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.

4.1.1 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*.

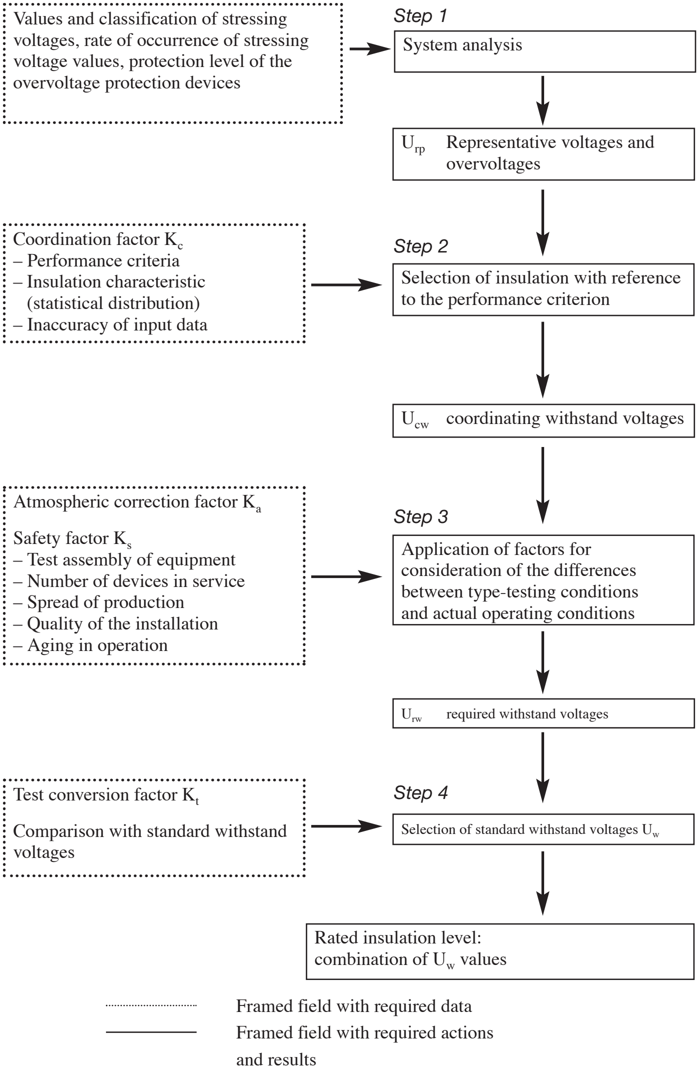


Fig. 4-1

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.

4

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.

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
ε_{pi}, ε_{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.

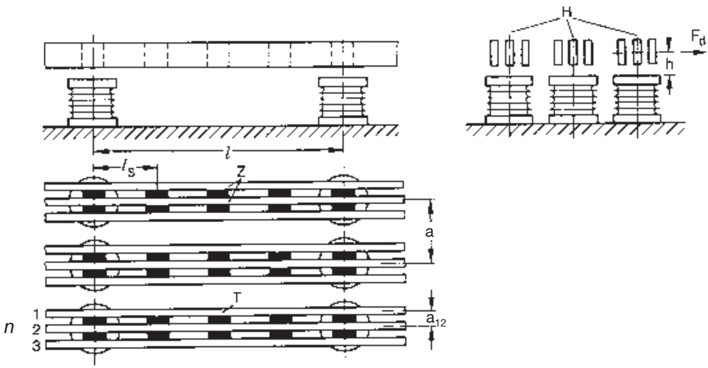


Fig. 4-2

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 e l e c t r o d y n a m i c f o r c e 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

$$\frac{1}{a_s} = \frac{k_{12}}{a_{12}} + \frac{k_{13}}{a_{13}} + \ldots + \frac{k_{1n}}{a_{1n}}$$

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	2.0	2.4	2.7	3.3	4.0	—	—	—
	1	2.8	3.1	3.4	4.1	4.7	5.4	6.7	8.0
	0.5	—	1.3	1.5	1.8	2.2	—	—	—
	1	1.7	1.9	2.0	2.3	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	—	1.4	1.5	1.8	2.0	—	—	—
	1	1.7	1.8	2.0	2.2	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.

