the fast-start power set receive their energy from the network.

The total cost of all rotating UPS installations (purchase, maintenance, operation) is high. For this reason, they are primarily used with high power requirements.

15.1.4 Uninterruptible power supply with static rectifiers (static UPS installations)

Uninterruptible power supply systems that operate with static rectifiers and storage batteries are increasingly being installed in many areas, particularly for small to medium output applications.

Operation

ABB UPS installations are based on a rotary converter. The UPS circuit diagram shows the six most important components (Fig. 15-2):

- rectifier/battery charger (6-pulse) (GR)
- battery (B)
- inverter (WR)
- static reversing switch (SW)
- static bypass (SB)
- maintenance bypass (WB)

All components are installed in one housing. The controller electronics for the rectifier, inverter and the bypass area are completely independent of one another. This means that a fault in one area cannot cause a fault in the adjacent area.

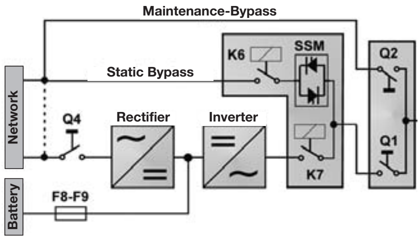

Fig.15-2

UPS circuit diagram

Features

UPS function

The **U**ninterruptible **P**ower **S**upply (UPS) is connected to the circuit between the power supply network and the power consumers (load). They are designed to guarantee a constant voltage supply for the load. If a network failure occurs, it can supply the load for a preset period (autonomous period). The UPS has also other advantages compared to conventional supply systems (network, engine-powered generators, etc.):

Better output characteristics

Monitoring the UPS output voltage and frequency guarantees constant output power. Variations in the system voltage and frequency, which are generally present in electrical power systems, do not influence the output voltage of the UPS.

Decoupling system distortions

The double conversion from AC to DC and back to AC filters out all system distortions. All UPS consumers are also fused for protection against power system faults, which can occur in industrial power supply systems. This is particularly important for sensitive electronic equipment such as computer systems, control systems and medicinal equipment.

Complete protection against power system faults

If the power supply system fails, the UPS supplies energy to the load from the battery. The battery is connected to the UPS rectifiers and inverters. The inverter supplies power to the load.

During standard operation, the inverter receives energy from the rectifier. The rectifier then charges the battery at the same time.

In the event of a power system fault, the connected battery automatically supplies power to the inverter. This means that the power supply to the load continues without interruption. However, the battery can only supply the load for a specified period (autonomy period). If longer periods of autonomy are required, it is worthwhile supplying the UPS with a diesel generator as an emergency power supply. In this case, the autonomy period is calculated for the period between network failure and full generator power.

Rectifier/battery charger

In the standard configuration, the charger is a 6-pulse three-phase rectifier. It converts the network AC voltage to DC voltage. It is normally connected directly to the power supply system via commutating reactors (no galvanic isolation). The commutating reactors reduce the system perturbations of the rectifier. The charger feeds the battery and the inverter. The battery is connected to the charger via a saturable reactor to reduce the residual ripple of the DC voltage. This ensures maximum battery life.

The rectifier is designed to supply the inverter and charge the battery with the maximum loading current simultaneously at maximum load. The floating charging voltage for standard batteries (maintenance-free lead battery) with 192 cells is kept constant at 432 V (2.25 V per cell). The battery is charged with I/U characteristic. This means that the charging current limit is reached by reducing the intermediate circuit voltage. This ensures that the battery is not damaged by excessive charging current. A 12-pulse rectifier is optional and requires the addition of a second rectifier bridge in the UPS cabinet and a phase-shifting transformer in a separate accessory cabinet.

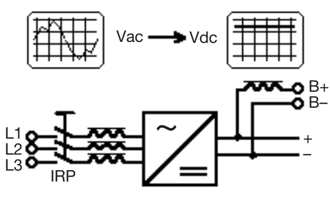

Fig.15-3

6-pulse
rectifier circuit diagram

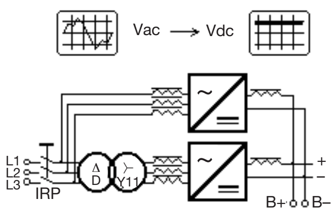

Fig.15-4

12-pulse
rectifier circuit diagram

Battery

The battery supplies the inverter in the event of a short interruption or a system failure. The battery is designed to continue to supply the load for a specified period (autonomy period) depending on the battery capacity and the actual load.

The number of cells in the battery depends on the type and also on the customer-specific requirements. The standard number is 192 cells for lead-acid and 300 cells for NiCd batteries. The battery capacity (Ah) depends on the UPS output and the required autonomy period.

Inverter

The inverter, which is supplied by the rectifier or the battery, converts the DC voltage fed from the rectifier or the battery into a.c. voltage with constant voltage and frequency, a form of power suitable for the power supply of highly sensitive electronic equipment.

Pulse duration modulation is used to generate the AC voltage. The output voltage (harmonic content < 1%) is smoothed by a high operating frequency of the power semiconductor and the use of an output filter (transformer and capacitors).

Every phase-to-earth voltage at the output of the inverter is regulated separately. This ensures that the UPS output voltages remain constant even under very non-symmetrical loads.

For protection of the inverter, the inverter electronics restrict the inverter output current to 150% of the rated current in the event of a short circuit. In the event of overload, it restricts the inverter output voltage to no more than 125 % of the rated power. If a serious overload occurs, it automatically switches to bypass mode, if the bypass is available.

Saturation monitoring or an “electronic fuse” protects the inverter transistors from destruction by short circuits.

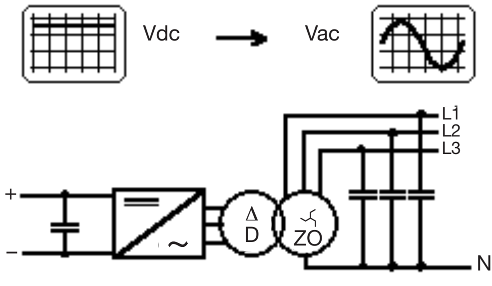

Fig. 15-5

Inverter circuit diagram

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Static switches

The circuit diagram shows the two static switches, which are thyristor switches. In standard operation, SW is closed and SB is open. This switches the load to the inverter output.

In the event of an overload or the destruction of an inverter, SB is closed and SW is open, switching it to an auxiliary power supply (network, output of another UPS, diesel generator, etc.). The two switches, SW and SB, are always closed at the same time for a short period when switching between inverter and bypass mode. This prevents any interruption in the power supply even in the event of a fault. This condition is essential to enable all demands by the connected sensitive devices on the voltage supply to be met.

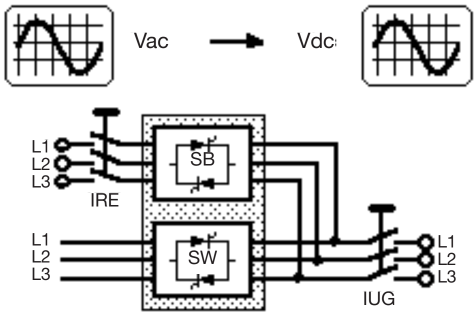

Fig.15-6

Static switch circuit diagram

Maintenance bypass

During UPS maintenance work, the maintenance bypass supplies the connected load directly over the network. The maintenance bypass consists of a switch (IBY).

The UPS installations allow switching from the various operating modes to the maintenance bypass without interrupting power. If the maintenance bypass is activated, the rest of the UPS can be switched completely voltage-free to allow maintenance or repair (up to the input and output terminals and their connections to the IRP, IRE, IUG, IB circuit-breakers).

To prevent faulty switching of the IBY maintenance bypass switch, which could be caused by parallel switching between inverter and maintenance bypass system, the IBY maintenance bypass switch is electronically interlocked against the static SW reversing switch. If IBY is closed, SW opens automatically. This prevents parallel switching between inverter and maintenance bypass system.

ABB can supply an external wall-mounted uninterruptible maintenance bypass switch as an option. This switch enables simple switchover to the maintenance bypass with no possibility of faulty switching and without interrupting the load. This makes it possible to switch all power to the UPS by shutting off its power supply completely.

Fig. 15-7

Internal maintenance bypass circuit diagram

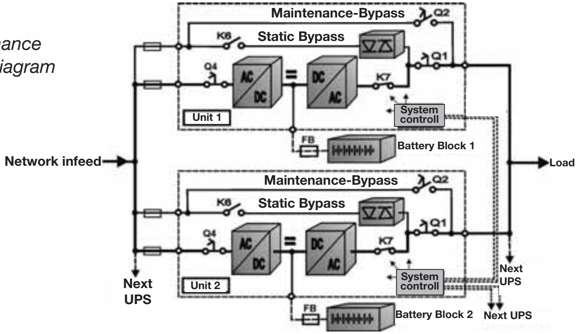

Table 15-2

ABB UPS system range with technical data

Type		ABB/Mini	ABB/MP2	ABB/PX3	ABB/PX4
Unit capacity	kVA	1 to 10	7.5 to 25	10 to 200	150 to 800
Input voltage permis- sible voltage tolerance	V %	230/1ph. ± 10	400/230 ± 10	400/230 ± 10	400/230 ± 10
Input frequency permis- sible frequency tolerance	Hz %	50 (60) ± 5	50 (60) ± 5	50 (60) ± 5	50 (60) ± 5
Output voltage	V	230/1ph.	230/1ph.	400/230	400/230
voltage tolerance at:					
– symmetrical load	%	± 3	± 1	± 1	± 1
– at 50 % step change in load	%	± 4	± 4	± 4	± 4
– at 100 % step change in load	%	± 6	± 10	± 5	± 10
Output frequency frequency tolerance	Hz %	50 (60) ± 0.5	50 (60) ± 0.5	50 (60) ± 0.5	50 (60) ± 0.5
Distortion factor	%	< 4	< 3	< 2	< 3
Current carrying capacity:					
– inverter 1 min.	%	120	150	150	150
– static bypass 1 min.	%	150	200	200	200
Total efficiency	%	83	90	90	93
Noise level	db(A)	ca. 50	ca. 60	ca. 61	ca. 63

Notes on all ABB UPS types:

System configuration: on-line (double conversion)
setting ranges for input and output voltages:
380/220 V/400/230V/415/240 V

acc. IEC 62040-3

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15.2 High speed transfer devices

15.2.1 Applications, use and functions

In power and industrial plants, large motors and other important loads must have a backup in case the general power supply system fails, because otherwise availability, production, profitability and safety will be restricted or people may be injured and the environment and process equipment may be damaged.

With high outputs, backup generators are no longer sufficient. A second power supply ready for immediate operation is required. It is important for the second power supply to be independent of the effects of a fault in the general power supply system. The supply must come from another transmission network or a different power generator.

The transfer to the second power supply is generally done at the same voltage level as the large loads, i.e. in the rated voltage ranges up to 24 kV. However, in some situations, the transfer is done in the low-voltage network or at the level of a transmission voltage. This can basically involve switching over one large load, such as a motor, and also switching over a whole group of important loads linked together over one busbar section.

In order to minimize feedback effects on the loads and power supply, the switching must be performed with very short transfer times with regard to the physical processes in the network and at the loads. This task is handled by high-speed transfer devices, which are based on digital hardware technology and can be integrated into every modern installation protection system.

To take full advantage of the possibilities of high-speed transfer devices, the general design must meet the following requirements:

- At least two synchronous power supplies, generally independent of each other.
- Circuit-breakers with short operating times.
- The switchgear installation must be suitable for system transfers.
- Fast protection relays for initiating the high-speed transfer device

Transfers initiated by operational conditions can be started manually using the high speed transfer device, but in the event of a fault, the transfer system reacts automatically.

Examples of applications of the ABB high speed transfer device are shown in figures 15-18a and 15-18b.

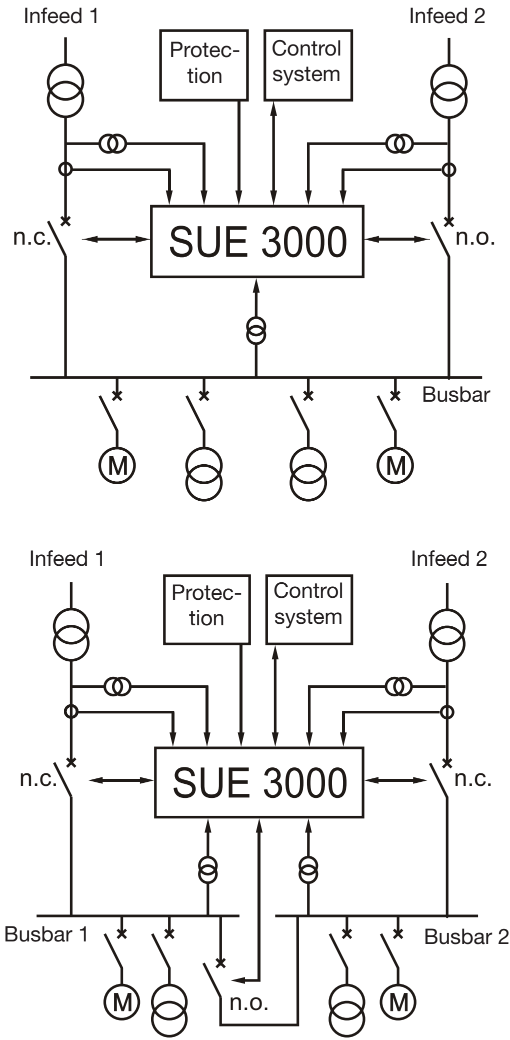

Fig. 15-8

Example switchgear configurations with high speed transfer devices
a) Single busbar with 2 incoming feeders
b) Single busbar with 2 incoming feeders and bus sectionalizer

15.2.2. Integration in the switchgear system

ABB's SUE 3000 high speed transfer device can be easily integrated in both newly erected and existing switchgear installations. All the standard voltage levels are supported.

The most important interfaces are those with the following components:

•Switchgear installation (circuit-breakers, voltage transformers, measuring current transformers (optionally protection current transformers), overcurrent relays etc.

•Protection systems (block, transformer, differential, cable, overcurrent and undervoltage protection etc.)

•Control systems/control room (remote control, signalling system)

•Auxiliary voltage supply (DC power supply).

Additional interlocks, releases or blocks in conjunction with other components may be required because of the large number of individual design options for a switchgear installation as well as the operational conditions.

Fast, direct and undelayed starting by external protection relays is also important for optimum conformity with all demands on the high-speed transfer device.

15.2.3. Design of high speed transfer devices

ABB‘s SUE 3000 high speed transfer system is based on a microprocessor system with real time capability.

The measurement and analog signal processing functions are performed by a digital signal processor (DSP).

The control function and the interface to the binary input and output assemblies are handled by a microcontroller (MC). A communications processor (CP) is required to establish communications with a substation automation system.

The process interface can in principle be described as follows:

- Analog inputs for detection of current and voltage signals from conventional instrument transformers or combination sensors.
- Binary inputs with optocouplers for electrical isolation of the external signals to be processed.
- Binary outputs with conventional relays or optionally with solid-state relays for activation of the switching devices in the panels.
- A maximum of six analog inputs with 0 … 20 mA or 4 … 20 mA are optionally available.
- In addition, max. four analog outputs with 0 … 20 mA or 4 … 20 mA are also available.
- Optional communications interface to an ABB substation automation system or third-party automation system.

15.2.4. Function

One fundamental function of the high speed transfer device is to ensure, in the case of excitation, that a minimum transfer time during which the compensation processes during switchover present no hazard to the connected loads is achieved.

For this purpose, it must be equipped with fast processing logic and high precision analog signal processing.

The device continuously compares the busbar voltage with the voltage of the back-up feeder. The transfer criteria are generated from the monitoring process of the voltage amplitudes and the differences in frequency and phase angle.

The different transfer situations described below are initiated at the moment of excitation based on the current system status.

Excitation of the high-speed transfer device is normally performed either manually from the control room or by suitable fast protection relays. Basically, if a limit value defined as an undervoltage in the currently used feeder is reached, an undervoltage excitation can also be independently generated. The transfer direction – either from the main to the back-up power supply or vice versa – is identified by monitoring the corresponding circuit-breaker positions. The high-speed transfer device is only ready for operation when both circuit-breakers that are to be actuated are definitely in different switching states (plausibility check) and are in the service position.

Switching commands from the high-speed transfer device to the circuit-breakers are sent directly to the control coils – bypassing all switchgear interlocks that might be present.

Permanent calculation of network conditions

One extremely important feature of high speed transfer devices is that the synchronization criteria named above are permanently calculated and therefore always available.

In the case of excitation, therefore, the transfer mode required has already been determined and can be initiated directly. The probability of short-time switchover is thus significantly increased. Systems which only initiate determination of the network condition at the instant of excitation do not, taking account of the physical circumstances, have any chance of performing a short-time transfer with minimum dead time.

15.2.5. Transfer modes

The decisive criterion for the type of transfer is the network condition at the moment of excitation of the high-speed transfer device. The optimum transfer mode is then dynamically selected taking account of the physical circumstances.

There are four different transfer modes available:

- Short-time transfer
- Transfer at the 1st phase coincidence (beat transfer)
- Residual voltage transfer
- Time-controlled transfer

Short-time transfer is the optimum transfer mode to ensure minimum interruption of the power supply in the case of a fault. Where network conditions do not permit this mode, less rapid transfer modes are selected.

Figure 15-9 shows the run-down of an isolated busbar (voltage and phase) and the possible connection times.

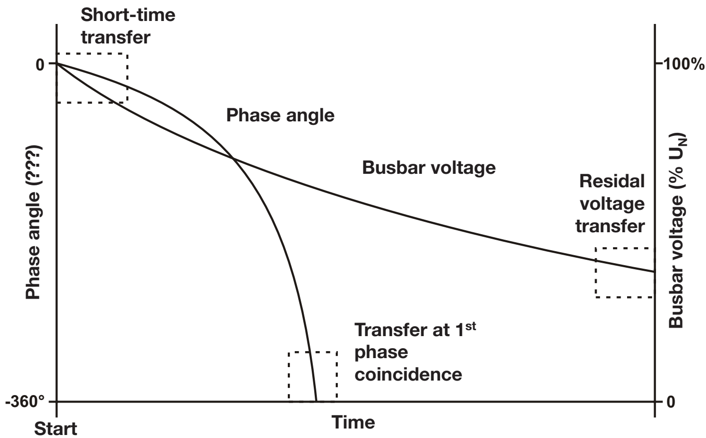

Fig. 15-9

Run-down of a busbar with the possible connection times

Performance of short-time transfers is the preferred and most important functional principle of the SUE 3000.

A short-time transfer occurs when the main and back-up feeders are within specified limits at the instant of excitation, i.e. the slip and phase angle between the networks are limited and the back-up voltage is above a minimum value.

During this process, the high-speed transfer device sends OFF and ON commands to the circuit-breakers in principle simultaneously. The pause without power that occurs for the loads in this case depends almost entirely on the difference between the opening and closing times of the switching devices. As these are normally in the range of a few milliseconds with modern switchgear, further operation of the system without interruption can be assumed.

Figure 15-10 shows an example oscillogram of a short-time transfer with a break of approx. 20 ms without current.

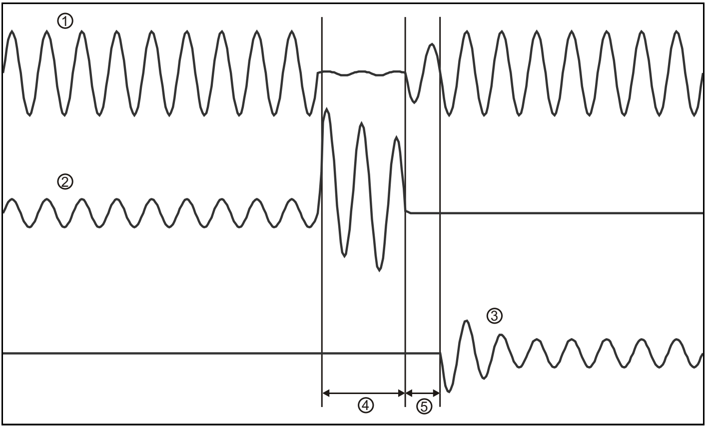

Fig. 15-10 Oscillogram of a short-time transfer
1. Busbar voltage
2. Main feeder current
3. Back-up feeder current
4. Main feeder breaking time
5. Break with no current

A transfer at the 1st phase coincidence (beat transfer) is performed when conditions are not synchronous at the instant of excitation and therefore a short-time transfer cannot be carried out for physical reasons.

The feeder in use is first switched off without delay. The connected loads then have no power supply and run down in accordance with their specific characteristics.

Various times at which compliance with physical limits is ensured are available for connection of the back-up feeder.

In a beat transfer, the opening command is issued immediately and connection of the back-up supply takes place at the first minimum of the difference between back-up and busbar voltage (U_{Backup}-U_{BB}).

The high speed transfer device performs predictive calculations to determine the development of the differential voltage and the time of the first beat minimum. To compensate for the process time of the system itself (system time and circuit-breaker closing time), the ON command is issued within a defined connection window in advance of the first actual minimum of the differential voltage.

The differential voltage resulting at the instant of transfer is thus exclusively determined by the residual voltage of the busbar. The synchronized connection facilitates an extremely process-friendly and nevertheless minimal switchover time.

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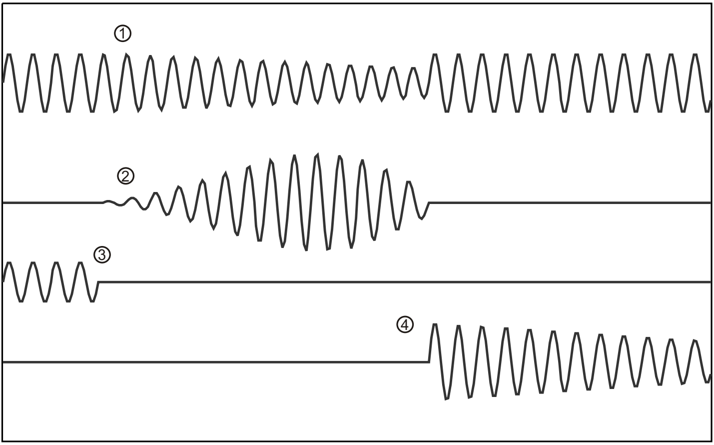


Fig. 15-11 Oscillogram of a transfer at the first phase coincidence

1. Busbar voltage

2. Differential voltage (U_{Backup}-U_{BB})

3. Main feeder current

4. Back-up feeder current

Residual voltage transfer is used when connection at the 1st phase coincidence is not possible. The conditions at the instant of excitation and opening of the previously feeding circuit-breaker are identical to those in a beat transfer. Only connection of the back-up feeder differs significantly from the scenario in a beat transfer.

Connection of the back-up feeder takes place when the busbar voltage has dropped to a pre-set permissible level.

Connection takes place without synchronization, i.e. irrespectively of the phase angle or differential frequency. As, however, the busbar voltage has decayed to a sufficiently low residual level, the compensation processes on connection (instantaneous surge, load restarting current, voltage dip) can be safely handled.

A *time-controlled transfer* takes place when, during a transfer operation (which does not take place in short time), no other connection event has been detected on expiry of a set period.

This case is not expected when the high speed transfer device is working under normal operating parameters, and can normally only occur when several faults arise almost simultaneously.

For this reason, time-controlled transfer is to be regarded as a pure safety facility.