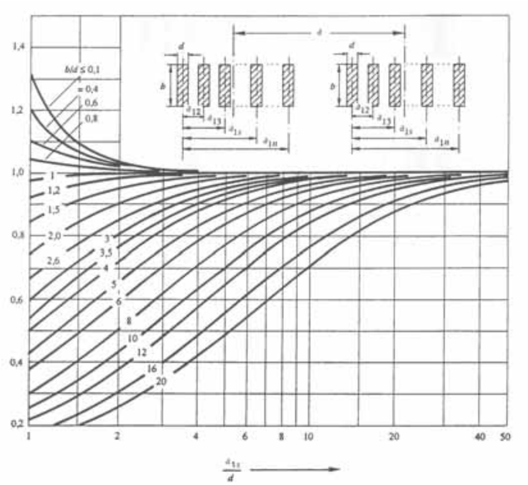


Fig. 4-3

Correction factor k_{1s} for calculating the effective conductor spacing

Main conductor stress: $\sigma_m = V_\sigma \cdot V_r \cdot \beta \cdot \dfrac{F_m \cdot l}{8 \cdot Z}$

Sub-conductor stress: $\sigma_s = V_{\sigma s} \cdot V_r \cdot \dfrac{F_s \cdot l_s}{16 \cdot Z_s}$

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 $\sigma_{tot} < 0.8 \cdot R'_{p0.2}$

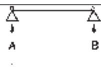
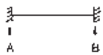
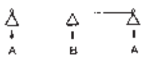
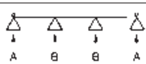
However, in two-phase a.c. systems $V_F \cdot V_r$ does not require a value greater than 2 and in three-phase systems no greater than 2.7.

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. γ = 3.56 and l for the distance between two stiffening elements must be used for calculating the sub-conductor stresses.

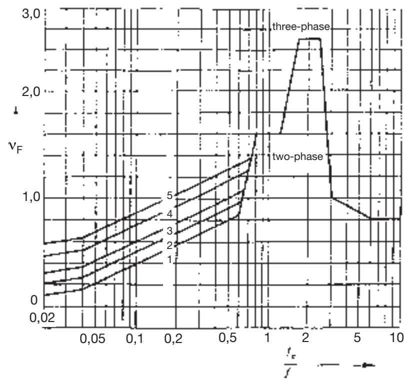


Fig. 4-4
Factor V_F to determine the forces on supports

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

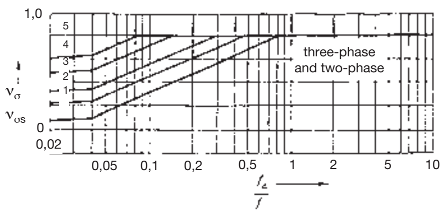


Fig. 4-5

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 $f_c > 2.4\,f$.

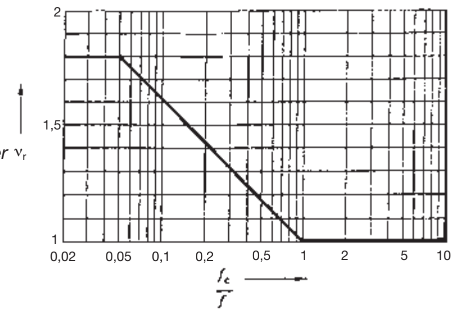


Fig. 4-6

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.

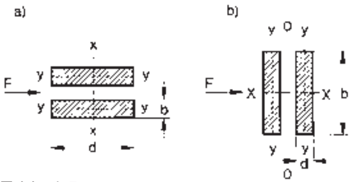
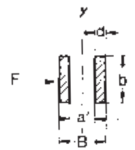


Fig. 4-7

Direction of force and bending axes with conductor packets

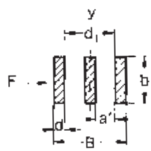
Table 4-5

Formulae for calculating the ideal moments of inertia and resistance of composite main conductors with stiffening elements (100 % values).