In conclusion, selection of the transfer mode is made dynamically on the basis of the current network conditions.

Assuming normally synchronized networks, short-time transfers are as a rule performed. The principle of issuing commands simultaneously to the circuit-breakers guarantees the shortest possible transfer times and safe, virtually uninterrupted power supply to the process concerned. If there is mechanical failure of the breaker that is to be opened, there is a short-time coupling of the two (synchronous) feeders which, however is detected and automatically corrected (decoupling) by the high speed transfer device, thereby preventing impermissible, long-duration coupling of the networks.

If the networks are not synchronized at the instant of excitation, a short-time transfer is not initiated. The resulting dead times without power vary depending on the installation, with the load that is to be switched determining the run-down response of the busbar voltage and thus the transfer duration.

The various types of transfer can be selectively activated and deactivated depending on the direction. This ensures that the optimum transfer concept for the entire installation can be implemented with regard to the special requirements.

A short-time transfer is the smoothest type of transfer and in most cases guarantees continued operation of the installation with no interruption. The busbar voltage generally remains stable and the closing currents after the transfer are limited.

When conditions allow switching at the 1st phase coincidence, this type of transfer – a short-time transfer was not possible – is the second best choice, followed by the residual voltage-dependent and the long-time transfer. If the back-up networks are not stable enough for certain transfers, the high-speed transfer device can send signals to initiate targeted load shedding before switching.

The high-speed transfer device is designed to initiate the optimum possible transfer automatically depending on the general conditions.

15.3 Stationary batteries and battery installations[1)]

15.3.1 Foreword

All references to batteries refer to secondary (rechargeable) batteries.

Stationary battery sets are used in switchgear installations as sources of energy for network independent power supply of controller protection, regulating and signal circuits and similar.

The battery DC power can also be used via inverters to generate secure AC power. In installations with modern technology, the power supply modules for computers and the electronic protection and also standard data processing devices such as PCs, monitors and printers are powered by an uninterruptible power supply (UPS) (see section 15.1.4).

15.3.2 Definitions

The IEC 60050-486 standard defines the basic terms for batteries.

For easier referencing, some definitions below bear a reference to the appropriate IEC paragraph (IEC 60050-486-nn-nn).

Nominal voltage:

The suitable approximate value of the voltage used to identify a cell, a battery or an electrochemical system.

The nominal voltage of a cell is a specified value. In the lead-acid battery it is 2.0 V, in the nickel-cadmium battery it is 1.2 V.

Note: The operating voltage window for the battery is of greater importance than its nominal voltage (see 15.3.4).

Capacity: Rated capacity:

Quantity of electricity (ampere-hours) which a single cell can deliver when discharged at the reference test current to a final voltage, at +20°C, after charging under specific conditions. In international texts, C is the standard symbol for capacity.

Notes:

- The rated capacity is assigned to a cell by its manufacturer.
- Two cells from two different manufacturers, having the same rated capacity, do not necessarily have the same performance for e.g. 3 hours discharge. It is thus very important to distinguish between the battery rated capacity vs. the ability of the battery to supply the required current in a given voltage window and discharge time.

Capacity: Required capacity

The minimum rated battery capacity required as determined by the IEEE sizing calculation. The required capacity shall be calculated by the supplier on the basis of specific project parameters (i.e. load profile, back-up time, temperature range for sizing, voltage window, required recharge time, aging factor) for each battery type separately (see battery sizing chapter 15.3.7).

1) We are thankful for contribution provided by Fa. Saft batteries.

End-of-discharge voltage:

The specified voltage at which a discharge of a battery is terminated. This parameter may be determined by the connected loads or by battery limitations. For stationary applications, it is advisable to use the lowest permissible end-of-discharge voltage, thus the largest possible number of cells that will satisfy the manufacturer's charging recommendations. This will result in the most economic battery for the application.

Important notes:

- For lead-acid cells deep discharge must be avoided to preserve battery performance and life. A lead-acid battery should not be discharged beyond the voltage recommended by the manufacturer for the specific discharge rate being used.
- Nickel-cadmium cells can tolerate complete discharge with no permanent deterioration of performance or life. Nickel-cadmium battery life will not be preserved by specifying a "high" end-of-discharge voltage. For stationary nickel-cadmium applications, it is recommended to use an end-of-discharge voltage as close as possible to 1.00 volt per cell (see 15.3.7 for more details).

Gassing:

The formation of gas produced by electrolysis of the electrolyte.

During charge, float charge, and overcharge, gases are emitted from all stationary secondary cells and batteries. Gases produced are hydrogen and oxygen. When emitted into the surrounding atmosphere, an explosive mixture may be created. The higher the charging voltage the higher the overcharge current and consequently the higher the gassing.

Float charge:

An operation during which the battery is permanently connected to a source of constant voltage sufficient to maintain the battery in a fully charged condition.

Boost charge:

An accelerated charge generally at a high rate for a limited period. This is carried out at higher voltage than the float voltage and may be used to recharge a battery in a specified time.

Equalizing charge:

Extended charge to correct deviations in voltage or electrolyte gravity between cells in a battery. Sometimes mistakenly used interchangeably with ‘boost charge.’

The term ‘equalizing’ may refer to overcoming voltage imbalances between cells within a battery.

- In lead-acid cells, it may refer to inducing mixing of the electrolyte to overcome concentration gradients that may exist following a discharge or water addition. The mixing effect is produced by the agitation of gas bubbles as they are liberated from the plates and rise to the surface.
- In nickel-cadmium cells, the electrolyte concentration does not change with state of charge, so such mixing is unnecessary.

Commissioning charge:

It is recommended that a good first charge should be given to the battery, either when the battery is delivered full of electrolyte or empty of electrolyte. A high level of charge voltage is necessary for this operation. For nickel cadmium batteries, a constant current charge is always preferable.

Always refer to battery manufacturer installation and operating instructions for exact value and procedure.

Internal resistance:
The internal resistance of a cell is dependent on the cell design, electrolyte temperature and the state of charge. The typical values given in Table 15-3 are based on a fully charged battery.

15.3.3 Types and specific properties of batteries

A battery comprises secondary cells interconnected. A secondary cell is made up of a single or multi-compartment (monoblock) container inside which positive and negative plates, separators, electrolyte and connections are fitted. This container is then closed by a lid through which the terminals pass and which is fitted with either an opening for the escape of gas and possibly the addition of water, or a special system to limit the escape of gas.

Two types of cells are used in stationary batteries:

Vented cells:
- (IEC 60050-486-01-18): vented cell; a secondary cell having a cover provided with an opening through which gaseous products may escape.

Note: the opening may be fitted with a venting system.

Closed cell, with 2 sub-categories:

valve regulated (secondary) cell:
- (IEC 60050-486-01-20): a secondary cell which is closed under normal conditions but which has an arrangement which allows the escape of gas if the internal pressure exceeds a predetermined value. The cell cannot normally receive addition to the electrolyte.

Closed lead-acid cells are of the valve-regulated type (VRLA).

gastight sealed (secondary) cell:
- (IEC 60050-486-01-21): a secondary cell which remains closed and does not release either gas or liquid when operated within the limits of charge and temperature specified by the manufacturer. The cell may be equipped with a safety device to prevent dangerously high internal pressure. The cell does not require addition to the electrolyte and is designed to operate during its life in its original state.

Sealed gastight nickel-cadmium batteries are for portable applications only and are not suitable for float charging applications with constant voltage chargers (not used in stationary applications).

Gases are emitted from industrial lead-acid or nickel-cadmium batteries, thus ventilation, forced or natural is necessary.

Switchgear installations primarily use two types of battery chemistries:

Lead-acid batteries

They are made with electrodes of lead and lead alloys and dilute sulfuric acid (H_2SO_4) as electrolyte. They are used in switchgear installations, substations and power plants to provide power requirements for long operational periods, such as emergency lighting, protection and communication systems.

The IEC standards for lead-acid batteries are:

- IEC 60896-11 Stationary lead-acid batteries - Part 11: Vented types - General requirements and methods of tests
- IEC 60896-21 Stationary lead-acid batteries - Part 21: Valve regulated types - Methods of test
- IEC 60896-22 Stationary lead-acid batteries - Part 22: Valve regulated types – Requirements

Major lead-acid battery technologies:

- OPzS : with positive tubular plates
- OGi : with positive and negative grid plates (also called pasted or flat plates)
- GroE : with positive large-surface-area plates (also called Planté cells)

Negative plates are always pasted plates. All of the above cell types are available as vented cells.

Valve-regulated lead-acid (VRLA) cells use either pasted or tubular positive plates. These cells have immobilized electrolyte to promote recombination of gases (H_2 and O_2) generated during charging. One method of immobilization is to add a gelling agent. Alternatively, the electrolyte can be absorbed into a glass fiber mat separator, and these 'absorbed glass mat' (AGM) cells invariably use pasted positive plates.

Advantages of lead-acid batteries:

- low initial cost
- reliable operation of vented cells under mild operating conditions
- no topping-up requirements for VRLA batteries (but at the cost of additional failure modes)

Disadvantages of lead-acid batteries:

- severely reduced operating life at high temperature (for every 10°C increase over 20°C, the reduction of operating life will be 50%)
- limited capacity availability at low temperature,
- high power versions (e.g. automotive types) have short life on float
- end of life by sudden failure
- additional failure modes for VRLA types

Some of the additional failure modes for VRLA batteries, particularly dryout, result in an increase in internal resistance and a decrease in high-rate discharge capability. VRLA batteries are more sensitive to factors like high temperatures and overcharging which can result in thermal runaway with total failure of individual cells. For these reasons they are not generally used in switchgear applications.

Nickel-cadmium batteries

They are made with nickel hydroxide for the positive plates and cadmium hydroxide for the negative plates. The electrolyte is an aqueous solution of potassium hydroxide (KOH).

Nickel-cadmium cells are used in switchgear installations, substations and power plants, gensets, off-shore platforms, to provide power requirements for long or short backup times, under extreme temperatures (hot or cold) and where reliability and low life cycle cost are essential.

The IEC standards for nickel cadmium batteries are:

- IEC 60623 Secondary cells and batteries containing alkaline or other non-acid electrolytes – Vented nickel-cadmium prismatic rechargeable single cells.
- IEC 62259 Nickel-Cadmium prismatic rechargeable single cells with partial gas recombination.

Nickel-cadmium batteries are classified by the IEC 60623 or 62259 into three major cell designations:

L : low rate of discharge (typically with a discharge duration 2 hours or longer)
M : medium rate of discharge (typically with discharge duration of 30 minutes to 3 hours)
H : high rate of discharge (typically with discharge duration lower than 40 minutes)

Important electrode types used in nickel-cadmium cells:

- pocket-plates, type L, M, H. Pocket plates preferred for switchgear installations
- sintered plates, e.g. for aircraft applications
- plastic bonded electrodes for negative plates and sintered electrodes for positive plates, type H. They are used for engine starting or UPS applications for less than 30 minutes
- fiber plates, type L, M, H, (e.g. for motor/traction vehicle batteries).

Advantages of nickel-cadmium batteries:

- long life (in excess of 20 years is achieved), predictable aging
- high reliability (no sudden death) even at high temperatures
- influence of high temperatures on life time is minor
- low Life Cycle Cost
- high available capacity at low temperatures
- wide operating temperature range
- fast recharging possible
- high mechanical and electrical stability
- life time not affected by deep discharges (stationary applications)
- resistant to overcharging
- good cycle life
- no plate corrosion

Disadvantages of nickel-cadmium batteries:

- higher price (initial investment)
- must be used in upright position
- at high cyclic stress and high temperatures, pocket-type cells may require, depending upon the application, new alkaline electrolyte after several years (usually not needed for stand-by applications such as switchgear)
- wide voltage window for charging/discharging

For a quick overview of the electrical characteristics of lead-acid and nickel-cadmium batteries, please see also table 15-3.

Table 15-3

Specific properties of batteries.

Name	Dimension	Lead-acid batteries OPzS	GroE	GroE-H	NiCd batteries L	H
Rated capacity *C*	Ah	C_{10}	C_{10}	C_{10}	C_5	C_5
Rated discharge current	A	$I_{10} = 0{,}1 \cdot C_{10}$	$I_{10} = 0{,}1 \cdot C_{10}$	$I_{10} = 0{,}1 \cdot C_{10}$	$I_5 = 0{,}2 \cdot C_5$	$I_5 = 0{,}2 \cdot C_5$
Rated end-point voltage at 20 °C	V/cell	1,80	1,80	1,80	1,00	1,00
Single level charge	V/cell		between 2,18 and 2,25		1,43 to 1,50	1,41
Two lefel charge		-	-	-	-	-
First step (high level)	V/cell		between 2,30 and 2,40		1,45 to 1,70	1,45
Second step (Float charge voltage)	V/cell		between 2,18 and 2,25		1,40 to 1,42	1,40
Electrolyte density[1]	kg/dm^3	1,24	1,24	1,22	1,2	
					L / M / H	
Internal resistance R_i/Cell (typical value)	mΩ/100 Ah	3,0	2,0	1,4	1,4 / 0,8 / 0,4	0,4
Load capability	-	L	M	H	L / M / H	H
Recomended operating temperature range			+5°C to +35°C		-20°C to +50°C	
Reduced time temperature range[2]			-30°C to +50°C		-50°C to +70 °C	

[1] For lead acid batteries, it can vary from manufacturer to manufacturer.
For Ni-Cd batteries, any interpretation of density measurements is not meaningfull as electrolyte is only an ion carrier and does not take part in the chemical reaction. It will not give any information of the state of charge or health of the Ni-Cd battery.
[2] for reduced time, and with special precautions. Consult battery manufacturer.

15.3.4 Charging and discharging batteries

Charging

Batteries shall be charged to maintain them ready for emergency case.

Charging is the operation during which a battery receives from an external circuit electrical energy which is converted into chemical energy (IEC 60050-486-01-11).

Charging characteristics:

W-charge characteristic: This is a simple charger where the charge current decreases as the cell voltage increases to a specific set-point. This charge characteristic will keep the battery at an active charge state and will counter the self-discharge

U-characteristics:

The battery limits the charge current when under constant voltage. The battery lowers the charge current with increasing charge level.

I-characteristics

The charger supplies the battery at a constant current while battery voltage is free to evolve according to the state of charge.

Combinations of these characteristics are possible:

IU-charge characteristic: one of the most common charge methods.

The IU characteristic charges the battery at a constant current until a set cell voltage is reached. The rectifier/charger then maintains the voltage constant, while the charge current decreases. This type of rectifier/charger is often used in standby applications and can be kept connected to the battery for an indefinite period of time.

Note:

Normally the battery charge current is the difference between the output current of the rectifier/charger and the load current.

Depending on battery technology and application batteries are either charged by single level or two level charge.

The two most commonly used IU charging modes are described below:

Charge at single voltage level (also called single rate charge or single level charge)
The single rate charge is the most common and the simplest. It is used principally when the battery availability is not subject to a critical constraint of recharge time.

The single level charge voltage is necessarily a compromise between a voltage high enough to give an acceptable charge time and low enough to give a low water usage.

Charge at two voltage levels (also called dual rate charge or two level charge)

The two level charge gives battery availability in a shorter time than is possible with a single rate charger.

- 1st level: the high level allows the battery capacity to be restored in a specified time to a high level (e.g. reaching ≥ 85% available capacity in 10 hours) which assures a further discharge.
- 2nd level: the low level (float charge) permits the completion of the battery charge bringing it to and maintaining it a state close to full charge while limiting water consumption.

For most of OPzS, OGi, GroE and Ni-Cd batteries a two level charge is recommended.

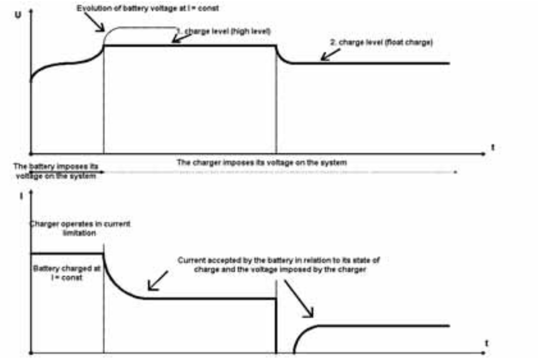


Figure 15-12 below illustrates this 2 level charge.

- For lead-acid, the typical charging current is 0.1C10A. Maximum current is 0.3C10A.
- For nickel-cadmium, it can be 0.1C5A or 0.2 C5A. In general 0.2 C5A is recommended. Maximum is 1 to 3 C5A.

Discharging

The discharge is the operation during which the battery restores the energy, which was previously stored in chemical form, in electrical form to an external circuit.

The cell end-of-discharge voltage should be as low as possible to obtain the maximum autonomy.

- For lead-acid batteries the manufacturers define the minimum cell voltages depending upon the discharge rate in order to avoid deterioration and preserve battery life. Deep discharges shall be avoided.
- For nickel-cadmium batteries, end-of-discharge voltage should be as close as possible to 1.00 V/cell. Nickel-cadmium batteries accept to go below 1.00 V/cell, regardless of the discharge rate.

Note:

When a Ni-Cd battery has been float charged (constant voltage) for several months, there will be a drop in the discharge voltage curve. This voltage drop does not affect the Ah capacity of the cell but does reduce the available autonomy at high end-of-discharge voltages. This voltage drop is called float effect and must be taken into account when sizing batteries by using manufacturers' published performance data under prolonged constant voltage.

In order to insure proper performance of the battery it is recommended to size with IEEE methodology (see battery sizing section15.3.7).

15.3.5 Rectifier / Charger

The electrical demands on rectifiers / chargers are numerous and vary widely in nature.

The rectifier / charger must be able to supply the current to the connected load and to recharge the battery in the same time.

If the battery charging voltage exceeds the maximum allowable value for the load and the battery cannot be charged off-line, the following actions may be taken in the power system:

- the use of counter cells (dropping diodes)
- main and end cells
- dual rectifier system (high rate interlock)
- DC/DC converter or DC stabilizer in the load circuit output.

Use of counter cells (dropping diodes)

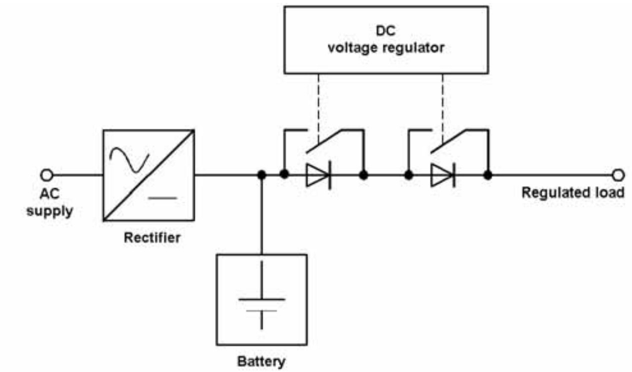


Figure 15-13

A number of diode groups is connected to the load circuit and switched in or out by a voltage sensing control circuit.

End cell switching (use of main and end cells)

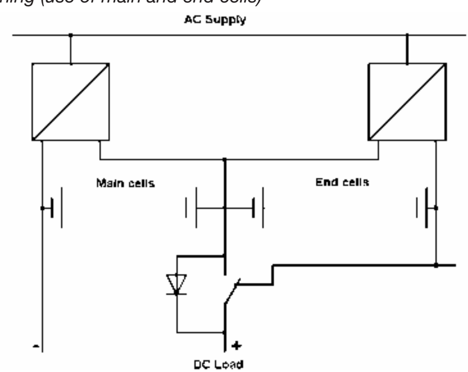


Figure 15-14

The battery is split into two sections: main cells and end cells so as to reduce voltage variations to the load. When the battery is discharged, the two groups are connected in serious via the end cell switch. A diode is connected in parallel over the end cell switch to prevent temporary disconnection of the load during switching.

When the mains come back, the main cells are recharged by the main rectifier while the auxiliary charger recharges the end cells.

Dual rectifier system (high rate interlock)

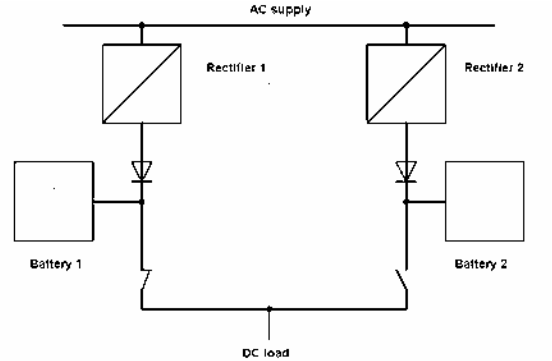


Figure 15-15

This parallel redundant system provides 100% standby if each of the rectifiers and batteries are designed for the full load. Both sections are connected to a common bus bar and can operate in parallel or independently. Boost charge (high rate charge) is done on one battery string when disconnected from the bus bar, while the other battery string is on float charge and connected to the bus bar, thus to the load. Once the high level charge is completed on the first battery sting, the charger switches to the float charge level and is connected to the bus bar, while the second battery string is disconnected from the bus bar and gets the boost charge.

Rectifiers should have a possibility for manual switch over to high level charge for battery commissioning.

In this case, the connected loads or the distribution panel must be switched off if the allowable load voltage is exceeded. It is also desirable that the rectifier should revert automatically to float mode after a preset time to prevent accidental overcharging.

15.3.6 Operating modes

If loads are supplied directly from a battery and the battery is disconnected from the loads for charging, this is referred to as straight battery operation (Fig. 15-16a).

During parallel operation (Fig. 15-16b), loads, rectifiers and battery are continuously connected in parallel. In this case, a distinction is made between buffer operation (battery is used to keep constant voltage and to cover peaks) and parallel operation (battery supplies power only if the rectifier fails). Parallel operation predominates.

Under switchover mode, the battery is disconnected from the loads; it is kept fully charged. If the standard power source fails, the consumers are switched to the battery (Fig. 15-16c).

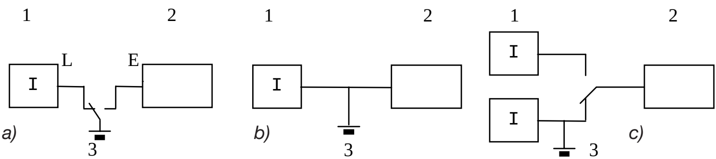


Fig. 15-16

a) discharge-charge *b) parallel operation* *c) switchover operation*

1 DC source, 2 consumer, 3 battery

15.3.7 Battery sizing

A large amount of data and operating conditions must be considered when dimensioning a battery.

It includes:

- Complete load profile (permanent load, pulses, peaks, sequence vs. time, usually in amperes).
- The battery voltage window (permissible voltage tolerance of loads)
- End-of-discharge voltage per cell, to be calculated by battery or power system-supplier. Typical value for lead-acid is between 1.60 and 1.90 volt per cell; for nickel-cadmium it is between 1.00 and 1.14 volt per cell.
- Voltage drop between the battery terminals and the load(s),
- Minimum ambient temperature around the battery, used for sizing, at which the battery must be able to perform the duty cycle.
- Aging factor and/or design margin. Recommended aging factor for lead-acid is 1.25. For nickel-cadmium, the choice of aging factor is essentially an economic one, but 1.25 is typically used for both, nickel-cadmium and lead-acid.
- Proposed battery technology
- Other constraints if applicable e.g. topping up intervals, footprint, minimum recharge time….

The following IEEE documents are strongly recommended for battery sizing:

a) IEEE 485-1997 for lead-acid batteries

b) IEEE 1115-2000 for nickel-cadmium batteries

c) IEEE 1184-1994 for selection and sizing of UPS batteries (both lead-acid and nickel-cadmium)

The battery manufacturers generally have computer programs to size in compliance with these standards.

It is important to perform one full IEEE sizing calculation for each specific battery type under consideration, since discharge performance for different times will vary from manufacturer to manufacturer and for battery technology to battery technology. Compare the IEEE sizing sheets to evaluate battery performance and sizing parameters used.

Notes:

- It is never sufficient to calculate the capacity of a battery from the product of current x discharge time only.
- Nickel-cadmium battery life will not be preserved by imposing a "high" end-of-discharge voltage like 1.14 V/cell.

15.3.8 Installing batteries

For all battery installations pls. follow:

- EN 50272-2: Safety requirements for secondary batteries and battery installations. Part 2: Stationary batteries
- Battery manufacturer's Installation & Operating instructions.

Types of installation

Batteries are usually installed on steel racks if separate battery rooms are available.

Otherwise they are mostly housed in cabinets.

The most convenient type of installation from the point of view of maintenance is on racks with steps and tiers. Unless other specified, racks are non seismic. For seismic specify the UBC Zone.

EN 50272-2 explains in paragraph 10 the different kinds of battery accommodations: separate battery rooms, specially separated areas in electrical accommodations, cabinets or enclosures, battery compartments (combi-cabinets).

Working distance within battery rooms

EN 50272-2 specifies in paragraph 10.4.1 that in order to allow emergency evacuation, an unobstructed escape path shall be maintained at all times with a minimum width of 600mm.

However, practice has shown that these aisle widths are often too narrow, so the recommended widths between floors mounted racks are at least 800mm and 1000mm between tier racks.

Notes:

- EN 50272-2 paragraph 10.4.1 also states that to allow temporary equipment to be placed in the access way, the width is increased to 1200 mm if no other information is available.
- North-American standard NFPA 70 requires an access clearance to all electrical equipment of at least 915mm.

Battery rooms and ventilation

Please refer to EN 50272-2.

The requirements for the structural design of battery rooms are considered in more detail in section 4.7.4 of this manual.

Please refer to EN 50272-2 for complete details.

15.4 Installations and lighting in switchgear systems

The operation, control and monitoring of switchgear installations inside and outside requires that they be supplied with energy (station service) and lighting.

15.4.1 Determination of the electrical power demand for equipment

The power demand P_{max} is calculated from the sum of the connected loads ΣP_i for the individual load groups and multiplied by the demand factor g.

$$P_{max} = \Sigma P_i \cdot g$$

The demand factor g is based on experience. See table 15-4.

Table: 15-4

Typical values for demand factor g for:

	Offices	Switchgear systems
Lighting	0.8	0.8
Receptacles	0.1	0.1
Air conditioning, ventilation	1	1
Heating	1	1
Lifts	0.5 / 0.7	—
Kitchen equipment	0.5	—
Outside lighting (floodlight installations)	—	1
Cranes	—	0.7
Control and signalling equipment	—	0.5
Data processing equipment	Depending on individual case	

Equipment for station service

The equipment for station service in switchgear installations is described in sections 7.1 and 7.2.

In most cases, low-voltage distributors in the form of switchgear cabinets or distribution boxes are used, with all requirements for maximum operational dependability regarding design and equipment selection being met.

Important consumers and functions are supplied with d.c. voltage, which also ensures an uninterrupted power supply even in the event of a malfunction when stationary batteries are used.

15.4.2 Laying and installation systems

The complex cable and wiring networks comprise a significant portion of the entire installation system. For this reason, the correct selection of materials and systems appropriate for the application is particularly important. Installations with multiple fire compartments require appropriate barriers between them. If emergency exits are provided, they must be installed in F90; materials conforming to DIN 4102 must be used. Fasteners and installation materials that are easy to install must be selected to allow economical installation. Proper tools and construction equipment are also required to ensure rational installation work processes.

See section 13.2.4 for information on laying cables and wiring.

The manufacturer's working guidelines must also be observed.

There are single modules and complete layout systems for the various layout types.

The fastening methods and layout materials must be selected in accordance with the anticipated stresses caused by mechanical, thermal, chemical or other environmental effects. The following must also be taken into account:

- adequate heat dissipation,
- safe isolation of the power and communications circuits and the networks for standby power,
- open or covered configuration,
- sufficient flexibility for changes and retrofitting,
- technical fire protection measures.

The following are used for individual installation:

- plastic and metal nail, screw, bracket and glue clips,
- plastic and metal installation conduits, rigid and flexible
- (see tables 15-5 to 15-9 for specifications).

The following are used for composite installation:

- plastic register clips and line-up saddles of plastic,
- plastic and metal bracket clips,
- plastic and metal strips and clamps,
- plastic and metal underfloor, wall and ceiling ducting,
- mesh cable racks of round steel bars,
- plastic and metal gutters and trays,
- metal racks and cable conduits.

Installation systems have been developed from the layout systems for interiors that not only protect and support elements for the wiring but also include tap boxes and terminal boards.

This development has been greatly assisted by construction technology which now offers not just the wall area but also the floor and ceiling for horizontal energy distribution. The window sill area is also available for this purpose.

Typical installation systems comprise:

Underfloor installation

with single- and multiple-duct metal or plastic conduits for laying power and communications wiring with floor-level or sub-floor connections for different components. The conduits can be laid in or on the unfinished floor, in the flooring material or flush with the floor.

Covered accesses for every terminal point must be included with a special design of the system. The wiring is run to the floor below on troughs or racks. The sub-floor installation is also suitable for double-floor systems.

Designs for every type of floor construction are available. The right design should be selected on the basis of the specific requirements and conditions and economy of installation.

Window sill conduit installation (preferred for office spaces)

using plastic or metal conduits with built-in installation devices for power and communications wiring. The conduits are generally a component of the structural sill covering. Sufficient heat dissipation must be provided for installations adjacent to heaters and air-conditioning units.

In laboratories, the conduits are also used for utilities.

Terminal board installation

in the ceiling area, in combination with a suitable rack system. The terminal board consists of a plastic or metal housing with separate compartments for the power and communications circuits. Protection and switchgear is also included as well as terminals and terminal blocks. The terminal board can also be supplied as a complete module with added ceiling or built-in lights.

This installation system provides a wiring network without individual tapping boxes and is preferably used for decentralized supply of large spaces and anywhere that individual tapping boxes cannot be used for technical or structural reasons.

Busbar trunking system installation

in the vertical shafts of the central part of the building and as a connection between transformer and low-voltage main switchgear installation. This installation system has been developed from the classical plug-in busway installation used in industrial power supplies and has been switched from the horizontal to the vertical with slightly modified components.

The open or closed duct installation is preferably used for laying cables and wiring to individual consumers in the switchgear compartments and areas.

Plastic or steel conduits are used depending on the demands on the mechanical strength of the installation. They are installed in the ground, on and in the walls or ceilings of buildings and on structural framework.

15.4.3 Change to electrical installation conduits to EN 50086

The new standard changed the classifications, the markings and the VDE tests. As a consequence, for example, conduits with medium compression resistance are sufficient for laying in concrete.

The four digit code classifies conduits and accessories by compression resistance, impact resistance, and minimum and maximum service temperature during transport, storage and use of the product.

The new nominal bores are stated in the metric system.

Table 15-5

Classification and marking

First digit	Second digit	Third digit	Fourth digit
Compression resistance	Impact resistance	Minimum service temperature	Maximum service temperature
1 very light (125 N)	1 very light (0,5 kg/100mm)	1 +5°C	1 +60°C
2 light (320 N)	2 light (1,0 kg/100mm)	2 -5°C	2 +90°C
3 medium (750 N)	3 medium (2,0 kg/100mm)	3 -15°C	3 +105°C
4 heavy (1250 N)	4 heavy (2,0 kg/300mm)	4 -25°C	4 +120°C
5 very heavy (4000N)	5 very heavy (6,8 kg/300mm)	5 -45°C	5 +150°C
			6 +250°C
			7 +400°C

Guideline values for installation conduits can be found in tables 15-6 to 15-8 below (average values; observe the manufacturer's data).

Table 15-6

Non-threadable heavy gauge steel conduits and flexible, corrugated steel conduits with heavy compression resistance

Type	Rigid heavy gauge steel conduits non-threadable				Flexible, corrugated steel conduits for heavy pressure loads			
	Diameter		Bundle Tube lenght 3 m		Diameter		Ring	
	Inner mm	Outer mm	Content m	Weight kg	Inner mm	Outer mm	Content m	Weight kg
16	13.3	16.0	30	12.2	11.7	16.0	25	
20	17.3	20.0	30	15.9	15.7	20.0	25	
25	22.1	25.0	30	24.3	20.2	25.0	25	
32	29.0	32.0	21	19.6	26.7	32.0	25	
40	37.0	40.0	15	18.3	34.2	40.0	25	
50	47.0	50.0	15	23.6	43.7	50.0	25	
63	59.9	63.0	15	28.5				

Application:

Usable for surface and underplaster installations in domestic and industrial buildings, and at high thermal loads.

Table 15-7

Pliable plastic conduits with medium and heavy compression resistance

Type	Pliable plastic conduit, medium compression resistancve				Pliable heavy gauge plastic conduit, heavy compression resistance			
	Diameter		Ring		Diameter		Ring	
	Inner mm	Outer mm	Content m	Weight kg	Inner mm	Outer mm	Content m	Weight kg
16	10.9	16.0	50	3.6	10.5	16.0	50	4.8
20	14.2	20.0	50	5.5	13.7	20.0	50	7.3
25	18.6	25.0	50	6.6	18.4	25.0	50	8.7
32	24.3	32.0	25	4.5	24.1	32.0	25	6.3
40	31.3	40.0	25	6.0	30.9	40.0	25	8.5
50	40.0	50.0	25	7.7	39.5	50.0	25	11.0
63	50.5	63.0	25	11.2	50.3	63.0	25	14.8

Application:

Concrete, cavity, surface and underplaster installation, plant and machinery installation, outdoor and buried installation

Table 15-8

Rigid plastic conduits with light and heavy compression resistance

Type	Rigid plastic conduit, light compression resistance				Rigid heavy gauge plastic conduit, heavy compression resistance			
	Diameter		Ring		Diameter		Ring	
	Inner mm	Outer mm	Content m	Weight kg	Inner mm	Outer mm	Content m	Weight kg
16	14.3	16.0	111	6.7				
20	18.3	20.0	111	9.5	16.6	20.0	57	7.7
25	22.6	25.0	57	6.9	21.2	25.0	57	10.4
32					27.9	32.0	21	5.5
40					35.3	40.0	21	7.4
50					45.4	50.0	21	10.2

Application:

Light compression resistance for simple surface installation

Heavy compression resistance for all surface installations in industry and plant construction

There is a direct relationship between the internal diameter of the conduit, the approved space factor of the wiring in the conduit and the maximum permissible conduit length between the cable insertion points. This must be considered when planning the installation.The limited options for pulling wiring and cables into the conduits require that some selection criteria be met:

– external diameter of cable,
– number of cables per conduit,
– permissible cable bending radii,
– permissible cable pull force,
– internal diameter of conduit,
– permissible conduit length between two cable pull points,
– number of conduit bends between two cable pull points,
– permissible space factor of the conduits based on heat given off by cables.

These cable data can be found in the manufacturers' lists.

Table 15-9 shows an overview of typical values for space factors, for pull lengths of 3-35 m with various conduit types and various installation types for single cables and bundled cables.

Table 15-9

Selection of conduits and conduit filling factor, typical values for space factors with manual insertion

Approved space factors of conduits with a max. draw length	3 m	6 m	9 m	12 m	20 m	25 m	30 m	35 m
PVC/steel conduit in open conduit installation, single cable								
D_{Ri} = 18 – 44 mm	0.7	0.7	0.5	0.5	—	—	—	—
≥ 45 mm	0.4	0.4	0.4	0.4	0.4	0.4	0.4	—
PVC/steel conduit in open conduit installation, bundled cable								
D_{Ri} = 18 – 44 mm	0.6	0.5	0.4	0.3	—	—	—	—
≥ 45 mm	0.3	0.3	0.3	0.3	0.3	0.3	—	—
PVC/steel conduit in closed conduit installation, single cable								
D_{Ri} = 18 – 44 mm	0.4/0.3	0.4/0.3	0.3/0.2	0.3/0.2	—	—	—	—
≥ 45 mm	0.2/0.2	0.2/0.2	0.2/0.2	0.2/0.2	—	—	—	—
Z\x conduit bend								
PVC/steel conduit in closed conduit installation, bundled cable								
D_{Ri} = 18 – 44 mm	0.4/0.3	0.4/0.3	0.3/0.2	0.3/0.2	—	—	—	—
≥ 45 mm	0.2/0.2	0.2/0.2	0.2/0.2	0.2/0.2	—	—	—	—
Z\x conduit bend								
PVC/concrete conduit in ground or concrete, single cable								
D_{Ri} ≤ 50 mm	0.5	0.5	0.5	0.5	0.5	—	—	—
> 50 mm	0.4	0.4	0.4	0.4	0.4	0.4	0.4	0.4
PVC/concrete conduit in ground or concrete, bundled cable								
D_{Ri} ≤ 50 mm	0.4	0.4	0.4	0.4	0.4	—	—	—
> 50 mm	0.3	0.3	0.3	0.3	0.3	0.3	0.3	0.3

D_{Ri} = interior conduit diameter (mm)

The effective space factor is calculated from the square of the interior diameter of the conduit (D_{Ri}) and the sum of the squares of the external diameters of all cables (ΣD_{KA}^2) that will be pulled into the conduit according to the following formula:

$$P_r = \frac{\Sigma D_{KA}^2}{D_{Ri}^2} \leqq P_r \text{ zul.}$$

Conduits with an interior diameter of less than 18 mm (in ground and concrete less than 50 mm) should generally not be used.

If the cables are pulled in by machine, as is often the case with conduit installations in ground or concrete, the max. draw length may not exceed 100 m.

15.4.4 Lighting installations

Installations for lighting indoor and outdoor switchgear installations and their auxiliary equipment are subject to very varied requirements regarding intensity of lighting, limiting glare, colour and colour reproduction.

Table 15-10 lists recommendations conforming to EN 12464-1.

Workplace directive ASR 7/3 and EN 12464-1 specify nominal lighting intensities for illuminating workplaces. ASR 7/3 was released by the Federal Minister for Labour and Social Affairs and therefore forms the legal basis for lighting workplaces.

The levels in EN 12464-1 are in some cases higher than those in ASR 7/3.

Planners of lighting installations should take into consideration that lights become dirty and that they deteriorate with age. For this reason, a planning factor is calculated into new installations.

Standard planning factors for contamination and deterioration:

1.25	standard,
1.43	enhanced,
1.67	strong.

These factors are multiplied by the rated value of the required illumination intensity to find the required installation intensity.

The specified rated lighting intensities E_m are rated values of the average lighting intensity. They must not be below these values. The quality criteria of lighting colour, colour reproduction and limitation of glare are covered in ASR 7/3 and DIN 5035, which has partly been replaced by EN 12464-1.

In addition to the lighting intensity required, further quantitative and qualitative quality characteristics such as visual comfort, visual performance and safety are to be taken into account in the implementation of good lighting systems.

The main characteristics in determination of the lighting environment are:

- luminance distribution
- lighting intensity
- glare
- light direction
- light colour and colour reproduction
- flicker
- daylight

The figures presented in table 15-10 are maintenance values for lighting intensity on the assessment scale for the visual task concerned.

The General Colour Reproduction Index Ra has been introduced for objective designation of a light source's colour reproduction properties. The maximum possible Ra value is 100. This value decreases as the colour reproduction quality deteriorates.

The degree of direct glare from luminaires in an indoor lighting system is to be determined in accordance with the tables of the CIE Unified Glare Rating (UGR) method. The formulae and notes on calculation are presented in EN 12464-1.

Table 15-10

Lighting requirements for spaces, functions and activities (based on EN 12464-1)

Type of space or activity	Rated lighting intensity E_m lx	Colour reproduction index R_a	Degree of direct glare UGR_L
Traffic zones			
Passageways and corridors	100	40	28
Stairs, escalators and moving walkways	150	40	25
Loading ramps and loading areas	150	40	25
Spaces for breaks, sanitary rooms and first aid rooms			
Canteens	200	80	22
Rest areas	100	80	22
Cloakrooms, washrooms and toilets	200	80	25
Sanitation rooms	500	80	19
Rooms for medical treatment	500	90	16
Control rooms			
Rooms for building service equipment and switchgear rooms	200	60	25
Telex and mail rooms, telephone exchanges	500	80	19
Storerooms and cold stores			
Stock and warehousing rooms	100	60	25
Despatch and packaging rooms	300	60	25
High bay stores			
Passageways without human traffic	20	40	
Passageways with human traffic	150	60	22
Control stand	150	60	22

Table 15-10 (continued)

Chemicals industry, plastics and rubber industries			
Process engineering plant with remote control	50	20	-
Process engineering plant with occasional manual control	150	40	28
Constantly occupied workplaces in process engineering plant	300	80	25
Precision measuring rooms and laboratories	500	80	19
Cutting, reworking and inspection work	750	80	19
Electrical industry			
Assembly work, coarse (large transformers)	300	80	25
Assembly work, medium-fine (switchboards)	500	80	22
Assembly work, fine (telephones)	750	80	19
Assembly work, precision (measuring instruments)	1000	80	16
Electronics workshops, testing t and adjustmen	1500	80	16
Power stations			
Fuel supply systems	50	20	-
Boiler houses	100	40	28
Machine sheds	200	80	25
Ancillary rooms, e.g. pump stations,condenser rooms, etc. Switchgear system (in buildings)	200	60	25
Control rooms	500	80	16
Outdoor switchgear	20	20	-
Offices			
Filing, copying, passageways, etc.	300	80	19
Writing, reading, data processing	500	80	19
Technical drawing	750	80	16
CAD workstations	500	80	19
Conference rooms	500	80	19
Reception desk	300	80	22
Archives	200	80	25

15.4.5 Fire alarm systems

Fires can occur even in installations that are protected by structural measures.

An important component of preventive fire protection (see section 4.7.6) is fire alarm equipment that is automatically or manually activated in accordance with DIN VDE 0833 Parts 1+2. Both the directives of the VdS (association of property insurers) and the structural fire regulations must be observed.

If a fire can be detected early and action to extinguish it taken quickly and directly, the damage caused by the fire or the process of extinguishing it can be reduced.

Automatic fire alarm systems (EN 54) are recommended for switchgear installations, control rooms and data processing systems that are not continuously staffed.

Switchgear installations supplying hospitals and other critical installations must be equipped with fire alarm systems or be included in the general fire alarm system.

Fire alarms are forwarded to a central monitoring site. An incoming fire alarm automatically initiates the appropriate firefighting measures. Figure 15-17 shows a circuit diagram of an automatically or manually actuated alarm system.

Smoke, temperature or the optical appearance of flames are the quantities for early detection of fires that set off the alarm when maximum values are exceeded. These alarms actuate stationary extinguishing systems and also alert the fire department through a central monitoring system.

A fire alarm system generally consists of the following components:

– automatic fire alarms (heat, smoke, flames) installed in groups,

– central fire alarm,

– secure power supply from power system or battery,

– alarm equipment such as sirens, horns, flashing lights,

– actuation, tripping,

– transmission equipment for fire alarms to a continuously staffed monitoring centre (fire department).

The design of an automatic fire alarm system should also include any existing air intake and exhaust systems (corresponding placement of the spot alarms, otherwise an alarm may be delayed).

The components of a fire alarm system must comply with EN 54 and it must be planned and installed by specialist electricians certified to ISO 14675. The relevant work (planning, assembly, commissioning, testing and maintenance) is to be performed by professional specialists. The expertise of the firm concerned must be certified by a body accredited to EN 45011.

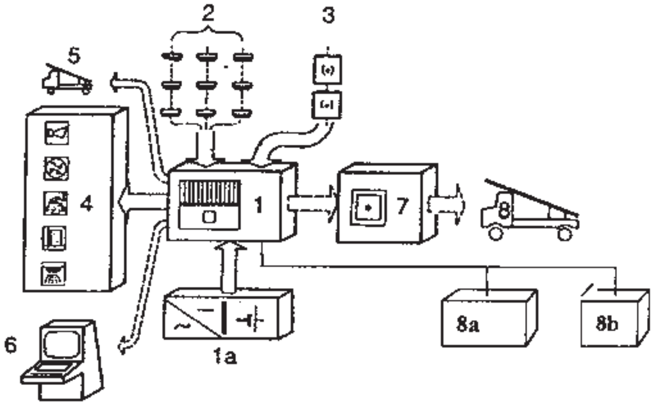


Fig.15-17

Circuit diagram of a fire alarm system

1 Central fire alarm,
1a Power supply (power system and battery)
2 Automatic fire detectors
3 Non-automatic fire alarm (manual alarm)
4 Alarms and actuation/tripping
5 Plant fire department
6 Building services (fault alarms)
7 Transmission equipment for fire alarms (main fire alarm)
8 Public fire department
8a Fire department control panel
8b Fire department key compartment

Monitored transmission channels

The regulations require the transmission channels between the detectors and the central alarm system, between the central alarm system and certain control devices and signalling devices, the transmission channels between activation devices and transmission facilities, control and alarm systems, and those between control rooms, to be available and monitored.

If the proper function of transmission channels which are not exclusively used for alarm systems can be impaired by other signals, a second transmission channel must be provided.

Faults such as wire breakage or short-circuits in a transmission channel, or faults in a section of a transmission line between individual central fire alarms and the transmission channels to the higher level central fire alarms or display and control devices must not impair the correct function of the system.

The power supply systems must comply with DIN 54-4 standard.

The power supply equipment must be capable of ensuring correct operation of the fire alarm system. Failure of each individual energy source in a part of the system must be detected as a fault.

16 Materials and Semi-Finished Products for Switchgear Installations

16.1 Iron and steel

16.1.1 Structural steel, general

The material specifications for structural steels to EN 10 029 apply to carbon steels and low-alloy steels: these are used in the hot-worked condition, and to a lesser extent after normalizing, for reasons of tensile strength and yield strength. The specifications are also valid for forgings, section steel, strip, and heavy and medium plates made from these steels.

Weldability is better with low-carbon steels having less than 0.22% C. Weldability is best with steels of grade 3, e.g. S235 (St 37-3 JR), and poorest with steels of grade 1. Killed steels are to be preferred to rimmed steel, especially if segregation zones might be encountered when welding.

Identification codes for structural steels are contained in EN 10027. This also shows the chemical composition and method of melting or casting.