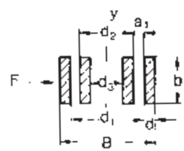
$$J_y = \frac{b}{12}(B^3 - a'^3)$$

$$Z_y = \frac{b}{6B}(B^3 - a'^3)$$



$$J_y = \frac{b}{12}(B^3 - d_1^3 + d^3)$$

$$Z_y = \frac{b}{6B}(B^3 - d_1^3 + d^3)$$



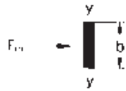
$$J_y = \frac{b}{12}(B^3 - d_1^3 + d_2^3 - d_3^3)$$

$$Z_y = \frac{b}{6B}(B^3 - d_1^3 + d_2^3 - d_3^3)$$

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 cm^4 and Z_y in cm^3, 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 cm^3	J_x cm^4	Z_y cm^3	J_y cm^4
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

$$\frac{\mu_0}{2 \cdot \pi} = 0.2 \frac{\text{N}}{(\text{kA})^2} .$$

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

$$F_f = 1{,}2\, F_{st} \sqrt{1 + 8\zeta \frac{\delta_m}{180°}}$$ 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

$$F_{pi} = F_{st} \left(1 + \frac{\nu_e}{\varepsilon_{st}} \xi \right)$$ 1), 2), 4)

If the sub-conductors do not come into contact during contraction ($j < 1$) F_{pi} is

$$F_{pi} = F_{st} \left(1 + \frac{\nu_e}{\varepsilon_{st}} \eta^2 \right)$$ 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

$$r = \frac{F'}{g_n\, m'} \quad \text{force ratio}^{2)}$$

$$\delta_k = \begin{cases} \delta_1 \left[1 - \cos\left(360° \frac{T_{K11}}{T_{res}} \right) \right] & \text{for } 0 \leq \frac{T_{k11}}{T_{res}} \leq 0{,}5 \\ 2\delta_1 & \text{for } \frac{T_{k11}}{T_{res}} > 0{,}5 \end{cases}$$

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 span[2)]

Where:

m' mass of a main conductor per unit length[2), 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 norm[2)]

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 elasticity[2)]

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.

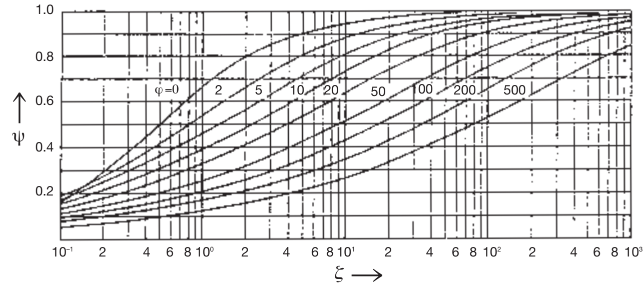


Fig. 4-8

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).