16.1.2 Dimensions and weights of steel bars and tubes

Table 16-1 Angle steel (L-bars) EN 10056-1

a) Isoceles

Symbol L a × s mm	Weight kg/m	Section modules $Zx = Zy$ cm³
20 × 3	0.88	0.28
25 × 3	1.12	0.45
25 × 4	1.45	0.59
30 × 3	1.36	0.65
30 × 4	1.78	0.85
35 × 4	2.09	1.18
40 × 4	2.42	1.55
40 × 5	2.97	1.91
45 × 4.5	3.06	2.20
50 × 4	3.06	2.46
50 × 5	3.77	3.05
50 × 6	4.47	3.61
60 × 5	4.57	4.45
60 × 6	5.42	5.29
60 × 8	7.09	6.89
65 × 7	6.83	7.18
70 × 6	6.38	7.27
70 × 7	7.38	8.41
75 × 6	6.85	8.41
75 × 8	8.99	11.0
80 × 8	9.63	12.6
80 × 10	11.9	15.4
90 × 7	9.61	14.1
90 × 8	10.9	16.1
90 × 9	12.2	17.9
90 × 10	13.4	19.8
100 × 8	12.2	19.9
100 × 10	15.0	24.6
100 × 12	17.8	29.1
120 × 10	18.2	36.0
120 × 12	21.6	42.7
130 × 12	23.6	50.4
150 × 10	23.0	56.9
150 × 12	27.3	34.8
150 × 15	33.8	83.5
160 × 15	36.2	95.6
180 × 16	43.5	130
180 × 18	48.6	145
200 × 16	48.5	162
200 × 18	54.3	181
200 × 20	59.9	199
200 × 24	71.1	235
250 × 28	104	433
250 × 35	128	529

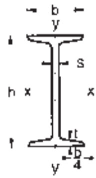
b) Scalene

Symbol L a × s mm	Weight kg/m	Section modules $Zx = Zy$ cm³	
30 × 20 × 3	1.12	0.62	0.29
30 × 20 × 4	1.46	0.81	0.38
40 × 20 × 4	1.77	1.42	0.39
40 × 25 × 4	1.93	1.47	0.62
45 × 30 × 4	2.25	1.91	0.91
50 × 30 × 5	2.96	2.86	1.11
60 × 30 × 5	3.36	4.07	1.14
60 × 40 × 5	3.76	4.25	2.02
60 × 40 × 6	4.46	5.03	2.38
65 × 50 × 5	4.35	5.14	3.19
70 × 50 × 6	5.41	7.01	3.78
75 × 50 × 6	5.65	8.01	3.81
75 × 50 × 8	7.39	10.4	4.95
80 × 40 × 6	5.41	8.73	2.44
80 × 40 × 8	7.07	11.4	3.16
80 × 60 × 7	7.36	10.7	6.34
100 × 50 × 6	6.84	13.08	3.89
100 × 50 × 8	8.97	18.2	5.08
100 × 65 × 7	8.77	16.6	7.53
100 × 65 × 8	9.94	18.9	8.54
100 × 55 × 10	12.3	23.2	10.5
100 × 75 × 8	10.6	19.3	11.4
100 × 75 × 10	13.0	23.8	14.0
100 × 75 × 12	15.4	28.0	16.5
120 × 80 × 8	12.2	27.6	13.2
120 × 80 × 10	15.0	34.1	16.2
120 × 80 × 12	17.8	40.4	19.1
125 × 75 × 8	12.2	29.6	11.6
125 × 75 × 10	15.0	36.5	14.3
125 × 75 × 12	17.8	43.2	16.9
135 × 65 × 8	12.2	33.4	8.75
135 × 65 × 10	15.0	41.3	10.8
150 × 75 × 9	15.4	46.7	13.1
150 × 75 × 10	17.0	51.6	14.5
150 × 75 × 12	20.2	61.3	17.1
150 × 75 × 15	24.8	75.2	21.0
150 × 90 × 10	18.2	53.3	21.0
150 × 90 × 12	21.6	63.3	24.8
150 × 90 × 15	26.6	77.7	30.4
150 × 100 × 10	19.0	54.2	25.9
150 × 100 × 12	22.5	64.4	30.7
200 × 100 × 10	23.0	93.2	26.3
200 × 100 × 12	27.3	111	31.3
200 × 100 × 15	33.75	137	38.5
200 × 150 × 12	32.0	119	70.5
200 × 150 × 15	39.6	147	86.9

Permissible tolerance 50 mm ± 1 mm, up to 100 mm ± 1,5 mm.

Tabelle 16-2

Small-I-beams, serie I, DIN 1025 part 1

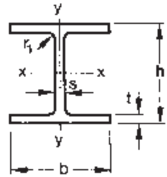


Symbol	Dimensions in mm				Weight	Section modules for bending axis	
						x – x	y – y
						W_x	W_y
I	*h*	*b*	*s*	*t*	kg/m	cm^3	cm^3
80	80	42	3.9	5.9	5.94	19.5	3.00
100	100	50	4.5	6.8	8.34	34.2	4.88
120	120	58	5.1	7.7	11.1	54.7	7.41
140	140	66	5.7	8.6	14.3	81.9	10.7
160	160	74	6.3	9.5	17.9	117	14.8
180	180	82	6.9	10.4	21.9	161	19.8
200	200	90	7.5	11.3	26.2	214	26
220	220	98	8.1	12.2	31.1	278	33.1
240	240	106	8.7	13.1	36.2	354	41.7
260	260	113	9.4	14.1	41.9	442	51
280	280	119	10.1	15.2	47.9	542	61.2
300	300	125	10.8	16.2	54.2	653	72.2
320	320	131	11.5	17.3	61	782	84.7
340	340	137	12.2	18.3	68	923	98.4
360	360	143	13	19.5	76.1	1 090	114
380	380	149	13.7	20.5	84	1 260	131
400	400	155	14.4	21.6	92.4	1 460	149
450	450	170	16.2	24.3	115	2040	203
500	500	185	18	27	141	2750	268
550	550	200	19	30	166	3610	349

Information: international standard W △ Z.

Table 16-3

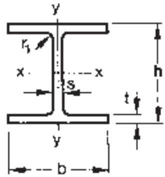
Wide flange I-beams with parallel flanges, serie I PB = HE - B
DIN 1025 Part 2



Symbol	Dimensions in mm					Weight	Section modules for bending axis	
							x – x	y – y
							W_x	W_y
I PB I	*h*	*b*	*s*	*t*	r_1	kg/m	cm^3	cm^3
100	100	100	6	10	12	20.4	89.9	33.5
120	120	120	6.5	11	12	26.7	144	52.9
140	140	140	7	12	12	33.7	216	78.5
160	160	160	8	13	15	42.6	311	111
180	180	180	8.5	14	15	51.2	426	151
200	200	200	9	15	18	61.3	570	200
220	220	220	9.5	16	18	71.5	736	258
240	240	240	10	17	21	83.2	938	327
260	260	260	10	17.5	24	93.0	1 150	395
280	280	280	10.5	18	24	103	1 380	471
300	300	300	11	19	27	117	1 680	571
320	320	300	11.5	20.5	27	127	1 930	616
340	340	300	12	21.5	27	134	2 160	646
360	360	300	12.5	22.5	27	142	2 400	676
400	400	300	13.5	24	27	155	2 880	721
450	450	300	14	26	27	171	3 550	781
500	500	300	14.5	28	27	187	4 290	842
550	550	300	15	29	27	199	4 970	872
600	600	300	15.5	30	27	212	5 700	902
650	650	300	16	31	27	225	6 480	932
700	700	300	17	32	27	241	7 340	963
800	800	300	17.5	33	30	262	8 980	994
900	900	300	18.5	35	30	291	10 980	1 050
1000	1000	300	19	36	30	314	12 890	1 090

Tabelle 16-4

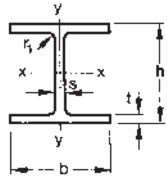
Wide flange I-beams light design, serie I PBI = HE - A
DIN 1025 part 3



Symbol	Dimensions in mm					Weight	Section modules for bending axis	
							x – x	y – y
							W_x	W_y
I PB I	*h*	*b*	*s*	*t*	r_1	kg/m	cm^3	cm^3
100	96	100	5	8	12	16.7	72.8	26.8
120	114	120	5	8	12	19.9	106	38.5
140	133	140	5.5	8.5	12	24.7	155	55.6
160	152	160	6	9	15	30.4	220	76.9
180	171	180	6	9.5	15	35.5	294	103
200	190	200	6.5	10	18	42.3	389	134
220	210	220	7	11	18	50.5	515	178
240	230	240	7.5	12	21	60.3	675	231
260	250	260	7.5	12.5	24	68.2	836	282
280	270	280	8	13	24	76.4	1010	340
300	290	300	8.5	14	27	88.3	1260	421
320	310	300	9	15.5	27	97.6	1480	466
340	330	300	9.5	16.5	27	105	1680	496
360	350	300	10	17.5	27	112	1890	526
400	390	300	11	19	27	125	2310	571
450	440	300	11.5	21	27	140	2900	631
500	490	300	12	23	27	155	3550	691
550	540	300	12.5	24	27	166	4150	721
600	590	300	13	25	27	178	4790	751
650	640	300	13.5	26	27	190	5470	782
700	690	300	14.5	27	27	204	6240	812
800	790	300	15	28	30	224	7680	843
900	890	300	16	30	30	252	9480	903
1000	990	300	16.5	31	30	272	11190	934

Table 16-5

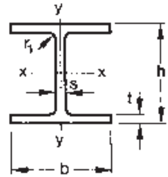
Wide flange I-beams reinforced design, serie I PBv = HE - M
DIN 1025 part 4



Symbol	Dimensions in mm					Weight	Section modules for bending axis	
							x – x	y – y
							W_x	W_y
i PBv	*h*	*b*	*s*	*t*	r_1	kg/m	cm^3	cm^3
100	120	106	12	20	12	41.8	190	75.3
120	140	126	12.5	21	12	52.1	288	112
140	160	146	13	22	12	63.2	411	157
160	180	166	14	23	15	76.2	566	212
180	200	186	14.5	24	15	88.9	748	277
200	220	206	15	25	18	103	967	354
220	240	226	15.5	26	18	117	1220	444
240	270	248	18	32	21	157	1800	657
260	290	268	18	32.5	24	172	2160	780
280	310	288	18.5	33	24	189	2550	914
300	340	310	21	39	27	238	3480	1250
320	359	309	21	40	27	245	3800	1280
340	377	309	21	40	27	248	4050	1280
360	395	308	21	40	27	250	4300	1270
400	432	307	21	40	27	256	4820	1260
450	478	307	21	40	27	263	5500	1260
500	524	306	21	40	27	270	6180	1250
550	572	306	21	40	27	278	6920	1250
600	620	305	21	40	27	285	7660	1240
650	668	305	21	40	27	293	8430	1240
700	716	304	21	40	27	301	9200	1240
800	814	303	21	40	30	317	10870	1230
900	910	302	21	40	30	333	12540	1220
1000	1008	302	21	40	30	349	14330	1220

Table 16-6

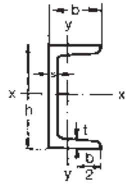
Medium wide flange I-beams, serie I PE
DIN 1025 Part 5



Symbol	Dimensions in mm					Weight	Section modules for bending axis	
							x – x	y – y
							W_x	W_y
I PE	*h*	*b*	*s*	*t*	r_1	kg/m	cm^3	cm^3
80	80	46	3.8	5.2	5	6.00	20.0	3.69
100	100	55	4.1	5.7	7	8.10	34.2	5.79
120	120	64	4.4	6.3	7	10.4	53.0	8.65
140	140	73	4.7	6.9	7	12.9	77.3	12.3
160	160	82	5.0	7.4	9	15.8	109	16.7
180	180	91	5.3	8.0	9	18.8	146	22.2
200	200	100	5.6	8.5	12	22.4	194	28.5
220	220	110	5.9	9.2	12	26.2	252	37.3
240	240	120	6.2	9.8	15	30.7	324	47.3
270	270	135	6.6	10.2	15	36.1	429	62.2
300	300	150	7.1	10.7	15	42.2	557	80.5
330	330	160	7.5	11.5	18	49.1	713	98.5
360	360	170	8.0	12.7	18	57.1	904	123
400	400	180	8.6	13.5	21	66.3	1160	146
450	450	190	9.4	14.6	21	77.6	1500	176
500	500	200	10.2	16.0	21	90.7	1930	214
550	550	210	11.1	17.2	24	106	2440	254
600	600	220	12.0	19.0	24	122	3070	308

Table 16-7

steel channel, DIN 1026-1



Symbol	Dimensions in mm				Weight	for bending axis[1]			
						x – x		y – y	
U	*h*	*b*	*s*	*t*	kg/m	W_x cm³	J_x cm⁴	W_y cm³	J_y cm⁴
30 × 15	30	15	4	4.5	1.74	1.69	2.53	0.39	0.38
30	30	33	5	7	4.27	4.26	6.39	2.68	5.33
40 × 20	40	20	5	5.5	2.87	3.79	7.58	0.86	1.14
40	40	35	5	7	4.87	7.05	14.1	3.08	6.68
50 × 25	50	25	5	6	3.86	6.73	16.8	1.48	2.49
50	50	38	5	7	5.59	10.6	26.4	3.75	9.12
60	60	30	6	6	5.07	10.5	31.6	2.16	4.51
65	65	42	5.5	7.5	7.09	17.7	57.5	5.07	14.1
80	80	45	6	8	8.64	26.5	106	6.36	19.4
100	100	50	6	8.5	10.6	41.2	206	8.49	29.3
120	120	55	7	9	13.4	60.7	364	11.1	43.2
140	140	60	7	10	16.0	86.4	605	14.8	62.7
160	160	65	7.5	10.5	18.8	116	925	18.3	85.3
180	180	70	8	11	22.0	150	1350	22.4	114
200	200	75	8.5	11.5	25.3	191	1910	27.0	148
220	220	80	9	12.5	29.4	245	2690	33.6	197
240	240	85	9.5	13	33.2	300	3600	39.6	248
260	260	90	10	14	37.9	371	4820	47.7	317
280	280	95	10	15	41.8	448	6280	57.2	399
300	300	100	10	16	46.2	535	8030	67.8	495
320	320	100	14	17.5	59.5	679	10870	80.6	597
350	350	100	14	16	60.6	734	12840	75.0	570
380	380	102	13.5	16	63.1	829	15760	78.7	615
400	400	110	14	18	71.8	1020	20350	102	846

[1] J moment of inertia
W section modules

Table 16-8

Dimensions and weight in kg/m (7,85 kg/dm³) for flat steel
DIN 59200
Weights are not in standards.

	Thickness s in mm												
Width b mm	5	6	8	10	12	15	20	25	30	40	50	60	80
160	6.28	7.54	10.0	12.6	15.1	18.8	25.1	31.4	37.7	50.2	62.8	75.4	100
180	7.07	8.48	11.3	14.1	17.0	21.2	28.3	35.3	42.4	56.5	70.7	84.8	113
200	7.85	9.42	12.6	15.7	18.8	23.6	31.4	39.3	47.1	62.8	78.5	94.2	126
220	8.64	10.4	13.8	17.3	20.7	25.9	34.5	43.2	51.8	69.1	86.4	104	138
240	9.42	11.3	15.1	18.8	22.6	28.3	37.7	47.1	56.5	75.4	94.2	113	151
250	9.81	11.8	15.7	19.6	23.6	29.4	39.3	49.1	58.9	78.5	98.1	118	157
260	10.2	12.2	16.3	20.4	24.4	30.6	40.8	51.0	61.2	81.6	102	122	163
280	11.0	13.2	17.6	22.0	26.4	33.0	44.0	54.9	65.9	87.9	110	132	176
300	11.8	14.1	18.8	23.6	28.3	35.3	47.1	58.9	70.7	94.2	118	141	188
320	12.6	15.1	20.1	25.1	30.1	37.7	50.2	62.8	75.4	100	126	151	201
340	13.3	16.0	21.4	26.7	32.0	40.0	53.4	66.7	80.1	107	133	160	214
350	13.7	16.5	22.0	27.5	33.0	41.2	55.0	68.7	82.4	110	137	165	220
360	14.1	17.0	22.6	28.3	33.9	42.4	56.5	70.6	84.8	113	141	170	226
380	14.9	17.9	23.9	29.8	35.8	44.7	59.7	74.6	89.5	119	149	179	239
400	15.7	18.8	25.1	31.4	37.7	47.1	62.8	78.5	94.2	126	157	188	251
450	17.7	21.2	28.3	35.3	42.4	53.0	70.7	88.4	106	141	177	212	283
500	19.6	23.6	31.4	39.3	47.2	59.0	78.7	98.3	118	157	196	236	314
550	21.6	25.9	34.5	43.2	51.8	64.8	86.4	108	130	173	216	259	345
600	23.6	28.3	37.7	47.1	56.5	70.7	94.2	118	141	188	236	283	377
650	25.5	30.6	40.8	51.0	61.2	76.5	102	128	153	204	255	306	408
700	27.5	33.0	44.0	55.0	65.9	82.4	110	137	165	220	275	330	440
750	29.4	35.3	47.1	58.9	70.7	88.3	118	147	177	236	294	353	471
800	31.4	37.7	50.2	62.8	75.4	94.2	126	157	188	251	314	377	502
900	35.3	42.4	56.5	70.7	84.8	106	141	177	212	283	353	424	565
1000	39.2	47.1	62.8	78.5	94.2	118	157	196	236	314	392	471	628
1100	43.2	51.8	69.1	86.4	104	130	173	216	259	345	432	518	691
1200	47.1	56.5	75.4	94.2	113	141	188	235	283	377	471	565	754

Table 16-9

Dimensions of steel conduits, pluggable, EN 50086

Size	16	20	25	32	40	50	63
Outer Ø mm	16.0	20.0	25.0	32.0	40.0	50.0	63.0
Inner Ø mm	13.3	17.3	22.1	29.0	37.0	47.0	59.9
Min insertion mm	16	20	25	30	32	42	50

16.1.3 Stresses in steel components

The permissible stresses in steel components for transmission towers and structures for outdoor switchgear installations are laid down in DIN VDE 0210. Values for different kinds of stress, such as tensile, shear, compressive and bearing stresses are specified for the steel sections are given.

Remarks:

Structural steels to EN 10 025, screws and bolts to DIN 267. Permissible weld stresses for welded towers are given in DIN 18800, Part 1.

According to VDE 0210, structural steels of grade S 235 JR (St 37-2) and above may be used for overhead power lines.

16.2 Non-ferrous metals

16.2.1 Copper for electrical engineering

Various unalloyed grades of copper are used as conductor materials: oxidized, oxygen-free and oxygen-free deoxidized copper materials.

The most frequently used oxidized copper grades Cu-ETP and Cu-FRHC contain up to 0.04% oxygen, and in the soft condition have a conductivity of at least 58 MS/m, a tensile strength of 200 MPa and are suitable for cold forming. Hydrogen embrittlement can occur during heat treatment, soldering and welding unless an inert gas atmosphere (MIG, TIG) is used.

Oxygen-free copper Cu-OF (obtained from copper cathodes of maximum purity) is totally free of oxygen, also has a conductivity of at least 58 MS/m, is free of vaporizable elements and thus suitable for use in vacuum interrupters and in superconductor technology. Oxygen-free deoxidized (with phosphorus) copper is only suitable for that application in special grades (free of vaporizable elements).

Standards for semi-finished products in copper and copper alloys (with small amounts of additives) for use in electrical engineering

EN 13599:2002-07 to EN 13605:2002-10 for sheet, tubes, bars, sections and wires

Product designations

Description	Relevant EN standard	Material designation Material no.	Condition designation	Nominal dimensions in mm
Sheet	EN 13601	Cu-ETP	R290	6.0 x 600 x 2000
Sheet	EN 13601	CW004A	R290	6.0 x 600 x 2000

Material designations

Example 1 Designation to ISO 1190-1:1982-11: Cu-ETP or
Material no. to EN 1412:1995-12: CW004A
(formerly E-Cu58, E-Cu57; old designation: E-Cu)
Preferred conductor material in switchgear, contains oxygen.

Example 2 Designation to ISO 1190-1:1982-11: Cu-OF or
Material no. to EN 1412:1995-12: CW008A
(formally OF-Cu; old designation: OFHC)
For vacuum interrupter manufacture, oxygen-free.

Condition designations (Examples from EN 1173:1995-12)

M - As manufactured, without specified requirements for mechanical properties

D - Drawn, without specified requirements for mechanical properties

H... - Condition described with minimum value for hardness (Vickers or Brinell)

R... - Condition described with minimum value for tensile strength in MPa (N/mm^2)

See section 13.1.1 for special properties of conductor materials.

16.2.2 Brass and bronze

As brass and bronze are predominantly structural materials in electrical engineering, the stipulations for copper and copper alloys apply here for general use.

Material designations

Example 1 Designation to ISO 1190-1:1982-11: CuZn28 or
Material no. to EN 1412:1995-12: CW504L
Brass with 28% Zn for spring parts in plug connectors.

Example 2 Designation to ISO 1190-1:1982-11: CuSn6 or
Material no. to EN 1412:1995-12: CW452K
Tin bronze with 6% Sn for sheets, bars, sections and wires.

See section 13.1.1 for special properties of conductor materials.

16.2.3 Aluminium for electrical engineering

Aluminium is used in electrical engineering both as a structural material, e.g. for enclosures, guides and force transmission components, and as a conductor material – and in that application both as a wrought alloy (wires and semi-finished products) and as a cast alloy (die cast cage rotors). Pure aluminium alloys (99.5% Al), alloys of the AlMgSi group and aluminium-zirconium alloys (TAL) are mainly used as conductors. Ultra-pure aluminium (99.99% and above) is used for special purposes (capacitor foil, semiconductor and low temperature technology).

The electrical conductivity and mechanical strength of aluminium alloys are determined by the alloy components, by mechanical forming and by heat treatment. As a rule, these two properties are found to change inversely to each other.

Standards for semi-finished products in aluminium and aluminium alloys for use in electrical engineering

EN 14121:2003-08 for strips, sheets and plates
EN 40501-2:1985-06 for tubes
EN 40501-3:1985-06 for bars and sections
EN 1715-1/-2:1997-11 for cast wire rods in EAl

Product designations

Description	Relevant EN standard	Material designation Material no.	Condition designation	Nominal dimensions in mm
Sheet	EN 14121	EN AW-1350A	- F	6.0 x 600 x 2000
Sheet	EN 14121	EN AW-EAl 99.5(A)	- F	6.0 x 600 x 2000

Material designations

Example 1 Numerical designation to EN 573 (1:1994-12): EN AW-1350A or
Alphanumerical designation to EN 573-2 (1994-12),
Standard: EN AW–1350A [EAl 99.5(A)]
Exception: EN AW-EAl 99.5(A)
(formerly E-Al), mainly used as electrical conductors.

Example 2 Numerical designation to EN 573-1 (1994-12): EN AW-6101B or
Alphanumerical designation to EN 573-2 (1994-12),
Standard: EN AW-6101B [EAl MgSi(B)]
Exception: EN AW-EAl MgSi(B)
(formerly E-AlMgSi0,5), material for conductor bars of high tensile strength.

The prefix „E" before „Al" fundamentally identifies aluminium grades for electrical engineering. In the alphanumerical designation, the main alloy components follow the „Al". Appended figures indicate the purity of the aluminium and the percentage of the components.

Condition designation (to EN 515:1993-12)

F - As manufactured, without specified requirements for mechanical properties
O... - annealed) Each of the following figures is a code
H... - strain hardened) for details of the treatment and condition.
T... - heat treated) They are not indicators of mechanical properties. See the relevant standards for semi-finished products for those data.

See section 13.1.1 for special properties of conductor materials.

16.3 Insulating materials

16.3.1 Solid insulating materials

Table 16-10

Abbreviations and properties of solid insulating materials

Abbreviation	Material	Bulk density	Bending strength	Tensile strength	Impact strength	Elasticity modulus	Linear thermal expansion	Thermal conductivity	Limiting temperature	Tracking resistance	Electric strenght	Volume resistivity	Dielectric constant	Product label
		ISO 1183	ISO 178	ISO 527	ISO 180	ISO 187	ISO 11359	DIN 52612	ISO 306	IEC 60112	IEC 60243-2	IEC 60093	IEC 60250	
		ρ kg/dm³	σ_b MPa	σ_z MPa	a_n kJ/m²	E MPa	α_1 10^{-4}/K	λ W/(m · K)	°C	Comparative figure	E_d kV/mm	ρ_D $\Omega \cdot$ cm	ε_r (50 Hz)	
	Insulating materials for cables and conductors													
PVC-P	polyvinyl chloride non-rigid	1.3				150	1 – 2	0.2	60	600	10 – 25	10^{15}	3.5 – 7.5	Astralon, Mipolam, Trovidur
PVC-U	polyvinyl chloride rigid	1.38	100	50	30	2 500	1.0	0.2	90	600	30 – 40	10^{15}	3.3 – 4	Vestolit, Vinoflex, DC-Fix, Pegulan, Hostalit Fibres: PW, Rhovyl, Thermovyl
PE	high-pressure polyethylene	0.917	80	12	without rupture	100	1.8	0.3	80	600	40	10^{17}	2.25	Lupolen H, Vestolen, Trolen
	low-pressure polyethylene	0.96	80	25	without rupture	1 400	2.0	0.5	95	600	45	10^{17}	2.3	Hostalen, Marlex Foils: Baulen, Hellaflex Fibres: Polytrene, Trofil
XLPE (VPE)	cross-linked polyethylene				without rupture		2.5		130	600	>45	10^{17}	2.4	Cable insulation (XLPE)

(continued)

Table 16-10 (continued)

Abbreviations and properties of solid insulating materials

Abbreviation	Material	Bulk density	Bending strength	Tensile strength	Impact strength	Elasticity modulus	Linear thermal expansion	Thermal conductivity	Limiting temperature	Tracking resistance	Electric strenght	Volume resistivity	Dielectric constant	Product label
		ISO 1183	ISO 178	ISO 527	ISO 180	ISO 187	ISO 11359	DIN 52612	ISO 306	IEC 60112	IEC 60243-2	IEC 60093	IEC 60250	
		ρ kg/dm³	σ_b MPa	σ_z MPa	a_n kJ/m²	E MPa	α_1 10^{-4}/K	λ W/(m · K)	°C	Comparative figure	E_d kV/mm	ρ_D $\Omega \cdot$ cm	ε_r (50 Hz)	
	Insulating materials for foils, semi-finished products, struct. comp.(thermoplastics, mouldings)													
PC	polycarbonate (PC 300)	1.2	75	65	without rupture	2 200	0.6	0.2	130	275	25	10^{15}	3.0	Lexan, Makrolon
PTFE	polytetrafluorethylene	2.2	19	20	without rupture	4 000	0.6	0.24	250	600	35	$>10^{18}$	2.0	Teflon, Hostaflon TE, Fluon
PS	polystyrene	1.05	100		22	2 000	0.8	0.14	60-90	375-475	50	$>10^{16}$	2.5	Polystyrol, Styroflex, Novodur,Trolitul, Styron, Vestyron Foils: Trolit, Elektroiso.
	foam polystyrene	0.02–0.06	0.3-2.5	0.3-5.5										Styropor
PET	polyethylene terephthalate	1.38	117	54	without rupture	2 800	0.6	0.2	120	250	30	10^{17}	3.5	Foils: Hostaphan, Mylar Fibres: Diolen, Dacron
PF	phenolic formaldehyde resins	1.4–1.9	50–60	20–25	20–120	6 000–16 000	0.15–0.3	0.7–0.3	100-150	125-175	5–20	10^{8}–10^{11}	4–15	Albertit, Bakelite, Formica, Pertinax
	PF-Hgw 2072	1.6–1.8	200	100	50	14 000	0.2–0.4	0.3	130	25-150	20–25	10^{11}	5	with woven glass silk VDE 0334
MF Re-	melamine resins	1.5	40–80	15–30	3.5–25	6 000– 13 000	0.1–0.5	0.3–0.7	100–140	600	10–30	10^{8}–10^{12}	6–10	Albamit, Chemoplast, sopal, Ultrapas, Bakelite
	MF-Hgw 2272 (in sheet)	1.8–2.0	270	120	50	14 000	0.1–0.2	0.3	130	600	20–25	10^{10}	7.0	Woven glass silk to VDE 0334
	melamine phenolic resins	1.6	70-80	30	6	6 000–8 000	0.15–0.3	0.35	120	600	30	10^{10}	6.0–15.0	Aminoplast, Phenoplast Moulding compound

(continued)

Table 16-10 (continued)

Abbreviations and properties of solid insulating materials

Abbreviation	Material	Bulk density ISO 1183 ρ kg/dm^3	Bending strength ISO 178 σ_b MPa	Tensile strength ISO 527 σ_z MPa	Impact strength ISO 180 a_n kJ/m^2	Elasticity modulus ISO 187 E MPa	Linear thermal expansion ISO 11359 α_1 $10^{-4}/K$	Thermal conductivity DIN 52612 λ $W/(m \cdot K)$	Limiting temperature ISO 306 °C	Tracking resistance IEC 60112 Comparative figure	Electric strenght IEC 60243-2 E_d kV/mm	Volume resistivity IEC 60093 ρ_D $\Omega \cdot cm$	Dielectric constant IEC 60250 ε_r (50 Hz)	Product label
	Insulating materials for structural components (thermoplastics)													
PA 66	polyamide A	1.13	50-120	70	without rupture	2 000	0.7-1.0	0.2	120	600	25	10^{14}	4-8	Ultramid A, Durethan A, Zytel
PA 66	polyamide A with fibreglass	1.35	270	190	50	10 000	0.15-0.2	0.2	130	550	30	10^{12}		Ultramid A, Durethan A, Zytel
PA 6	polyamide B	1.14		60	without rupture	1 500	0.7-1.0	0.2	110	600	20-50	10^{12}-10^{15}	3.0-7.0	Ultramid B, Durethan B, Zytel
PA 6	polyamide B with fibreglass	1.38	250	180	65	10 000	0.2-0.3	0.2	120	550	30	10^{12}	3.0-7.0	Ultramid B, Durethan B, Zytel
GFN	PPO-reinforced	1.21			15	6 500			180					Noryl GFNZ halogenfree
PBT	polybutylene-terephthalate	1.3	90		without rupture	2 500	0.8	0.2	140	600	22-30	10^{16}	3.8	Vestadur, Pocan, Crastin
PBT	polybutyleneterephthalate with fibreglass	1.42	210	140	56	10 000	0.3	0.3	150	250	28-34	10^{15}	4.5	Vestadur, Pocan, Crastin
PUR	polyurethane (linear)	1.21	25–70	65	without rupture	2 200	0.6	0.2	130	220	20	10^{15}	3.0	
ABS	acrylic butadiene styrene	1.06			without	2 400	0.8	0.2	80	575	22	$>10^{15}$	3.3	Novodur, Terluran

(continued)

Table 16-10 (continued)

Abbreviations and properties of solid insulating materials

Abbreviation	Material	Bulk density ISO 1183 ρ kg/dm³	Bending strength ISO 178 σ_b MPa	Tensile strength ISO 527 σ_z MPa	Impact strength ISO 180 a_n kJ/m²	Elasticity modulus ISO 187 E MPa	Linear thermal expansion ISO 11359 α_1 10^{-4}/K	Thermal conductivity DIN 52612 λ W/(m · K)	Limiting temperature ISO 306 °C	Tracking resistance IEC 60112 Comparative figure	Electric strenght IEC 60243-2 E_d kV/mm	Volume resistivity IEC 60093 ρ_D $\Omega \cdot$ cm	Dielectric constant IEC 60250 ε_r (50 Hz)	Product label
	Cast resin mouldings (duroplastics)													
EP	epoxy resins (with 60–70 % filler)	1.6–1.8	70–80	75	10–68	14 000	0.3	0.6	125	600	30	10^{15}	4.2	Araldite 60 % powdered quartz, Resodip
	EP-Hgw 2372.2 (flame resistant)	1.7–1.9	350	220	100	18 000	0.1–0.2	0.3	155	180	40	10^{12}	4.0	EP + woven glass silk to VDE 0334
UP	unsaturated polyester resins (with 60-70 % filler)	1.6–1.8	40–60		10–40		0.3		110-130	600	25	10^{15}	4.5–7.5	Supraplast
	UP-Hgw 2472 (in sheet)	1.6–1.8	200	100	100	10 000	0.15–0.3	0.3	130	500-600	25–30	10^{12}	5.0	Glass mat to VDE 0334
PUR	polyurethane resin with 60-70% filler	1.6-1.8	120	70-100	10-100	10 000	0.4	0.8	110	600	30	10^{15}	4,3	Baygal, Baymidur

(continued)

Table 16-10 (continued)

Abbreviations and properties of solid insulating materials

Abbreviation		Material	Bulk density ISO 1183 ρ kg/dm³	Bending strength ISO 178 σ_b MPa 1)	Bending strength ISO 178 σ_b MPa 2)	Tensile strength ISO 527 σ_z MPa 1)	Tensile strength ISO 527 σ_z MPa 2)	Impact strength ISO 180 a_n kJ/m²	Elasticity modulus ISO 187 E MPa	Linear thermal expansion ISO 11359 α_1 10^{-4}/K	Thermal conductivity DIN 52612 λ W/(m · K)	Limiting temperature ISO 306 °C	Tracking resistance IEC 60112 Comparative figure	Electric strenght IEC 60243-2 E_d kV/mm	Volume resistivity IEC 60093 ρ_D $\Omega \cdot$ cm	Dielectric constant IEC 60250 ε_r (50 Hz)	$\varepsilon_r \tan\delta \cdot 10^3$ 3)	Product label
		Ceramic insulating materials, e.g. post insulators, insulators, bushings																
KER	110.1	predominantly aluminium silicate	2.4	60	40	30	25	1.8		0.038	1.6			30–35	10^{11}–10^{12}	6	17/120	Porcelain, Hard porcelain, Melatith,
KER	110.2		2.5	100	80	60	45	2.2		0.045	2.3			30–35	10^{11}–10^{12}	6	17/120	Karbowid 1203
KER	220	predominantly magnesium silicate	2.6	120	120	60	45	3		0.07	2.3			20	10^{12}	6	2.5/65	Skalit Frequenta, Calit,
KER	221		2.8	140	140	60	45	4		0.06	2.3			30	10^{12}	6	1.0/15	Dettan
KER	310	predominantly titanium oxide	3.5–	900–		300–				0.06–				10–		60		
KER	311		3.9	1500		800				0.08				20		40		
KER	610	sintered corundum Al_2O_3	3.4	–	120	183	40			0.07	16			25		7		AD 85 Degussit
KER	611		3.9	–	90					0.08	36							AD 99.9 furnace ceramic
		zirconium ceramic	3.1	552						0.04	110							furnace ceramic

1) Glazed 2) Unglazed 3) 20 °C / 100 °C

Note: The values given for mechanical properties may vary in practice, depending on how the materials are processed and the shape of the insulator.

16.3.2 Liquid insulating materials

Mineral oils are predominantly used as liquid insulating materials in transformers, high voltage cables (>110 kV), capacitors, instrument transformers, oil-cooled rectifiers and switching devices. All these applications make use of the high dielectric strength (breakdown voltage) of mineral oil, which however can be greatly impaired by moisture or foreign bodies. When used in switching devices, oil also serves to influence the arcing process. In transformers, the dissipated heat in the windings is conducted away by the oil, predominantly by convection. This depends upon the kinematic viscosity being as low as possible in the entire service temperature range.

A further factor of decisive importance for the suitability of an oil is its resistance to oxidative ageing, which can lead to the formation of oil sludge, to increased viscosity, to tarnishing film on contact surfaces and to drops in dielectric properties. Resistance to ageing can be improved by adding inhibitors.

In applications with especially high dielectric field stresses, such as capacitors, cables, instrument transformers and extra-high voltage transformers, so-called „gas-proof" insulating oils are notable for their ability to bind the hydrogen which may be created by discharges in areas of very high dielectric field strength.

These versatile properties can be achieved in oil manufacture by selecting suitable crude oil, distilling, refining and mixing with additives. As the requirements are varied, there is a wide range of oils available.

Synthetic esters or silicone oil are used in place of insulating oils in transformers which are intended for particular applications (e.g. excavators or locomotives) or for particular locations (e.g. hospitals) with a view to the potential environmental effects on the one hand and the fire risk on the other hand if a fault should occur.

Property	Unit	Transformer-oil	Low temperature switchgear oil	Liquid silicone	Transformer ester
		IEC 60296		IEC 60836	IEC 61099
Density	kg/dm³ at 20 °C	max 0.895		max. 0.970	max. 1.000
Kin. viscosity	mm²/s at 40 °C	max. 12	max. 3.5	40 ± 4	max. 35
	mm²/s at	max. 1800 – 30 °C	max. 400 – 40 °C	– –	max. 3000 – 20 °C
Pour point	°C	max. – 40	max. – 60	max. –50	max. – 45
Thermal conductivity	W/cmK at 25 °C	~ 0.0013		~ 0.0015	~ 0.0015
Spez. heat coefficient of expansion	J/g K 1/K	~ 1.9 ~ 0.0008		~ 1.5 ~ 0.001	~ 2.1 ~ 0.001
Dielectric constant	at	~ 2.2 25 °C	~ 2.4 25 °C	~ 2.55 90 °C	~ 3.2 25 °C
Dielectric loss factor	at 90 °C	max. 0.500		max. 0.001	max. 0.03
Discruptive discharge voltage	kV	min. 30/70		min. 40	min. 45
Flashpoint P.M.	°C	min. 135	min. 100	min. 240	min. 250
Flammability	–	Flammable		Flammable retardant	Flammable retardant
Gases	–	Explosive		Explosive	Explosive
Ecological aspects	–	Non biodegradable		Non biodegradable	Non biodegradable

16.3.3 Gaseous insulating materials

Table 16-12

Properties of air and sulphur hexafluoride (SF_6)

Gas	Density[1)] kg/m³	Discruptive discharge voltage E_d kV/mm (50 Hz)	Dielectric constant ε_r (50 Hz)
Air (dry)	1.205	2.1	1.000576
Sulphur hexafluoride	6.07	6	1.002

1) at 20 °C and 1013 mbar

Curves of pressure, temperature and density for SF_6 gas are shown in Fig. 11-1. The insulating and arc-quenching properties of this gas are dealt with in Sections 10.4.4 and 11.2.2.

16.4 Semi-finished products

16.4.1 Dimensions and weights of metal sheets

Table 16-13

Weight per 1 m² of sheet, in kg

Thickness *s* in mm treadplate	Steel	Aluminium	Copper	Brass	Zinc	Ribbed sheet	Profiled
0.5	3.925	1.34	4.45	4.275	3.6	–	–
0.75	5.888	2.01	6.657	6.413	5.4	–	–
1	7.85	2.68	8.9	8.55	7.2	–	–
1.5	11.775	4.02	13.35	12.825	10.8	–	–
2	15.7	5.36	17.8	17.10	14.4	–	–
2.5	19.63	6.7	22.25	21.38	18.0	–	–
3	23.6	8.04	26.7	26.65	21.6	30	25
4	31.4	10.72	35.6	34.20	28.8	38	34
5	39.3	13.4	44.5	42.75	36	46	42
6	47.2	16.08	53.4	51.3	43.2	54	51
8	64.0	21.6	71.6	68.4	57.6	70	67

Normal panel size 1000 mm × 2 000 mm
Switchboard sheet 1250 mm × 2 500 mm
Ribbed sheet and profiled treadplate 1250 mm × 2 500 mm

16.4.2 Slotted steel strip

Table 16-14

Slotted steel strip, hot-galvanized

Dimensions mm	Slot size mm	Weight kg / m	Standard roll, length m	in cut lengths 3 m approx., m / bundle
20 × 1.5	40 × 5.5	0.187	200	60
20 × 2	40 × 5.5	0.245	200	60
25 × 2	40 × 5.5	0.326	200	60
30 × 2.5	40 × 5.5	0.508	150	60
20 × 3	40 × 6.5	0.368	120	60
25 × 3	40 × 6.5	0.489	120	60
30 × 3	40 × 6.5	0.640	120	60
30 × 4	60 × 8.5	0.716	100	30
40 × 4	70 × 8.5	1.038	80	30
50 × 4	70 × 8.5	1.360	80	30

Steel earthing strip, hot-galvanized, DIN 48801

Dimensions mm	Weight kg / m	Standard roll m
20 × 2.5	0.400	100
30 × 3.5	0.840	100 (50)
30 × 4.0	0.961	30
40 × 5.0	1.600	50

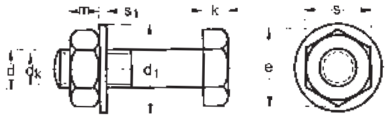
Accessories, plastic rawl plugs

Size mm	Plug length mm	Hole dia. mm	For screws dia. mm
5	25	5	2.5 – 4
6	30	6	3.5 – 5
6	60	6	3.5 – 5
8	40	8	4.5 – 6
8	75	8	4.5 – 6
10	50	10	6 – 8
12	60	12	8 – 10

16.4.3 Threads for bolts and screws

Table 16-15

Bolts and screws with metric thread, DIN 7990, dimensions in mm
Nuts EN 24034
Washer DIN 7989



Bolt threads Nominal dia-meter *d*	Thickness of head *k*	Thickness of nut *m* *max*	Width across flats *s*	angles *e*	washer d_1	s_1	Drill hole pass throught dia.	for thread dia.
12	8	12.2	18	19.9	24	8	14	10.2
16	10	15.9	24	26.2	30	8	18	14
20	13	19	30	33.0	37	8	22	17.5
24	15	22.3	36	39.6	44	8	26	21
30	19	26.4	46	50.6	56	8	33	26.5

Lock nuts DIN 7967
Washer for U-profile DIN 434
Washer alternative DIN 126
Spring washer DIN 128

16.4.4 Tighetening torques for hot dip galvanized hexagon screws

Guideline values for tightening torques to achieve an adequate pre-tension.

The tightening torques apply to lubricated and unlubricated screws with hot dip galvanizing.

The deviation can be up to ± 20%, depending on the supplier.

Quality	M12 Nm	M16 Nm	M20 Nm	M24 Nm	M27 Nm
5.6	39	91	179	309	437
6.9	68	163	323	546	764
8.8	86	210	408	704	1013
10.9	120	293	571	985	1422

16.4.5 Treads for electricial engineering

Table 16-16

Cable glands with metric threads acc. EN 5026, dimensions in mm

Nominal-value	External thread	Mounting hole Ø mm	Cable range[1)] Max Ø mm	Min Ø mm
12	M12 × 1.5	12.5	7	3
16	M16 × 1.5	16.5	10	5
20	M20 × 1.5	20.5	13	8
25	M25 × 1.5	25.5	17	11
32	M32 × 1.5	32.5	21	15
40	M40 × 1.5	40.5	28	19
50	M50 × 1.5	50.5	35	27
63	M63 × 1.5	63.5	48	35

[1)] Manufacturer information

17 Miscellaneous

17.1 DIN VDE, EN and IEC standards for substation design

The VDE catalogue of (primarily technical safety) standards for the entire field of electrical engineering in Germany is among the most important tasks of the VDE Verband der Elektrotechnik Elektronik Informationstechnik e.V. (VDE Association for Electrical Electronic & Information Technologies). The content, design, development and legal significance of the VDE catalogue of standards are described in detail in VDE publication 0022. Selected extracts of a fundamental nature are quoted below:

> "The stipulations contained in the VDE catalogue are drawn up by the Deutsche Elektrotechnische Kommission (DKE) of DIN and VDE.
>
> The DKE is the German national organization for compiling national and international standards and VDE standards in the entire field of electrical engineering in Germany."
>
> "Results of international work are to be adopted as far as possible without alteration into the VDE standards catalogue and simultaneously into the DIN catalogue of standards.
>
> In the interests of European and worldwide harmonization, the rules of CENELEC (European Committee for Electrotechnical Standardization) impose an obligation to adopt certain standards of the International Electrotechnical Commission (IEC) and also European standards (EN) and harmonization documents (HD) issued by CENELEC."
>
> The component parts of the VDE standards catalogue are:
> – the rules and other rules relating thereto,
> – VDE standards,
> – VDE guidelines,
> – attachments to rules, VDE standards and VDE guidelines.

"The results of the DKE's work on electrotechnical standardization, which include safety regulations where appropriate, are registered as DIN standards, with additional identification as VDE standard or VDE guideline, in the VDE standards catalogue. The results of this work also include draft standards, amendments and the draft standards of the VDE:"

Standardization work for the field of electrical engineering is conducted almost entirely on an international level. DKE is actively involved with the appointment of specialists to the working groups, committees and other bodies of the international organizations and submits position papers on drafts and other queries and approves the acceptance of regulations. The position papers are prepared by the relevant DKE committee.

Agreements between IEC and CENELEC on one hand and between CENELEC and DKE on the other regulate the incorporation of international standards into national standards. The national committee and the relevant DKE advisers section share the responsibility for the publication schedule of the international standard translated into German – without deviations or with only minor, clearly defined deviations – as a German standard.

VDE standards, guidelines and the associated supplements have an identification number combined from a DIN numbering system and a VDE classification number. The DIN numbering system also includes information on the origins of the content of the standard, while the VDE classification makes it much easier to find. The following scheme is used:

DIN EN 6 …	(VDE 0 …)	– European standard (EN), formed by using an IEC standard word by word (1st number = 6) *)
DIN EN 5 …	(VDE 0 …)	– European standard (EN) of other origin (1st number = 5)
DIN IEC 6 …	(VDE 0 …)	– IEC standard incorporated word for word but is not EN
DIN VDE 0 …	(VDE 0 …)	– IEC standard incorporated with deviations
		– CENELEC (HD) harmonization document that is not equivalent to an IEC standard
		– national standard

In comprehensive standards comprising several parts the part numbers are preceded by a hyphen or in the case of the VDE classification by the word "Part”.

Because the new identification system has only been defined since 1993, at present a whole series of VDE regulations is still valid whose DIN reference number was specified under a different system. They are to be adapted to the new system during the next technical revision.

Existing working results of the former type such as VDE guidelines, VDE standards, VDE codes of practice, VDE directives, VDE regulations, VDE publications are also being adapted to the above components of the VDE catalogue, when they are revised.

*) The number of the DIN numbering system corresponds to the new 5-digit numbering system, which is currently in the process of introduction by the International Electrotechnical Commission (IEC). It also begins with 6 in the first position followed by the former 2, 3 or 4-digit IEC reference number and zeros in the vacant positions.

The legal significance of the specifications standards of the VDE catalogue is clarified by the following citations from VDE 0022.

> "At the time of their publication VDE specifications are the basis for correct engineering practice."
>
> "According to § 1 of the 2nd implementing regulation effective 1 January 1987 to the energy supply act (2nd DVO to the EnWG, BGBl. (federal gazette)1987 I, p. 146), the generally accepted rules of engineering must be observed for the erection and maintenance of installations for the generation, transmission and supply of electricity. Where installations must meet the state of safety engineering set in the community on the basis of European Community regulations, these regulations are mandatory.”

The VDE standards must always be observed if one does not wish to be accused of not meeting the duty of care in the manufacture and maintenance of electrical installations and devices.