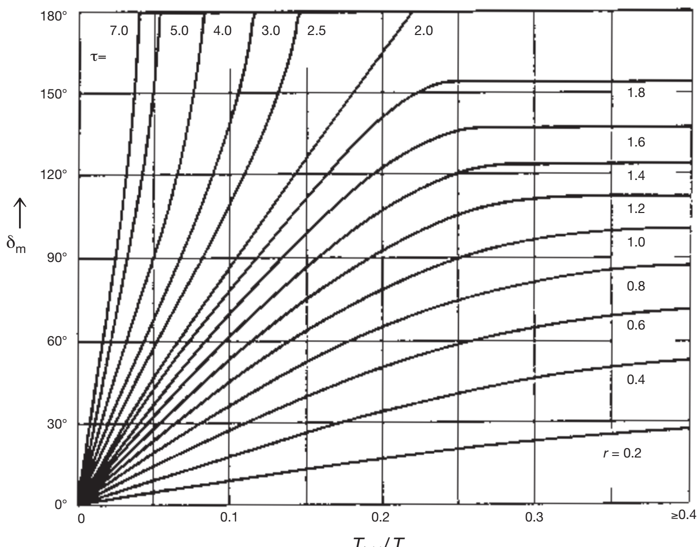


Fig. 4-9

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

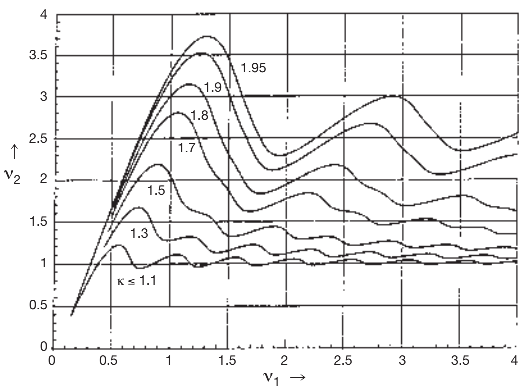


Fig. 4-10

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

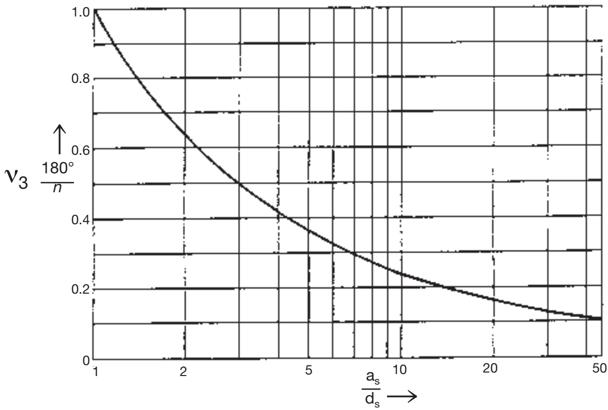


Fig. 4-11

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

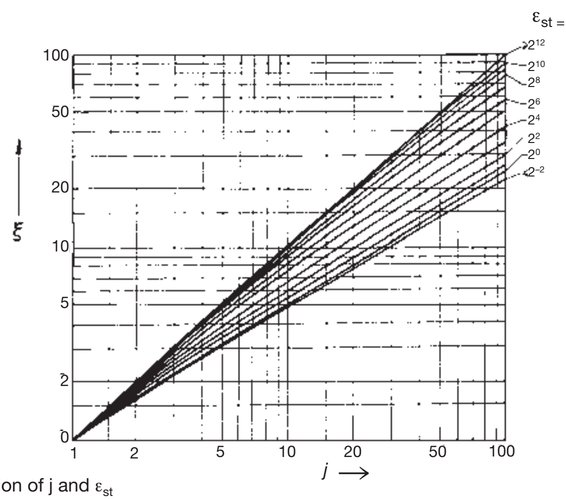


Fig. 4-12

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

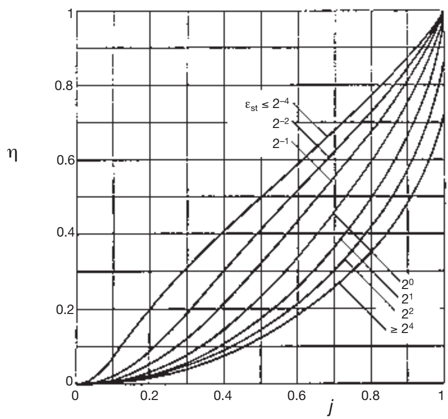


Fig. 4-13a

η as function of j and ε_{st} for 2.5 < a_s / d_s ≤ 5.0

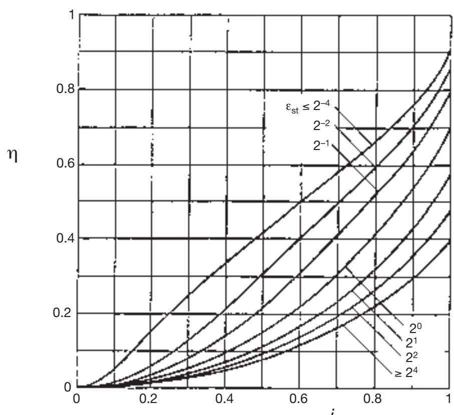


Fig. 4-13b

η as function of j and ε_{st} for 5.0 < a_s / d_s ≤ 10.0

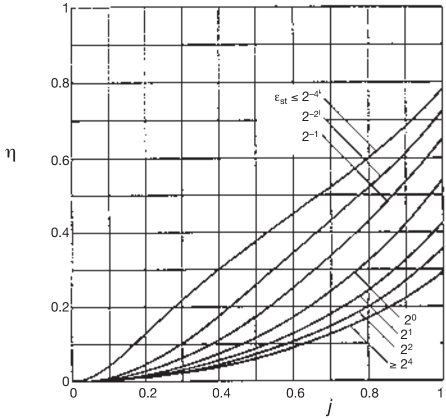


Fig. 4-13c

η as function of j and ε_{st} for $10.0 < a_s / d_s \le 15.0$

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, $F_{st} \le 0.4\ F_r$ 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 mm² 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 50² / 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 $T_{k11} \leq 0.5\, T_{res}$)	66.5	66.5	°
Load parameter φ (with $T_{k11} \geq T_{res}/4$)	0.656	0.656	
Effective modulus of elasticity E_s (with $F_{st}/A \leq \sigma_{fin}$)	23791	23342	N/mm²
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 $\delta_m \geq 70°$)	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 $j \geq 1$)	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 ($l_c = l$)

$$b_h = \begin{cases} C_F C_D b_C & \text{for } \delta_m \geq 90° \\ C_F C_D b_C \sin\delta_m & \text{for } \delta_m \leq 90° \end{cases} \quad \text{for} \quad l_C = l$$

and with strained conductors, which are attached to support structures by insulator strings (length l_i).