The following list shows an overview of the most important DIN VDE (IEC , EN, ISO) standards for switchgear engineering. They are listed with their full numbering as at end of 2005 and the month in which they became effective. Because of the extent of the current DIN VDE catalogue of standards , this list cannot be considered complete. For example, later amendments, draft standards, supplements and drafts have generally not been included. The majority of listed DIN VDE standards also have corresponding IEC or EN standards. Where this is not the case, international standards are given if possible.

For improved clarity and to save space, some titles of standards are slightly abbreviated. In standard series the general header has not been repeated in the list of standards immediately following.

Group 1 Power installations

IEC 60364-1 mod.	**(VDE 0100 Part 100)** Erection of low voltage installations – scope, object and fundamental principles	2002-08
IEC 60050-826 Draft	**(VDE 0100 Part 200)** Electrical installations of buildings – Definitions	1998-06
IEC 60364-3 mod.	**(VDE 0100 Part 300)** Erection of power installations with nominal voltages up to 1000 V – Assessment of general characteristics of installations	1996-01
IEC 60364-4-41 mod.	**(VDE 0100 Part 410)** - Protection against electric shock	1997-01
IEC 60364-4-42 Draft	**(VDE 0100 Part 420)** - Protection against thermal effects	1991-11
IEC 60364-4-43 Draft	**(VDE 0100 Part 430)** – Protection of cable and cords against overcurrent	1991-11
IEC 60364-4-44/A3 Draft	**(VDE 0100 Teil 442)** Electrical installations of buildings – Protection of low voltage installations against faults between high-voltage systems and earth	1997-11

Numerous further parts

IEC 60364-7-729 Draft	**(VDE 0100 Part 729)** Erection of power installations with nominal voltages up to 1000 V – installation and connection of switchgear and controlgear and distrubution boards	1986-11
DIN VDE 0100 - 736	**(VDE 0100 Part 736)** – low voltages circuits in high-voltage switchboards	1983-11
DIN VDE 0100-737	**(VDE 0100 Part 737)** - Humid and wet areas and locations, outdoor installations	2002-01
DIN VDE 0100-739	**(VDE 0100 Part 739)** – additional protection in the case of direct contact in dwellings be residual current devices with In <= 30mA in TN systems and TT systems	1989-06
HD 637 S1 1999	**(VDE 0101)** Power installations exceeding 1 kV	2000-01
IEC 60909-0	**(VDE 0102)** Short-circuit currents in three-phase a.c. systems	2002-07
IEC 60909-3	**(VDE 0102 Part 3)** Currents during two separate simultaneous line-to-earth short circuits and partial short-circuit currents flowing through earth	2004-05
IEC 60865-1	**(VDE 0103)** Short-circuit currents - Calculation of effects – Definitions and calculation methods	1994-11
EN 50110-1	**(VDE 0105 Part 1)** Operation of electrical installations	2003-05
DIN VDE 0105-100	**(VDE 0105 Part 100)** Operation of electrical installations - General requirements	2000-06
DIN VDE 0105-103	**(VDE 0105 Part 103)** – Particular requirements for railways	1999-06
DIN VDE 0105-7	**(VDE 0105 Part 7)** – supplementary requirements for atmospheres endangered by potentially explosive material	1987-12
IEC 60664-1	**(VDE 0110 Part 1)** Insulation coordination for equipment within low-voltage systems - Principles, requirements and tests	2003-11

IEC 60071-1	**(VDE 0111 Part 1)** Insulation co-ordination - Definitions, principles and rules	1996-07
IEC 60071-2	**(VDE 0111 Part 2)** – Application guide	1997-09
IEC 60204-1	**(VDE 0113 Part 1)** Safety of machinery - Electrical equipment of machines - General requirements	1998-11
EN 50163	**(VDE 0115 Part 102)** Railway applications - Supply voltages of traction systems	2005-07
EN 50153	**(VDE 0115 Part 2)** Railway applications - Particular requirements for AC switchgear – Protective provisions relating to electrical safety	2003-07
EN 50122-1	**(VDE 0115 Part 3)** Railway applications - Protective provisions relating to electrical safety and earthing	1997-12
EN 50329	**(VDE 0115 Part 289)** Railway applications - Traction transformers	2003-09
DIN VDE 0118-1	**(VDE 0118 Part 1)** Erection of electrical installations in mines - General requirements	2001-11
DIN VDE 0118-2	**(VDE 0118 Part 2)** - Supplementary requirements for power installations	2001-11
IEC 61140	**(VDE 0140)** Protection against electric shock	2003-08
DIN VDE 0141	**(VDE 0141)** Earthing system for special power installations with nominal voltages above 1 kV	1989-07
EN 50186-1	**(VDE 0143 Teil 1)** Live-line washing systems for power installations with rated voltages above 1 kV – General requirements	1999-01
EN 50162	**(VDE 0150)** Protection against corrosion by stray current from direct current systems	2005-05

DIN VDE 0151	**(VDE 0151)** Material and minimum dimensions of earth electrodes with respect to corrosion	1986-06
EN 50178	**(VDE 0160)** Electronic equipment for use in power installations	1998-04
IEC 60079-14	**(VDE 0165 Teil 1)** Electrical apparatus for explosive gas atmospheres - Electrical installations in hazardous areas	2004-07
Numerous further parts		
DIN VDE 0168	**(VDE 0168)** Erection of electrical installation in open-cast mines, quarries and similar works	1992-01
IEC 60079-0	**(VDE 0170/0171 Teil 1)** Electrical apparatus for explosive atmospheres - General requirements	2004-12
IEC 62305-1	**(VDE 0185 Teil 1)** Protection against lightning - General principles	2004-08
Numerous further parts		
IEC 60446	**(VDE 0198)** Basic and safety principles for man-machine interface, marking and identification - Identification of conductors by colours or numerals	2004-05
IEC 60073	**(VDE 0199)** Basic and safety principles for man-machine interface, marking and identification - Coding principles for indicators and actuators	2003-05

Group 2 Conductors

EN 13599	Copper and copper alloys - Copper plate, sheet and strip for electrical purposes	2002-07
EN 14121	Aluminium and aluminium alloys - Aluminium sheet, strip and plate for electrotechnical applications	2003-08
EN 50341-1	**(VDE 0210 Part 1)** Overhead electrical lines exceeding AC 45 kV - General requirements; Common specifications	2002-03
EN 50423-1	Overhead electrical lines exceeding AC 1 kV up to and including AC 45 kV - General requirements	2005-05
IEC 61773	**(VDE 0210 Part 20)** Overhead lines - Testing of foundations for structures	1997-08
DIN VDE 0211	**(VDE 0211)** Planning and design of overhead power lines with rated voltages up to 1000 V	1985-12
IEC 61284	**(VDE 0212 Part 1)** Overhead lines - Requirements and tests for fittings	1998-05

Further parts: IEC 61854, IEC 61897

DIN VDE 0220-1	**(VDE 0220 Part 1)** Specifications for detachable cable clamps to be used in power cable installations up to 1000 V	1971-11
DIN VDE 0220-2	**(VDE 0220 Part 2)** Specifications for pressed connectors to be used in power cable installations	1971-11
DIN VDE 0220-3	**(VDE 0220 Teil 3)** Specifications for single- and multiple cable clamps with insulating parts in electrical power cable installations up to 1000 V	1977-10
DIN VDE 0228-1	**(VDE 0228 Part 1)** Proceedings in the case of interference on telecommunication installations by electric power installations; - general requirements	1987-12
DIN VDE 0228-2	**(VDE 0228 Part 2)** - interference by threephase installations	1987-12

Further parts: 3, 4, 5, 6.

DIN VDE 250-1	**(VDE 0250 Part 1)** Specifications for cables, wires and flexible cords for power installations; - general	1981-10
Numerous further parts		
DIN VDE 0262	**(VDE 0262)** XLPE insulated and PVC sheathed installation-cables with nominal voltage 0,6/1 kV	1995-12
DIN VDE 0265	**(VDE 0265)** Cables with plastic-insulation and lead-sheath for power installation	1995-12
DIN VDE 0266	**(VDE 0266)** Power cables with improved characteristics in the case of fire - Nominal voltages U0/U 0,6/1 kV	2000-03
DIN VDE 0271	**(VDE 0271)** Power cables - Specifications for power cables 0,6/1 kV and above for special applications	2005-10
DIN VDE 0276-1000	**(VDE 0276 Part 1000)** Power cables - Current-carrying capacity, general, conversion factors	1995-06
DIN VDE 0276-603	**(VDE 0276 Part 603)** - Distribution cables of rated voltage U0/U 0,6/1 kV;	2005-01
DIN VDE 0276-604	**(VDE 0276 Part 604)** - Power cables of nominal voltages U0/U 0,6/1 kV with special fire performance for use in power stations	2004-12
DIN VDE 0276-620	**(VDE 0276 Part 620)** Distribution cables of nominal voltages U0/U 3,6/6 kV to 20,8/36 kV	1996-12
DIN VDE 0276-621	**(VDE 0276 Part 621)** Medium voltage impregnated paper insulated distribution cables	1997-05
DIN VDE 0276-622	**(VDE 0276 Part 622)** Power cables having rated voltages from 3,6/6 (7,2) kV up to and including 20,8/36 (42) kV with special fire performance for use in power stations	2001-10
DIN VDE 0276-626	**(VDE 0276 Part 626)** Overhead distribution cables of rated voltage U0/U(Um):0,6/1 (1,2) kV	1997-01

DIN VDE 0276-632	**(VDE 0276 Part 632)** Power cables with extruded insulation and their accessories for rated voltages above 36 kV up to 150 kV , HD 632 S1	1999-05
DIN VDE 0276-633	**(VDE 0276 Part 633)** Tests on oil-filled (fluid-filled), paper- and polypropylene paper laminate-insulated, metal-sheathed cables and accessories for alternating voltages up to and including 400 kV HD 633 S1	1999-05
DIN VDE 0276-634	**(VDE 0276 Teil 634)** Tests on internal gas-pressure cables and accessories for alternating voltages up to and including 275 kV, HD 634 S1	1999-05
DIN VDE 0276-635	**(VDE 0276 Part 635)** Tests on external gas-pressure (gas compression) cables and accessories for alternating voltages up to and including 275 kV, HD 635 S1	1999-05
DIN VDE 0278-623	**(VDE 0278 Part 623)** Power cable accessories with nominal voltages up to 30 kV - Specification for joints, stop ends and outdoor terminations for distribution cables of rated voltage 0,6/1 kV, HD 623 S1	1997-01
DIN VDE 0278-629-1	**(VDE 0278 Part 629-1)** Power cable accessories with rated voltages U up to 30 kV -: Test requirements on accessories for use on power cables of rated voltage from 3,6/6 kV up to 20,8/36 kV; Cables with extruded insulation	2004-02
DIN VDE 0278-629-2	**(VDE 0278 Part 629-2)** Test requirements on accessories for use on power of rated voltages from 3,6/6 kV up to 20,8/36 kV; Cables with impregnated paper insulation	2004-02
DIN VDE 0281-1	**(VDE 0281 Part 1)** Cables of rated voltages up to and including 450/750 V and having thermoplastic insulation - General requirements, HD 21.1 S4	2003-09
IEC 60227-2	**(VDE 0281 Part 2)** Cables of rated voltages up to and including 450/750 V and having thermoplastic insulation - Test methods	2003-09

Numerous further parts

IEC 60245-1	**(VDE 0282 Part 1)** Cables of rated voltages up to and including 450/750 V and having cross-linked insulation - General requirements	2003-09
Numerous further parts		
DIN VDE 0289-1	**(VDE 0289 Part 1)** Definitions for cables, wires and flexible cords for power installation; - general definitions	1988-03
Numerous further parts		
DIN VDE 0291-1	**(VDE 0291 Part 1)** Specifications for filling compounds for cable accessories and for scalding compounds; Hot-cast filling compounds, filling-compounds for cold pressing-in, two-component cold-cast filling compounds and scalding compounds	1972-02
DIN VDE 0291-2	**(VDE 0291 Part 2)** Compounds for use in cable accessories; casting resinous compounds before cure and in the cured state [VDE Specification]	1997-06
DIN VDE 0293-1	**(VDE 0293 Part 1)** Identification of cores in cables and flexible cords used in power installations with nominal voltages up to 1000 V - Additional national specifications	2005-01
DIN VDE 0293-308	**(VDE 0293 Part 308)** Identification of cores in cables and flexible cords by colours	2003-01
EN 50334	**(VDE 0293 Part 334)** Marking by inscription for the identification of cores of electric cables	2001-10
IEC 60228	**(VDE 0295)** Conductors of insulated cables	2005-09
DIN VDE 0298-4	**(VDE 0298 Part 4)** Application of cables and cords in power installations - Recommended current-carrying capacity for sheathed and nonsheathed cables for fixed wirings in and around buildings and for flexible cables and cords	2003-08
DIN VDE 0298-300	**(VDE 0298 Part 300)** Guide to use of low voltage harmonized cables	2004-02

Group 3 Insulating materials

IEC 60505	**(VDE 0302 Part 1)** Evaluation and qualification of electrical insulation systems	2005-08
IEC 60610 (report)	**(VDE 0302 Part 2)** Insulation systems of electrical equipment; functional evaluation, ageing mechanisms and diagnostic procedures	1986-09
IEC 60611	**(VDE 0302 Part 3)** Insulation systems of electrical equipment; thermal endurance characteristics; fundamentals for test procedures	1986-09
Numerous further parts		
IEC 60112	**(VDE 0303 Part 11)** Method for the determination of the proof and the comparative tracking indices of solid insulating materials	2003-11
Numerous further parts		
IEC 60243-1	**(VDE 0303 Part 21)** Electrical strength of insulating materials - Test at power frequencies	1999-03
Numerous further parts		
IEC 60216-2	**(VDE 0304 Part 22** Guide for the determination of thermal endurance properties of electrical insulating materials - Part 2: Choice of test criteria	2004-08
Numerous further parts		
IEC 60296	**(VDE 0370 Part 1)** Fluids for electrotechnical applications - Unused mineral insulating oils for transformers and switchgear	2005-01
IEC 60422	**(VDE 0370 Part 2)** Supervision and maintenance guide for mineral insulating oils in electrical equipment	2003-04
DIN VDE 0370-3	**(VDE 0370 Part 3)** Method of sampling liquid dielectrics	1980-02
IEC 60156	**(VDE 0370 Part 5)** Insulating liquids - Determination of the breakdown voltage at power frequency - Test method	1996-03

Numerous further parts

IEC 60376	**(VDE 0373 Part 1)** Specification of technical grade SF6 for use in electrical equipment	2004-08
IEC 60480	**(VDE 0373 Part 2)** Guidelines for the checking and treatment of sulfur hexafluoride (SF6) taken from electrical equipment and specification for its re-use	2005-08

Group 4 Measurement, Control, Testing

IEC 61010-1	**(VDE 0411 Part 1)** Safety requirements for electrical equipment for measurement, control and laboratory use	2002-08
IEC 61557-1	**(VDE 0413 Part 1)** Electrical safety in low voltage distribution systems up to 1000 V a.c. and 1500 V d.c. - Equipment for testing, measuring or monitoring of protective measures - General requirements	1998-05
IEC 61557-2	**(VDE 0413 Part 2)** – Insulation resistance	1998-05
IEC 61557-3	**(VDE 0413 Part 3)** – Loop impedance	1998-05
IEC 61557-4	**(VDE 0413 Part 4)** – Resistance of earth connection and equipotential bonding	1998-05
IEC 61557-5	**(VDE 0413 Part 5)** – Resistance to earth	1998-05
IEC 61557-6	**(VDE 0413 Part 6)** – Residual current devices (RCD) in TT, TN and IT systems	1999-05
IEC 61557-7	**(VDE 0413 Part 7)** – Phase sequence	1998-05
IEC 61557-8	**(VDE 0413 Part 8)** – Insulation monitoring devices for IT systems	1998-05
IEC 60044-1	**(VDE 0414 Part 44-1)** Instrument transformers - Current transformers	2003-12
IEC 60044-2	**(VDE 0414 Part 44-2)** – Inductive voltage transformers	2003-12

IEC 60044-3	**(VDE 0414 Part 44-3)** – Combined transformers	2003-12
IEC 60044-5	**(VDE 0414 Part 44-5)** - Capacitor voltage transformers	2005-03
IEC 60044-6	**(VDE 0414 Part 7)** – Requirements for protective current transformers for transient performance	1999-10
IEC 60044-7	**(VDE 0414 Part 44-7)** - Electronic voltage transformers	2000-11
IEC 60044-8	**(VDE 0414 Part 44-8)** - Electronic current transformers	2003-06
IEC 62053-11	**(VDE 0418 Part 3-11)** Electricity metering equipment (a.c.): - Electromechanical meters for active energy (classes 0,5, 1 and 2)	2003-11
IEC 62053-21	**(VDE 0418 Part 3-21)** - Static meters for active energy (classes 1 and 2)	2003-11
IEC 62053-22	**(VDE 0418 Part 3-22)** - Static meters for active energy (classes 0,2 S and 0,5 S)	2003-11
IEC 62053-23	**(VDE 0418 Part 3-23)** - Static meters for reactive energy (classes 2 and 3)	2003-11
DIN VDE 0418-2	**(VDE 0418 Part 2)** Specifications for electric integrating meters; - Var-hour (reactive energy) meters	1966-03
DIN VDE 0418-3	**(VDE 0418 Part 3)** –Direct-current meters	1965-03
DIN VDE 0418-4	**(VDE 0418 Part 4)** – Maximum demand indicators	1967-07
DIN VDE 0418-5	**(VDE 0418 Part 5)** – Telemetering devices	1973-04
IEC 60514	**(VDE 0418 Part 6)** Acceptance inspection of class 2 alternating-current watt-hour meters	1995-07
IEC 61358	**(VDE 0418 Part 60)** Acceptance inspection for direct connected alternating current static watt-hour meters for active energy (classes 1 and 2)	1996-11

IEC 62053-31	**(VDE 0418 Part 3-31)** Electricity metering equipment (a.c.) - Pulse output devices for electromechanical and electronic meters (two wires only)	1999-04
IEC 62053-61	**(VDE 0418 Part 3-61)** - Power consumption and voltage requirements	1999-04
IEC 62054-2	**(VDE 0419 Part 1)** Electricity metering (a.c.) - Tariff and load control - Particular requirements for time switches	2005-06
IEC 62054-11	(**VDE 0420 Part 1)** - Particular requirements for electronic ripple control receivers	2005-06
IEC 60060-1	**(VDE 0432 Part 1)** High voltage test techniques; - general specifications and test requirements	1994-06
IEC 61180-1	**(VDE 0432 Part 10)** High-voltage test techniques for low-voltage equipment - Definitions, test and procedure requirements	1995-05
IEC 61180-2	**(VDE 0432 Part 11)** - Test equipment	1995-05
IEC 60060-2	**(VDE 0432 Part 2)** High-voltage test techniques - Measuring systems	1996-03
IEC 61083-1	**(VDE 0432 Part 7)** Instruments and software used for measurements in high-voltage impulse tests - Requirements for instruments	2002-01
IEC 61083-2	**(VDE 0432 Part 8)** Digital recorders for measurements in high-voltage impulse tests - Evaluation of software used for the determination of the parameters of impulse waveforms	1998-01
IEC 60270	(VDE 0434) High-voltage test techniques - Partial discharge measurement	2001-08
IEC 61810-1	**(VDE 0435 Part 201)** Electromechanical elementary relays - General and safety requirements	2004-07

IEC 61812-1	**(VDE 0435 Teil 2021)** Specified time relays for industrial use - Requirements and tests	1999-08
IEC 60255-8	**(VDE 0435 Part 3011)** Electrical relays	1998-06
- Thermal electrical relays		
IEC 60255-3	**(VDE 0435 Part 3013)** Electrical relays - Single input energizing quantity measuring relays with dependent or independent time	1998-07
IEC 60255-22-2	**(VDE 0435 Part 3022)** - Electrical disturbance tests for measuring relays and protection equipment; - Electrostatic discharge tests	1997-05
DIN VDE435-303	**(VDE 0435 Part 303)** Electrical relays - Static measuring relays (SMR)	1998-01
DIN VDE 0441-1	**(VDE 0441 Part 1)** Tests on insulators of organic material for systems with nominal alternating voltages greater than 1000 V - tests on materials	1985-07
DIN VDE 0441-2	**(VDE 0441 Part 2)** - tests on outdoor composite insulators with fibre glass core	1982-10
IEC 60660	**(VDE 0441 Part 3)** Insulators - Tests on indoor post insulators of organic material for systems with nominal voltages greater than 1 kV up to but not including 300 kV	2000-12
IEC 61466-1	**(VDE 0441 Part 4)** Composite string insulator units for overhead lines with a nominal voltage greater than 1 kV - Standard strength classes and end fittings	1997-10
IEC 61466-2	**(VDE 0441 Part 5)** - Dimensional and electrical characteristics	2002-12
IEC 60383-1	**(VDE 0446 Part 1)** Insulators for overhead lines with a nominal voltage above 1 kV - Ceramic or glass insulator units for a.c. systems; definitions, test methods and acceptance criteria	1997-05

DIN VDE 0446-2	**(VDE 0446 Part 2)** Regulations for insulators for overhead power lines, overhead equipment and telecommunication lines - Regulations for insulators for high-tension overhead lines and overhead equipment up to 1000 V as well as telecommunication overhead lines	1971-03
DIN VDE 0446-3	**(VDE 0446 Part 3)** - Regulations for fittings permanently connected to the insulators	1973-05
IEC 60383-2	**(VDE 0446 Part 4)** Insulators for overhead lines with a nominal voltage above 1000 V - Insulator strings and insulator sets for a.c. systems; definitions, test methods and acceptance criteria	1995-08
IEC 61325	**(VDE 0446 Part 5)** - Ceramic or glass insulator units for d.c. systems - Definitions, test methods and acceptance criteria	1996-04
IEC 60305	**(VDE 0446 Part 6)** - Ceramic or glass insulator units for a.c. systems - Characteristics of insulator units of the cap and pin type	1996-10
IEC 60433	**(VDE 0446 Part 7)** - Ceramic insulators for a.c. systems - Characteristics of insulator units of the long rod type	1999-04
IEC 60507	**(VDE 0448 Part 1)** Artificial pollution tests on high-voltage insulators to be used on a.c. systems	1994-04
IEC 60529	**(VDE 0470 Part 1)** Degrees of protection provided by enclosures	2000-09
EN 50102	**(VDE 0470 Teil 100)** Degrees of protection provided by enclosures for electrical equipment against external mechanical impacts	1997-09
IEC 61032	(VDE 0470 Part 2) Protection of persons and equipment by enclosures - Probes for verification	1998-10
IEC 60695-1-1	**(VDE 0471 Part 1-1)** Fire hazard testing - Guidance for assessing the fire hazard of electrotechnical products; General guidelines	2000-10

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Group 5 Machines, Converters

DIN VDE 0510	**(VDE 0510)** VDE specification for electric storage batteries and battery plants	1977-01
EN 50272-2	**(VDE 0510 Part 2)** Safety requirements for secondary batteries and battery installations - Stationary batteries	2001-12
IEC 60034-1	**(VDE 0530 Part 1)** Rotating electrical machines - Rating and performance	2005-04
IEC 60076-1	**(VDE 0532 Part 76-1)** Power transformers - General	2003-01
IEC 60076-2	**(VDE 0532 Part 102)** - Temperature rise	1997-12
IEC 60076-4	**(VDE 0532 Part 76-4)** - Guide to lightning impulse and switching impulse testing; Power transformers and reactors	2003-06
DIN VDE 0532-14	**(VDE 0532 Part 14)** Transformers and reactors - External protective spark gaps on bushings	2004-08
IEC 60289	**(VDE 0532 Part 289)** Reactors	2003-02
DIN VDE 0532-222	**(VDE 0532 Part 222)** Distribution transformers with cable boxes on the high-voltage and/or low-voltage side	1997-12
IEC 60076-3	**(VDE 0532 Part 3)** Power transformers - Insulation levels, dielectric tests and external clearances in air	2001-11
IEC 60214-1	**(VDE 0532 Part 214-1)** Tap-changers - Performance requirements and test methods	2003-12
IEC 60214-2	**(VDE 0532 Part 214-2)** -: Application guide	2004-04
IEC 60076-5	**(VDE 0532 Part 5)** Power transformers : Ability to withstand short circuit	2001-11

IEC 60076-11	**(VDE 0532 Part 726)** Dry-type transformers	2005-04
IEC 60076-10-1	**(VDE 0532 Part 76-10)** Determination of transformer and reactor sound levels - User guide	2002-04
DIN VDE 0558-1	**(VDE 0558 Part 1)** Semiconductor convertors; general specifications and particular specifications for line-commutated convertors	1987-07
IEC 60146-1-1	**(VDE 0558 Part 11)** Semiconductor convertors - specifications of basic requirements	1994-03
IEC 60146-2	**(VDE 0558 Part 2)** - Self-commutated semiconductor convertors including direct d.c. convertors	2001-02
IEC 62040-1-1	**(VDE 0558 Part 511)** Uninterruptible power systems (UPS) - General and safety requirements for UPS used in operator access areas	2003-10
IEC 62040-1-2	**(VDE 0558 Part 512)** - General and safety requirements for UPS used in restricted access locations	2003-10
IEC 62040-2	**(VDE 0558 Part 520)** Electromagnetic compatibility (EMC) requirements	2003-07
IEC 60146-1-3	**(VDE 0558 Part 8)** Semiconductor convertors -general requirements and line-commutated convertors -transformers and reactors	1994-03
DIN VDE 0560-1	**(VDE 0560 Part 1)** Specifications for capacitors -General requirements	1969-12
IEC 60871-1	**(VDE 0560 Part 410 / A100)** Shunt capacitors for a.c. power systems having a rated voltage above 1 kV - General; performance, testing and rating; safety requirements; guide for installation and operation	2003-07
IEC 60871-2	**(VDE 0560 Part 420)** - endurance testing	1998-12
IEC 60871-4	**(VDE 0560 Part 440)** - Internal fuses	1997-08

IEC 60143-1	**(VDE 0560 Part 42)** Series capacitors for power systems - General	2004-12
IEC 60143-2	**(VDE 0560 Part 43)** Series capacitors for power systems - Protective equipment for series capacitor banks	1995-12
IEC 60143-3	**(VDE 0560 Part 44)** - Internal fuses	1999-03
IEC 60831-1	**(VDE 0560 Part 46)** Shunt power capacitors of the self-healing type for a.c. systems having a rated voltage up to and including 1 kV - General; Performance, testing and rating; Safety requirements; Guide for installation and operation	2003-08
IEC 60831-2	**(VDE 0560 Part 47)** - Ageing test, self-healing test and destruction test	1997-09
IEC 60931-1	**(VDE 0560 Part 48)** Shunt power capacitors of the non-self-healing type for a.c. systems having a rated voltage up to and including 1 kV - : General; Performance, testing and rating; Safety requirements; Guide for installation and operation	2003-07
IEC 60931-2	**(VDE 0560 Part 49)** - Ageing test and destruction test	1997-08
IEC 60252-1	**(VDE 0560 Part 8)** AC motor capacitors General; Performance, testing and rating; Safety requirements; Guide for installation and operation	2002-05
IEC 60252-2	**(VDE 0560 Part 8)** - Motor start capacitors Numerous further parts	2004-02

DIN VDE 0603-1	**(VDE 0603 Part 1)** Consumer units and meter panels AC 400 V - consumer units and meter panels	1991-10
DIN VDE 0603-2	**(VDE 0603 Part 2)** Customer distribution boards and meter panels AC 400 V - Main line branch terminals	1998-03
EN 50085-1	**(VDE 0604 Part 1)** Cable trunking systems and cable ducting systems for electrical installations - General requirements	1998-04
DIN VDE 0604-2	**(VDE 0604 Part 2)** Trunking mounted on walls and ceilings for electrical installations - trunking for appliances	1986-05
DIN VDE 0604-3	**(VDE 0604 Part 3)** - skirting board ducts	1986-05
IEC 61386-1	**(VDE 0605 Part 1)** Conduit system for electrical installations - General requirements	2004-07
IEC 61386-21	**(VDE 0605 Part 21)** - Rigid conduit systems	2004-08
IEC 61386-22	**(VDE 0605 Part 22)** - Pliable conduit systems	2004-08
IEC 61386-23	**(VDE 0605 Part 23)** - Flexible conduit systems	2004-08
IEC 61386-24	**(VDE 0605 Part 24)** - buried underground	2004-01
IEC 60670-1	**(VDE 0606 Part 1)** Boxes and enclosures for electrical accessories for household and similar fixed electrical installations - General requirements	2005-10
IEC 60999 - 1	**(VDE 0609 Part 1)** Electrical copper conductors; Safety requirements for screw-type and screwless-type clamping units - General requirements and particular requirements for clamping units for conductors 0,2 mm2 up to 35 mm2	2000-12
IEC 60947-7-1	**(VDE 0611 Part 1)** Low-voltage switchgear and controlgear - Ancillary equipment; Terminal blocks for copper conductors	2003-07

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DIN VDE 0618-1	**(VDE 0618 Part 1)** Equipment for equipotential bonding; equipotential busher for main equipotential bonding	1989-08
EN 50262	**(VDE 0619)** Cable glands for electrical installations	2005-05
DIN VDE 0620 - 1	**(VDE 0620 Part 1)** Plugs and socket-outlets for household and similar purposes - General requirements	2005-04
IEC 60309-1	**(VDE 0623 Part 1)** Plugs, socket-outlets and couplers for industrial purposes - General requirements	2000-05

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IEC 61058-1	(**VDE 0630 Part 1)** Switches for appliances - General requirements	2003-03
DIN VDE 0630-12	**(VDE 0630 Part 12)** Switches for appliances for a rated voltage not exceeding 500 V and a rated current not exceeding 63 A - electronic switches	1988-09
IEC 60669-1	**(VDE 0632 Part 1)** Switches for household and similar fixed electrical installations - General requirements	2003-09

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DIN VDE 0634-1	**(VDE 0634 Teil 1)** Underfloor electrical installation -service units	1987-09
DIN VDE 0635	**(VDE 0635)** Low voltage fuses; D-fuses E 16 up to 25 A, 500 V; D-fuses up to 100 A, 750 V; D-fuses up to 100 A, 500 V [VDE Specification]	1984-02
IEC 60269-1	**(VDE 0636 Part 10)** Low-voltage fuses - General requirements	2005-11
IEC 60269-2	**(VDE 0636 Part 20)** - Supplementary requirements for fuses for use by authorized persons	2002-09

IEC 60269-2-1	**(VDE 0636 Part 201)** – Supplementary requirements for fuses for use by authorized persons		2004-10
DIN VDE 0636-2011	**(VDE 0636 Part 2011)** – national supplement : Protection of special electrical systems		1999-05
IEC 60269-3	**(VDE 0636 Part 30)** – Supplementary requirements for fuses for use by unskilled persons		2004-07
IEC 60269-3-1	**(VDE 0636 Part 301)** – Examples of types of standardized fuses		2003-06
DIN VDE 0636-3011	**(VDE 0636 Part 3011)** Supplementary requirements for fuses for use by unskilled persons; national supplement		1999-05
IEC 60269-4	**(VDE 0636 Part 40)** Supplementary requirements for fuse-links for the protection of semiconductor devices		2003-11
DIN VDE 0638	**(VDE 0638)** Low-voltage switchgears; fuse-switch-units; DO-system [VDE Specification]		1981-09
IEC 60898-1	**(VDE 0641 Part 11)** Circuit breakers for overcurrent protection for household and similar installations - Circuit-breakers for a.c. operation		2005-04
IEC 60898-2	**(VDE 0641 Part 12)** - Circuit-breakers for a.c. and d.c. operation		2002-07
DIN VDE 0642-100	**(VDE 0641 Part 100)** - Circuit-breakers screw-in in D-type fuse-bases DII for a.c. and d. c. operation		2004-05
IEC 60934	**(VDE 0642)** Circuit-breakers for equipment (CBE)		2001-12
IEC 60947-1	**(VDE 0660 Part 100)** Low-voltage switchgear and controlgear - General rules		2005-01
IEC 60947-2	**(VDE 0660 Part 101)** - Circuit breakers		2004-03
IEC 60947-4-1	**(VDE 0660 Part 102)** - Contactors and motor-starters - Electromechanical contactors and motor-starters		2004-09

IEC 60439-4 **(VDE 0660 Part 501)** 2005-06
- Particular requirements for assemblies for construction sites (ACS)

IEC 60947-3 **(VDE 0660 Part 107)** 2001-12
- Switches, disconnectors, switch-disconnectors and fuse-combination units

IEC 60947-4-3 **(VDE 0660 Part 109)** 2000-09
- Contactors and motor-starters; ac semiconductor controllers and contactors for non-motor loads

DIN VDE 0660-112 **(VDE 0660 Part 112)** 1987-02
- additional specification for d.c. air-break switches, air-break disconnectors and air-break switch-disconnectors exceeds 1200 V but not exceeds 3000 V

IEC 60947-6-1 **(VDE 0660 Part 114)** 2004-10
- Multiple function equipment - Automatic transfer switching equipment

IEC 60947-6-2 **(VDE 0660 Part 115)** 2003-11
- Multiple function equipment; Control and protective switching devices (or equipment) (CPS)

IEC 60947-4-2 **(VDE 0660 Part 117)** 2002-12
Contactors and motor-starters; AC semiconductor motor controllers and starters

IEC 60947-5-1 **(VDE 0660 Part 200)** 2005-09
- Electromechanical control circuit devices

IEC 60947-5-2 **(VDE 0660 Part 208)** 2005-05
- Proximity switches

DIN VDE 0660-209 **(VDE 0660 Part 209)** 1988-01
- additional requirements for proximity position switches for safety functions

IEC 60947-5-5 **(VDE 0660 Part 210)** 2005-11
- Electrical emergency stop device with mechanical latching function

IEC 60947-8 **(VDE 0660 Part 302)** 2004-04
- Control units for built-in thermal protection (PTC) for rotating electrical machines

IEC 60439-1 **(VDE 0660 Part 500)** 2005-01
Type-tested and partially type-tested assemblies

IEC 60439-4 **(VDE 0660 Part 501)** 2005-06
- Particular requirements for assemblies for construction sites (ACS)

IEC 60439-2	**(VDE 0660 Part 502)** - Particular requirements for busbar trunking systems (busways)	2005-02
IEC 60439-5	**(VDE 0660 Part 503)** - Particular requirements for assemblies for power distribution in public networks	2005-05
IEC 60439-3	**(VDE 0660 Part 504)** - Particular requirements for low-voltage switchgear and controlgear assemblies intended to be installed in places where unskilled persons have access for their use; Distribution boards	2002-05
DIN VDE 0660-505	**(VDE 0660 Part 505)** - Specification for house connection boxes and fuseboxes	1998-10
IEC 60890	**(VDE 0660 Part 507)** A method of temperature-rise assessment by extrapolation for partially type-tested assemblies (PTTA) of low-voltage switchgear and controlgear	1997-11
IEC 61117	**(VDE 0660 Part 509)** A method for assessing the short-circuit withstand strength of partially typetested assemblies (PTTA);	1993-09
IEC 62208	**(VDE 0660 Part 511)** Empty enclosures for low-voltage switchgear and controlgear assemblies - General requirements	2005-04
EN 50300	**(VDE 0660 Part 512)** - General requirements for low-voltage substation cable distribution boards	2005-03
IEC 62020	**(VDE 0663)** Electrical accessories - Residual current monitors for household and similar uses	2005-11
IEC 61008-1	**(VDE 0664 Part 10)** Residual current operated circuit-breakers without integral overcurrent protection for household and similar uses (RCCB's) - General rules	2005-06
IEC 61009-1	**(VDE 0664 Part 20)** Residual current operated circuit-breakers with integral overcurrent protection for household and similar uses (RCBO's) - General rules	2005-06

IEC 60427	**(VDE 0670 Part 108)** Synthetic testing of high-voltage alternating current circuit-breakers	2001-06
IEC 61166	**(VDE 0670 Part 111)** High-voltage alternating current circuit-breakers - Guide for seismic qualification	1994-08
IEC 60265-1	**(VDE 0670 Part 301)** High-voltage switches - Switches for rated voltages above 1 kV and less than 52 kV	1999-05
IEC 60265-2	**(VDE 0670 Part 302)** - High-voltage switches for rated voltages of 52 kV and above	1998-09
IEC 60282-1	**(VDE 0670 Part 4)** High-voltage fuses - Current-limiting fuses	2004-03
IEC 60644	**(VDE 0670 Part 401)** Specification for high-voltage fuse-links for motor circuit applications	1997-03
DIN VDE 0670-402	**(VDE 0670 Part 402)** A.c. switchgear and controlgear for voltages above 1 kV - application guide for the selection of fuse-links for transformer circuits	1988-05
IEC 61330	**(VDE 0670 Part 611)** High-voltage/low-voltage prefabricated substations	1997-08
EN 50052	**(VDE 0670 Part 801)** Cast aluminium alloy enclosures for gas-filled high-voltage switchgear and controlgear	1995-10
EN 50064	**(VDE 0670 Part 803)** Wrought aluminium and aluminium alloy enclosures for gas-filled high-voltage switchgear and controlgear	1995-10
EN 50068	**(VDE 0670 Part 804)** A.c. switchgear and controlgear for voltages above 1 kV - wrought steel enclosures for gas-filled high-voltage switchgear and controlgear	1993-08
EN 50069	**(VDE 0670 Part 805)** - welded composite enclosures of cast and wrought aluminium alloys for gas-filled high-voltage switchgear and controlgear	1993-08

EN 50089	**(VDE 0670 Part 806)** Cast resin partitions for metal enclosed gas-filled high voltage switchgear and controlgear	1994-04
EN 50187	**(VDE 0670 Part 811)** Gas-filled compartments for a.c. switchgear and controlgear for rated voltages above 1 kV and up to and including 52 kV	1997-05
IEC 60694	**(VDE 0670 Part 1000)** Common specifications for high-voltage switchgear and controlgear standards	2002-09
IEC 62271-2	**(VDE 0671 Part 2)** High-voltage switchgear and controlgear - Seismic qualification for rated voltages of 72,5 kV and above	2004-01
IEC 62271-100	**(VDE 0671 Part 100)** - Alternating current circuit-breakers	2005-11
IEC 62271-102	**(VDE 0671 Part 102)** - High-voltage alternating current disconnectors and earthing switches	2003-10
IEC 62271-105	**(VDE 0670 Part 105)** Alternating current switch-fuse combinations	2003-12
IEC 62271-200	**(VDE 0671 Part 200)** AC metal-enclosed switchgear and controlgear for rated voltages above 1 kV and up to and including 52 kV	2004-10
IEC 62271-203	**(VDE 0671 Teil 203)** Gas-insulated metal-enclosed switchgear for rated voltages above 52 kV	2004-11
IEC 60168	**(VDE 0674 Part 1)** Tests on indoor and outdoor post insulators of ceramic material or glass for systems with nominal voltages greater than 1 kV	2001-12
IEC 62155	**(VDE 0674 Part 200)** Hollow pressurized and unpressurized ceramic and glass insulators for use in electrical equipment with rated voltages greater than 1000 V	2004-03
IEC 60273	**(VDE 0674 Part 4)** Characteristics of indoor and outdoor post insulators for systems with nominal voltages greater than 1000 V	1993-08
IEC 60137	**(VDE 0674 Part 5)** Insulated bushings for alternating voltages above 1000 V	2004-07

IEC 60099-1	**(VDE 0675 Part 1)** Surge arresters - Non-linear resistor type gapped surge arresters for a.c. systems	2000-08
IEC 60099-4	**(VDE 0675 Part 4)** Metal-oxide surge arresters without gaps for a.c. systems	2005-06
IEC 60099-5	**(VDE 0675 Part 5)** Selection and application recommendations	2000-09
DIN VDE 0680-1	**(VDE 0680 Part 1)** Body protective equipment, protective devices and apparatus for work on electrically energized systems up to 1000 V - personal protective equipment and protective insulating devices	1990-05
DIN VDE 0680-3	**(VDE 0680 Part 3)** - Operating rods and current collecting devices	1977-09
DIN VDE 0680-4	**(VDE 0680 Part 4)** fuse handles for low-tension HRC-fuses [VDE Specification]	1980-11
DIN VDE 0680-6	**(VDE 0680 Part 6)** - Single-pole voltage tester up to 250 V a.c.	1977-04
DIN VDE 0680-7	**(VDE 0680 Part 7)** - socket spanner [VDE Specification]	1984-02
DIN VDE 0681-1	**(VDE 0681 Part 1)** Operating, testing and safe-guarding devices for work on electrically energized systems with rated voltages exceeding 1 kV; - general requirements for the parts 2 to 4	1986-10
DIN VDE 0681-2	**(VDE 0681 Part 2)** – VDE Specification for operating testing, and safe-guarding devices used when carrying out live-line-work on equipment with rated voltages exceeding 1 kV; -operating rods	1977-03
DIN VDE 0681-3	**(VDE 0681 Part 3)** – fuse tongs	1977-03
DIN VDE 0681-4	**(VDE 0681 Part 4)** - AC voltage detectors	1999-10
DIN VDE 0681-5	**(VDE 0681 Part 5)** – phase comperators	1985-06

DIN VDE 0681-6	**(VDE 0681 Part 6)** – voltage detectors to be used for overhead contact systems 15 kV, 162/3 Hz	1985-06
IEC 60900	**(VDE 0682 Part 201)** Live working - Hand tools for use up to 1000 V a.c. and 1500 V d.c.	2005-01
IEC 60832	**(VDE 0682 Part 211)** Insulating poles (insulating sticks) and universal tool attachments (fittings) for live working	1998-01
IEC 60903	**(VDE 0682 Part 311)** - Gloves of insulating material	2004-07
IEC 60984	**(VDE 0682 Part 312)** Sleeves of insulating material for live working	1994-10
IEC 61243-3	**(VDE 0682 Part 401)** - Voltage detectors ,Two-pole low voltage type	1999-09
IEC 61243-1	**(VDE 0682 Part 411)** - Voltage detectors , Capacitive type to be used for voltages exceeding 1 kV a.c.	2001-09
IEC 61229	**(VDE 0682 Part 551)** Rigid protective covers for live working on a.c. installations	1997-01
DIN VDE 0682-552	**(VDE 0682 Part 552)** – Insulating protective barriers above 1 kV	2003-10
IEC 61236	**(VDE 0682 Part 651)** Saddles, pole clamps (stick clamps) and accessories for live working	1996-11
IEC 61057	**(VDE 0682 Part 741)** Aerial devices with insulating boom used for life working exceeding 1 kV a.c.	2004-08
IEC 61230	**(VDE 0683 Part 100)** Live working - Portable equipment for earthing or earthing and short-circuiting	1996-11
IEC 61219	**(VDE 0683 Part 200)** Earthing or earthing and short-circuiting equipment using lances as a short-circuiting device	1995-01

Group 8 Information technology

DIN VDE 0800-1	**(VDE 0800 Part 1)** Telecommunications -general concepts - requirements and tests for the safety of facilities and apparatus	1989-05
DIN VDE 0800-2	**(VDE 0800 Part 2)** earthing and equipotential bonding	1985-07
DIN VDE 0800-3	**(VDE 0800 Part 3)** – Safety of installations with remote power feeding	2003-12
EN 50174-2	**(VDE 0800 Part 174-2)** Information technology - Cabling installation -Installation planning and practices inside buildings	2001-09
EN 50174-3	**(VDE 0800 Part 174-3)** – Installation planning and practices outside buildings	2004-09
EN 41003	**(VDE 0804 Part 100)** Particular safety requirements for equipment to be connected to telecommunication networks	1999-08
IEC 60950 - 1	**(VDE 0805 Part 1)** Information technology equipment - Safety - General requirements	2004-11
EN 50116	**(VDE 0805 Part 116)** - Routine electrical safety testing in production	1997-06 °
EN 50065-1	**(VDE 0808 Teil 1)** Signalling on low-voltage electrical installations in the frequency range 3 kHz to 148,5 kHz - General requirements, frequency bands and electromagnetic disturbances.	2002-02
DIN VDE 0812	**(VDE 0812)** Equipment wires and stranded equipment wires for telecommunicationssystems and data processing systems	1988-11
DIN VDE 0813	**(VDE 0813)** – Switchboard cables for telecommunication and data processing systems	1988-11
DIN VDE 0814	**(VDE 0814)** – Cords for telecommunication systems and information processing systems [VDE Specification]	1981-10

DIN VDE 0815	**(VDE 0815)** – Wiring cables for telecommunication and data processing systems	1985-09
DIN VDE 0816-1	**(VDE 0816 Part 1)** – External cables for telecommunication and data processing systems; cables insulated and sheathed with polyethylen, unit stranded	1988-02
DIN VDE 0816-2	**(VDE 0816 Part 2)** – signal and measuring cables, mining cables	1988-02
DIN VDE 0816-3	**(VDE 0816 Part 3)** – paper insulated cables	1988-02
DIN VDE 0817	**(VDE 0817)** – Cables with stranded conductors	1990-08
DIN VDE 0818	**(VDE 0818)** Self supporting telecommunication aerial cables on overhead power lines above 1 kV [VDE-Specification]	1983-02
EN 50288-1	**(VDE 0819 Part 1)** Multi-element metallic cables used in analogue and digital communication and control - Part 1: Generic specification	2004-08
EN 50290-2-20	**(VDE 0819 Part 100)** Communication cables - Part 2-20: Common design rules and construction; General	2002-07
EN 50290-2-21	**(VDE 0819 Part 101)** –PVC insulation compounds	2002-07
EN 50290-2-22	**(VDE 0819 Part 102)** – PVC sheathing compounds	2002-07
EN 50290-2-23	**(VDE 0819 Part 103)** – PE insulation	2002-07
EN 50290-2-24	**(VDE 0819 Part 104)** – PE sheathing	2002-10
EN 50290-2-25	**(VDE 0819 Part 105)** – Polypropylene insulation compounds	2002-10
EN 50290-2-26	**(VDE 0819 Part 106)** – Halogen free flame retardant insulation compounds	2002-10
EN 50290-2-27	**(VDE 0819 Part 107)** – Halogen free flame retardant thermoplastic sheathing compounds	2002-10
EN 50290-2-28	**(VDE 0819 Part 108)** – Filling compounds for filled cables	2002-10