$$b_h = \begin{cases} C_F C_D b_C \sin\delta_1 & \text{for } \delta_m \geq \delta_1 \\ C_F C_D b_C \sin\delta_m & \text{for } \delta_m \leq \delta_1 \end{cases} \quad \text{for} \quad l_C = l - 2\, l_i$$

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).

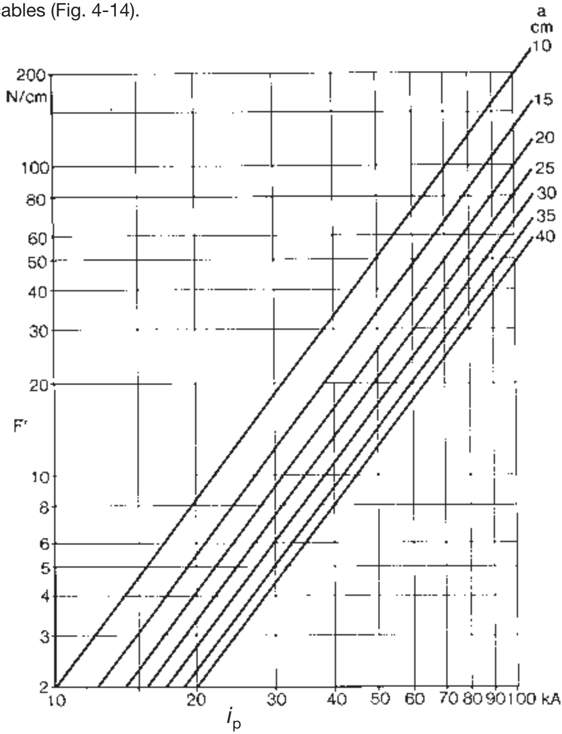


Fig. 4-14

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}.

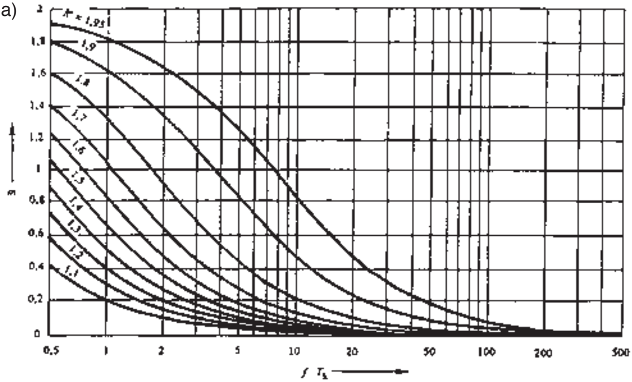
Electrical apparatus have sufficient thermal resistance if:

$$I_{th} \leqq I_{thr} \text{ for } T_k \leqq T_{kr}$$

$$I_{th} \leqq I_{thr} \cdot \sqrt{\frac{T_{kr}}{T_k}} \text{ for } T_k \geqq T_{kr}.$$

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)

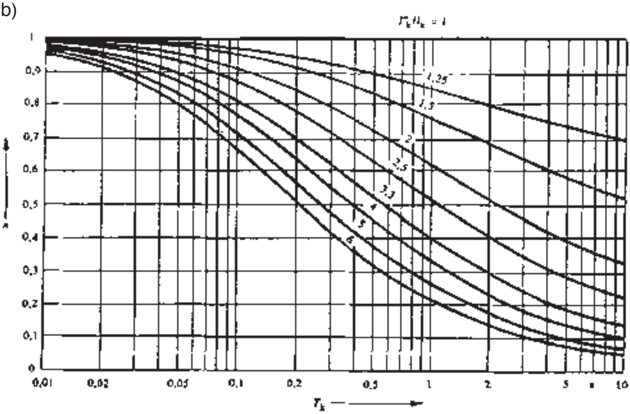


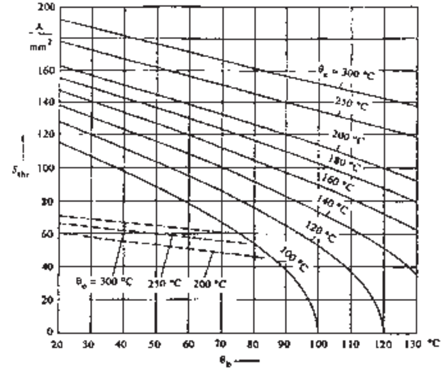
Fig. 4-15

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)



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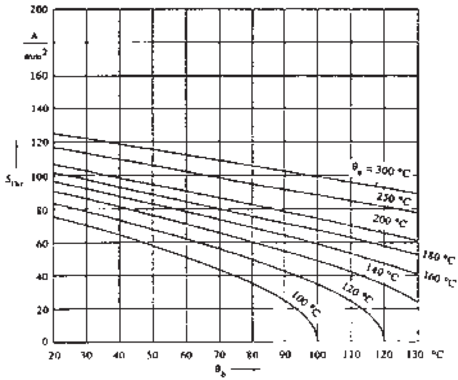


Fig. 4-16

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 ϑ_b = 80 °C and an end temperature ϑ_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.

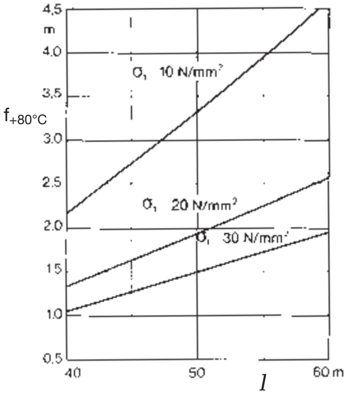


Fig. 4-17

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).

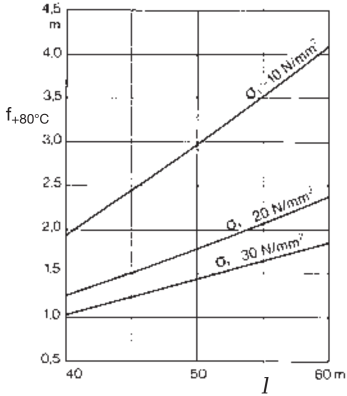


Fig. 4-18

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.

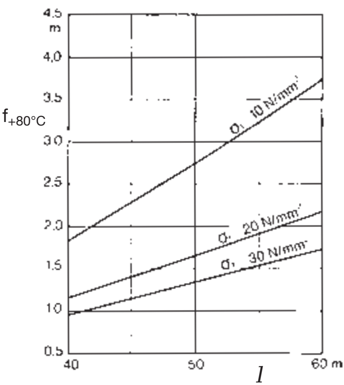


Fig. 4-19

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).

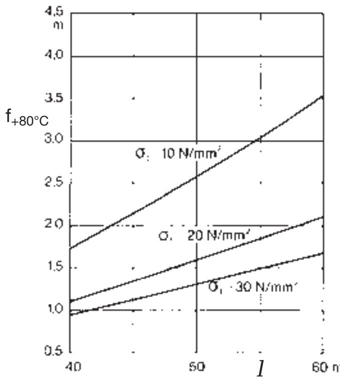


Fig. 4-20

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

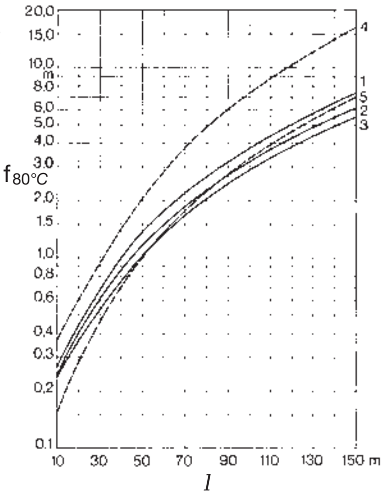
2 two-conductor bundles Al/St 380/50 mm², 245-kV-double-end strings, σ_1 30.0 N/mm² at – 5 °C and about 10 mm ice coating

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.