EN 50290-2-29	**(VDE 0819 Part 109)** – Cross-linked PE insulation compounds	2002-10
EN 50288-2-1	**(VDE 0819 Part 2-1)** Multi-element metallic cables used in analogue and digital communication and control - Part 2-1: Sectional specification for screened cables characterised up to 100 MHz - Horizontal and building backbone cables	2004-08
EN 50288-5-1	**(VDE 0819 Part 5-1)** – Multi-element metallic cables used in analogue and digital communication and control - Part 5-1: Sectional specification for screened cables characterized up to 250 MHz - Horizontal and building backbone cables	2004-08
IEC 60127-1	**(VDE 0820 Part 1)** Miniature fuses - Part 1: Definitions for miniature fuses and general requirements for miniature fuse-links	2003-08
IEC 60127-2	**(VDE 0820 Part 2)** – Cartridge fuse links	2004-04
IEC 60127-3	**(VDE 0820 Part 3)** – Sub-miniature fuse-links	2003-09
IEC 60127-4	**(VDE 0820 Part 4)** – Universal modular fuse-links (UMF)	2004-05
IEC 60127-6	**(VDE 0820 Part 6)** – Fuse-holders for miniature fuse-links	2003-10
IEC 60127-10	**(VDE 0820 Part 10)** - User guide for miniature fuses	2002-07
IEC 60691	**(VDE 0821)** Thermal-links - Requirements and application guide	2003-07
EN 50130-4	**(VDE 0830 Part 1-4)** Alarm systems - Part 4: Electromagnetic compatibility; Product family standard: Immunity requirements for components of fire, intruder and social alarm systems	2003-09
CLC/TS 50134-7	**(VDE 0830 Part 4-7)** - Social alarm systems - Part 7: Application guidelines Pre-Standard	2004-08
EN 50132-7	**(VDE 0830 Part 7-7)** – CCTV surveillance systems for use in security applications - Part 7: Application guideline	1997-07
DIN VDE 0833-1	**(VDE 0833 Part 1)** Alarm systems for fire, intrusion and hold-up - Part 1: General requirements	2003-05

DIN VDE 0833-2	**(VDE 0833 Part 2)** – Requirements for fire alarm systems	2004-02
DIN VDE 0833-3	**(VDE 0833 Part 3)** – Requirements for intrusion and hold-up alarm systems	2002-05
IEC 60825-1	**(VDE 0837 Part 1)** Safety of laser products - Part 1: Equipment classification, requirements and user's guide	2003-10
IEC 60825-2	**(VDE 0837 Part 2)** – Safety of optical fibre communication systems (OFCS)	2001-05
IEC 60555-1	**(VDE 0838 Part 1)** Disturbances in supply systems caused by household appliances and similar electrical equipment; part 1: definitions	1987-06
IEC 61000-3-2	**(VDE 0838 Part 2)** Electromagnetic compatibility (EMC) - Part 3-2: Limits - Limits for harmonic current emissions (equipment input current <=16 A per phase)	2005-12
IEC 61000-3-3	**(VDE 0838 Part 3)** - Part 3-3: Limits - Limitation of voltage changes, voltage fluctuations and flicker in public low-voltage supply systems, for equipment with rated current <=16 A per phase and not subjected to conditional connection	2006-06
IEC 61000-2-2	**(VDE 0839 Part 2-2)** - Part 2-2: Environment; Compatibility levels for low-frequency conducted disturbances and signalling in public low-voltage power supply systems	2003-02
IEC 61000-2-4	**(VDE 0839 Part 2-4)** - Part 2-4: Environment; Compatibility levels in industrial plants for low-frequency conducted disturbances	2003-05
IEC 61000-2-9	**(VDE 0839 Part 2-9)** - Part 2: Environment; section 9: Description of HEMP environment; radiated disturbance; basic EMC publication	1996-12
IEC 61000-2-10	**(VDE 0839 Part 2-10)** - Part 2-10: Environment; description of HEMP environment; conducted disturbance	1999-10
IEC 61000-6-4	**(VDE 0839 Part 6-4)** - Part 6-4: Generic standards; Emission standard for industrial environments	2002-08

IEC 61326 **(VDE 0843 Part 20)** 2004-05
Electrical equipment for measurement, control and laboratory use
– EMC requirements

DIN VDE 0845-1 **(VDE 0845 Part 1)** 1987-10
Protection of telecommunication systems against lightning, electrostatic discharges and overvoltages from electric power installations; provisions against overvoltages

IEC 60868-0 **(VDE 0846 Part 0)** 1994-08
Flickermeter
- Part 0: Evaluation of flicker severity

DIN VDE 0846-1 **(VDE 0846 Part 1)** 1985-08
Measuring apparatus for judgement of electromagnetic compatibility; measuring of harmonics of the mains voltages and currents up to 2500 Hz

VDE 0847-1 **(VDE 0847 Part 1)** 1981-11
Procedure of measurements for the electromagnetic compatibility; measurement of conducted interference units

IEC 61000-4-1 **(VDE 0847 Part 4-1)** 2001-06
Electromagnetic compatibility (EMC) - Part 4-1: Testing and measurement techniques

IEC 61000-4-2 **(VDE 0847 Part 4-2)** 2001-12
- Part 4-2: Testing and measurement techniques; Electrostatic discharge immunity

IEC 61000-4-3 **(VDE 0847 Part 4-3)** 2006-02
- Part 4-3: Testing and measurement techniques; Radiated, radio-frequency, electromagnetic field immunity test

IEC 61000-4-4 **(VDE 0847 Part 4-4)** 2005-07
Part 4-4: Testing and measurement techniques - Electrical fast transient/burst immunity test

IEC 61000-4-5 **(VDE 0847 Part 4-5)** 2006-02
Part 4-5: Testing and measurement techniques; Surge immunity test

IEC 61000-4-6 **(VDE 0847 Part 4-6)** 2003-01
Part 4-6: Testing and measurement techniques; Immunity to conducted disturbances, induced by radio-frequency fields

IEC 61000-4-7	**(VDE 0847 Part 4-7)** 2003-08 Part 4-7: Testing and measurement techniques; General guide on harmonics and interharmonics measurements and instrumentation, for power supply systems and equipment connected thereto	
IEC 61000-4-8	**(VDE 0847 Part 4-8)** 2001-12 Part 4-8: Testing and measurement techniques; Power frequency magnetic field immunity test	
IEC 61000-4-9	**(VDE 0847 Part 4-9)** 2001-12 Part 4-9: Testing and measurement techniques; Pulse magnetic field immunity test	
IEC 61000-4-10	**(VDE 0847 Part 4-10)** 2001-12 Part 4-10: Testing and measurement techniques; Damped oscillatory magnetic field immunity test	
IEC 61000-4-11	**(VDE 0847 Part 4-11)** 2005-02 Part 4-11: Testing and measurement techniques - Voltage dips, short interruptions and voltage variations immunity tests	
IEC 61000-4-12	**(VDE 0847 Part 4-12)** 2001-12 Part 4-12: Testing and measurement techniques; Oscillatory waves immunity tests	
IEC 61000-4-13	**(VDE 0847 Part 4-13)** 2003-02 Part 4-13: Testing and measurement techniques; Harmonics and interharmonics including mains signalling at a.c. power port, low frequency immunity tests	
IEC 61000-4-14	**(VDE 0847 Part 4-14)** 2005-02 Part 4-14: Testing and measurement techniques - Voltage fluctuation immunity test	
IEC 61000-4-15	**(VDE 0847 Part 4-15)** 2003-10 Part 4-15: Testing and measurement techniques; Flickermeter; Functional and design specifications	
IEC 61000-4-16	**(VDE 0847 Part 4-16)** 2005-04 Part 4-16: Testing and measurement techniques - Test for immunity to conducted, common mode disturbances in the frequency range 0 Hz to 150 kHz	
IEC 61000-4-24	**(VDE 0847 Part 4-24)** 1997-11 Part 4: Testing and measuring techniques; Section 24: Test methods for protective devices for HEMP conducted disturbances; basic EMC Publication	

IEC 61000-5-5	**(VDE 0847 Part 5-5)** Part 5: Installation and mitigation guidelines; Section 5: Specification of protective devices for HEMP conducted disturbance - Basic EMC publication	1997-02
DIN VDE 0848-1	**(VDE 0848 Part 1)** Safety in electrical, magnetic and electromagnetic fields - Part 1: Definitions, methods for measurement and calculation	2000-08
DIN 57850	**(VDE 0850)** Coupling devices for power line carrier systems	1980-03
IEC 60495	**(VDE 0850 Part 2)** Single sideband power-line carrier terminals	1995-02
DIN VDE 0851	**(VDE 0851)** Line traps for power line carrier systems (PLC line traps)	1993-02
IEC 60834-1	**(VDE 0852 Part 1)** Teleprotection equipment of power systems - Performance and testing - Part 1: Command systems	2000-12
DIN VDE 0852-2	**(VDE 0852 Part 2)** Performance and testing of teleprotection equipment of power systems - Part 2: Analogue comparison systems	1995-11
DIN VDE 0873	**(VDE 0873)** supplementary sheets 1, 2 und 3 Radio interference characteristics of overhead power lines and high-voltage equipment	
	Supplement 1 description of phenomena; identical with publication CISPR 60018-1, edition 1982	1986-06
	Supplement 2 methods of measurement and procedure for determining limits; identical with CISPR 18-2	1990-02
	Supplement 3 code of practice for minimizing the generation of radio noise; identical with CISPR 18-3	1991-01
DIN VDE 0873-1	**(VDE 0873 Part 1)** Measures against radio interference from electric utility plants and electric traction systems; radio interference from systems of 10 kV and above	1982-05
DIN VDE 0873-2	**(VDE 0873 Part 2)** Measures against radio interference from electric utility plants and electric traction systems; radio interference from systems below 10 kV and from electrical trains	1988-10
IEC 60794-1-1	**(VDE 0888 Part 100 - 1)** Optical fibre cable - Part 1-1: Generic specification; General	2002-11

IEC 60794-1-2	**(VDE 0888 Part 100 – 2)** Part 1-2: Generic specification - Basic optical cable test procedures	2004-07
EN 188000	**(VDE 0888 Part 101)** Generic specification: optical fibres	1994-02
IEC 60793-2-50	**(VDE 0888 Part 325)** Part 2-50: Product specifications - Sectional specification for class B single-mode fibres	2005-01
DIN VDE 0891-1	**(VDE 0891 Part 1)** Use of cables and insulated wires for telecommunication systems and information processing systems; - general directions	1990-05
DIN VDE 0891-2	**(VDE 0891 Part 2)** - special directions for equipment wires with solid or stranded conductors according to DIN VDE 0812	1990-05
DIN VDE 0891-3	**(VDE 0891 Part 3)** special directions for switchbord cables according to DIN VDE 0813	1990-05

Further parts: 4, 5, 6, 7, 8, 9.

17.2 Application of European directives to high-voltage switchgear installations. CE mark

The CE mark based on European Directives assists the free distribution of goods on the European market. It is directed to the national standards supervising bodies. When the manufacturer applies the CE mark, this states that the legal requirements for the commercial product have been met. The CE mark is not a quality designation, a safety designation or a designation of conformity to a standard.

The following three European Union Directives may be applicable to electrical switchgear installations:

The Machine Directive covers most types of machines, with the exception of certain special types that are specifically excluded. The power supply companies and the manufacturers in Europe (EURELECTRIC/UNIPEDE and CAPIEL) have always been of the unanimous opinion that high-voltage equipment is not subject to the Machine Directive. The European Commission now shares this view. It should also be noted that motors, by definition, are not covered by the Machine Directive.

The EMC Directive is intended for application to almost all electrical equipment.

However, fixed installations (which are assembled at the site of operation) have to meet the EMC protection requirements but they do not require a declaration of conformity, a CE mark nor an approval by any competent authority. This also applies to all primary and secondary devices in these installations (as components with no direct function).

The Low Voltage Directive (LVD) is applicable to independent low-voltage equipment which is also used in high-voltage switchgear and installations, such as control circuits, protection relays, measuring and metering devices, terminal strips, etc. This equipment must conform to the LVD and have a CE mark when purchased on the open market.

However, if control, measuring, protection and regulating equipment is a fixed component of high-voltage substations and/or switchgear, it is not covered by the Low- Voltage Directive, because by definition (as per IEC 50-441) they are considered to be high-voltage products.

In conclusion it is noted that high-voltage equipment and installations, including secondary installations, do not require a CE mark. However, they are subject to the relevant standards and regulations.

17.3 Quality in switchgears

The functional reliability of switchgear installations and hence the largely undisturbed transmission of electricity in a power network depends on the suitability and quality of the switchgear, components, systems and processes employed. Of growing importance in this regard is a forward-looking quality strategy with internationally harmonized standards and their main quality systems. The following brief review of the main international standards, terms and scope of quality assurance is intended to ease the switchgear engineer’s introduction to this complex subject.

According to the definition of the standard (ISO 8402), quality means the totality of the characteristics of a unit with reference to its ability to meet specified and predefined requirements. With regard to the customer-supplier relationship, this means that the supplier’s quality meets or exceeds the customer’s requirements and meets or exceeds the statutory requirements with regard to the products and the processes.

Necessary for optimizing this attribute is a quality management system, i.e. a clearly structured organization and procedures for implementing quality assurance, together with the requisite means. Quality assurance in this sense is the sum of all the activities of quality management, quality planning and quality control (see DIN 55 350-11).

The CEN members are required to adopt the series of European standards ISO 9000 to ISO 9004, which concern the setting up of a quality system. This standard must be given the status of a national standard without any modifications. The series comprises:

ISO 9000: Quality management systems -- Fundamentals and vocabulary

ISO 9001: Quality management systems -- Requirements

ISO 9004: Quality management systems -- Guidelines for performance improvements

The objective of these standards is to create customer confidence that the supplier's quality management system fulfils specified minimum requirements. This can be achieved by demonstrating the quality management system to the customer or an authorized body. All the planned, systematic confidence-building activities within this context are designated by ISO 9000 as quality assurance or demonstration of quality management, and comprise

– creation of a structural and workflow organization,

– qualification of staff and equipment,
– stipulation of authorities and responsibilities,
– mandatory documentation for stipulations and results,
– mandatory reporting up to the highest management level,
– management of risks and cost-effectiveness, and
– preventive actions to avoid quality problems.

17.4 Notable events and achievements in the history of ABB switchgear technology

1891	First three-phase current transmission over 178 kilometres from Lauffen on the Neckar to Frankfurt am Main.
1898	First oil circuit-breaker
1900	Oil circuit-breaker with automatic overcurrent trip
1908	35 kV switchgear installation with partitions between the three phases
1908	Transformer station for 50 kV
1912	65 kV switchgear installation with partitioned phases
1917	110 kV indoor switchgear with outdoor busbars
1922	110/20 kV indoor switching station with recessed oil circuit breakers
1922	Sheet steel control panel with control switches and breaker position indicators incorporated in a mimic display
1923	First miniature circuit-breaker with thermal and magnetic trip
1924	High-speed breaker for rectifier systems
1926	110 kV outdoor switchgear mounted on lattice-type columns
1928	First delivery of oil-insulated current transformers for 110 kV
1928	Distance relays for selective disconnection of faulted parts of network
1930	Illuminated mimic display for a 110/20 kV transformer station with electrical safety interlocks
1930	First delivery of water-type circuit-breakers for medium voltage
1932	First delivery of minimum-oil convector-type circuit-breaker for 110 kV
1933	First delivery of airblast circuit-breakers for 10 to 30 kV and 250 to 500 MVA
1938	Commissioning of first transformer station for 220/110/10 kV with resonant grounding and reactive current compensation, convector-type and highspeed airblast circuit-breakers
1939	Direct current transmission at 50 kV using rectifier
1939	Service trials of airblast high-speed circuit-breakers with auto-reclosure
1939	First delivery of oil-insulated current transformers for 220 kV
1943	First outdoor high-speed airblast circuit-breaker for 110 kV, 2500 MVA

1947 Improved high-speed, surge-free synchronizer with synchronizing pulse controller

1948 Small-oil-volume circuit-breaker for 12 kV, 24 kV and 36 kV, LOS pumping-piston arc-quenching principle with current-dependent assisted arc-quenching medium flow (CALOR-EMAG)

1950 First delivery of outdoor high-speed airblast breakers for 220 kV, 2500 MVA with automatic reclosing

1952 Outdoor high-speed circuit-breakers, current transformers and surge arresters delivered to the world's first 380 kV network in Sweden

1954 Commissioning of the world's first 20 MW, 100 kV HVDC system for Gotland, Sweden

1954 First high-current bus duct for 8 kA load current, open design, Al-C sections

1957 Outdoor airblast circuit-breakers of 12 000 MVA for Germany's first 380 kV transmission link from Rommerskirchen to Hoheneck

1957 Development of internal arc-resistant metal-enclosed switchboards with pressure relief, up to 36 kV (CALOR-EMAG)

1957 First electronic load-frequency control system

1958 First static audio-frequency transmitter using mercury-arc valves

1963 Network control centre with preselective control and mosaic-type illuminated display panel

1963 First delivery of oil-insulated current transformers for 550 kV

1965 High-speed airblast circuit-breakers, current transformers, voltage transformers and reactor coils for the world's first 735 kV transmission system in Canada

1966 First electronic busbar protection system for medium- and high-voltage systems

1966 First high-current bus duct in single-phase enclosure, Al-V sections

1967 First SF6 gas-insulated switchgear for 123 kV (CALOR-EMAG) in Germany and 170 kV in Switzerland

1968 Germany's first telecontrol system using integrated circuits

1969 "Combiflex" modular electronic protection relay system

1970 First 245 kV SF6 gas-insulated switchgear installation in Germany

1970 First delivery of 735 kV surge arresters to Canada

1972-73 Argentina's 500 kV network constructed including four turnkey outdoor switching stations and pantograph disconnectors

1972 First fully electronic ripple-control receiver

1972 World's first and biggest ripple-control system with thyristorized transmitters for a 110 kV network

1972	First power-control system with on-line state estimator program for Laufenburg, Switzerland
1973	765 kV outdoor airblast circuit-breakers and current transformers in the USA
1973	Network management / load-dispatching systems with process computer, central data processing and video terminals
1973	Airblast generator circuit-breaker for 27 kV, 160 kA and rated continuous current of 32 000 A
1974	First SF6 gas-insulated switchgear installations for 420 kV and 525 kV in Switzerland and Canada
1974	420 kV outdoor switching station with tubular busbars for 3000 A
1974	Introduction of the MNS metal-enclosed modular low-voltage system
1975	SLM rail-type low-voltage fused switch disconnector
1975	420 kV SF6 gas-insulated switchgear installation for Germany
1975	First residual-current protection switch
1975	First telecontrol system with adaptive signal routing
1976	Airblast generator circuit-breaker 27 kV, 250 kA and rated continuous current of 36 000 A
1976	First super-fast direction comparison protection system for high- and extrahigh voltage power lines
1978	"MODURES" modular electronic relay system for medium- and highvoltage installations
1979	Network control system for a sequence of run-of-river hydro generating plants
1980	World's biggest 123 kV SF6 gas-insulated switchgear installation for the Yanbu industrial complex in Saudi Arabia, with 57 circuit-breaker branches
1980-81	Introduction of metal-oxide surge arresters and world's first delivery to Denmark and for 735 kV to Canada
1980	World launch of the B series of modular contactors
1980	World's biggest 525 kV SF6 gas-insulated switchgear installation for the Itaipu hydroelectric power plant in Brazil, with 52 circuit-breaker branches
1980	Introduction of the vacuum-type circuit-breaker for voltages up to 36 kV (CALOR-EMAG)
1981	World's first digital fault locator for high-voltage power lines
1981	Delivery of 18 high-current bus ducts for the Itaipu hydro-electric plant in Brazil, service currents up to 28 kA
1982	World's first delivery of metal-oxide surge arresters for ultra-high voltage of 1600 kV to experimental facility in USA

1983	Commissioning of German Railway's first control centre for controlling traction power supply
1983	550 MW high-voltage direct-current (HVDC) coupling at Dürnrohr (Austria) connecting the grid systems of West and East Europe
1983	Isolated-phase, force-cooled generator busduct for 20.5 kV, 36 500 A, delivered to Sweden
1983	765 kV outdoor SF6 circuit-breakers delivered to the USA
1984	Delivery of world's largest HVDC system of 6300 MW, ± 600 kV for Itaipu, Brazil
1984	Outdoor SF6 circuit-breakers for 420 kV, 80 kA 4000 A
1984-89	Seven turnkey outdoor switchgear installations for the 500 kV network of Java / Indonesia
1984-85	Introduction of containerized modular high-current switchgear for gas turbine power plants
1984	Decentralized computers for transformer substations with telecontrol functions and local data processing
1985	Outdoor SF6 circuit-breakers employing self-blast principle
1985	Introduction of gas-insulated, medium-voltage switchgear, single-phase metal-clad for up to 24 kV
1985	Introduction of gas-insulated, medium-voltage switchgear, triple-phase metal-clad (ZV2), for up to 36 kV (CALOR-EMAG)
1985	SF6 generator circuit-breakers for 24 kV, 100 kA and rated continuous current of 12000 A
1985	First digital phase-comparison protection system for a high-voltage network
1986	Supraregional network control centres for 380 kV to 10 kV with multiple computers and complex, hierarchically structured telecontrol networks
1986	Introduction of hydraulic spring operating mechanisms for high-voltage circuit-breakers
1987	World's first 800 kV SF6 gas-insulated switchgear installation ready for operation in South Africa
1987	VD4 vacuum circuit-breaker series for 12 kV and 24 kV, particularly suited for compact switchboard designs (CALOR-EMAG)
1989	World's first integrated protection and control system for power generation, transmission and distribution
1989-91	Two turnkey outdoor switchyards for Thailand's 500 kV network
1990	1000th GIS switchgear bay ELK-O, 123 kV, delivered to Graz, Austria
1990	Delivery of the first digital distance and transformer differential protection relays

1990	World launch of EXLIM metal-oxide surge arresters for system voltagesup to 800 kV
1991	Delivery of the first remote-programmable ripple-control receivers with distributed intelligence, integral clock and background switching schedules
1992	Commissioning of the first multiterminal HVDC system of 2000 MW, ± 500 kV, between Quebec and New England
1995	Commissioning of UW8 transformer substation with unified digital station control system with station-level interlocking (LON) for SF6-insulated switchbays for 110 kV and 20 kV in Mannheim
1995	First delivery of gas-insulated medium voltage switchgear of type ZX1 – Start of the ZX range up to 40.5 kV with complete plug-in technology for cable terminations and busbar connections.
1997	VM1 vacuum circuit-breaker series with electromagnetic actuating system for 12 kV and 24 kV
1997	The world's first three-phase transformer equipped with high temperature superconductors.
1997	Market launch of SMART, an online monitoring system with decentralized architecture for SF6-insulated switchgear.
1998	Supply of the 20000th hydraulic spring operating mechanism
1998	Market launch of EXK-01, the world's most compact SF6-insulated 123 kV switchgear system.
1999	After a construction period of only 16 months, the ABB future factory in Ratingen, just outside Düsseldorf, officially commences production.
2001	Development of a highly compact gas-insulated 145 kV high voltage switchgear system for 4000 A operating current and 63 kA short-circuit current in three-phase design.
2003	Commissioning of the first database-aided production line at ABB in Germany for manufacture of embedded parts in Ratingen.
2005	Production of 23,300 vacuum interrupters in Ratingen in only one month.
2005	Delivery of the 40000th hydraulic stored energy spring mechanism
2005	The world's first HVDC light offshore system, Troll A Platform, Kollsnes, Norway