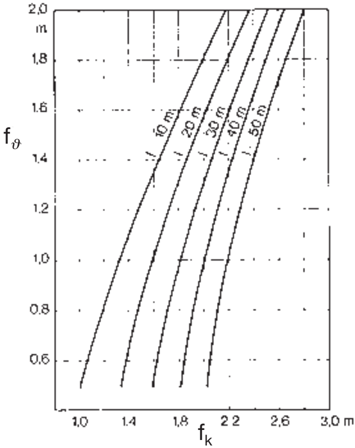


Fig. 4-22

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.

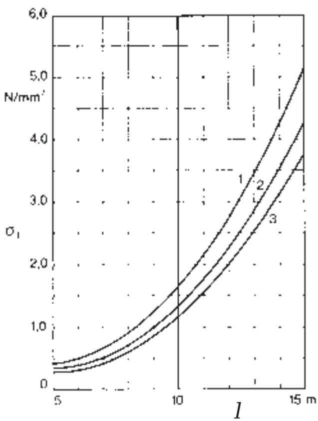


Fig. 4-23

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

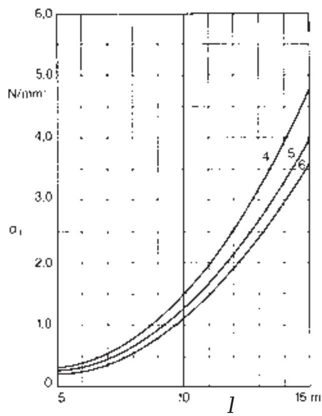


Fig. 4-24

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:

$$f_c = \frac{4 \cdot f_{max} \cdot c \cdot (l - c)}{l^2}$$

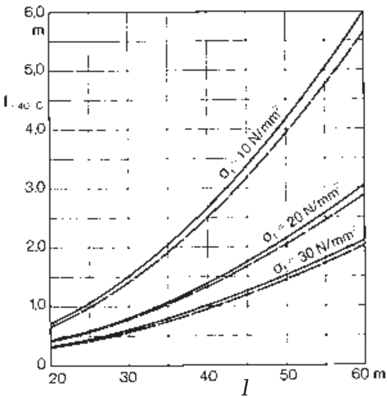


Fig. 4-25

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.

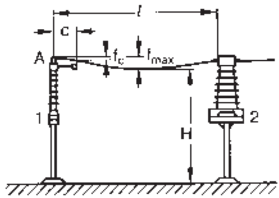


Fig. 4-26

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)

4

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:

$$E = \frac{U}{\sqrt{3}} \cdot \frac{\beta}{r_L \cdot \ln\left(\frac{a}{r_e} \cdot \frac{2 \cdot h}{\sqrt{4\,h^2 + a^2}}\right)}$$

where $\beta = \dfrac{1 + (n-1)\; r_L / r_T}{n}$

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

$$r_T = \frac{a_T}{2 \cdot \sin(\pi/n)}$$

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:

$$\Delta \vartheta = \frac{P_{\text{V eff}}}{\alpha \cdot A_{\text{M}}}$$

$\Delta \vartheta$ 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$^2 \cdot K$) sources of heat flow are primarily in the lower half of the panel,

4.5 W/(m$^2 \cdot K$) sources of heat flow are equally distributed throughout the height of the panel,

3 W/(m$^2 \cdot K$) 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.

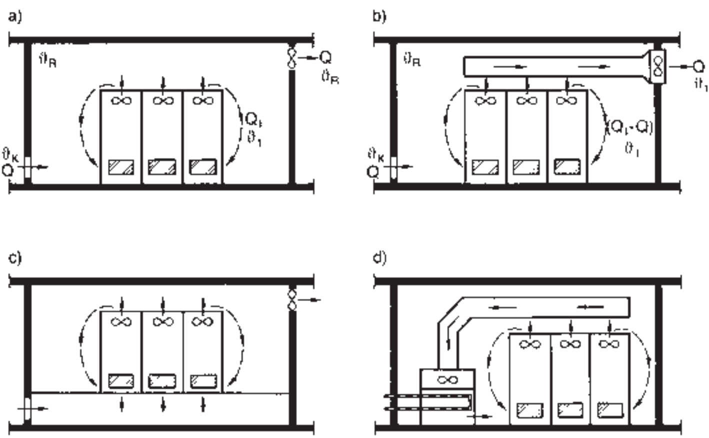


Fig. 4-27

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

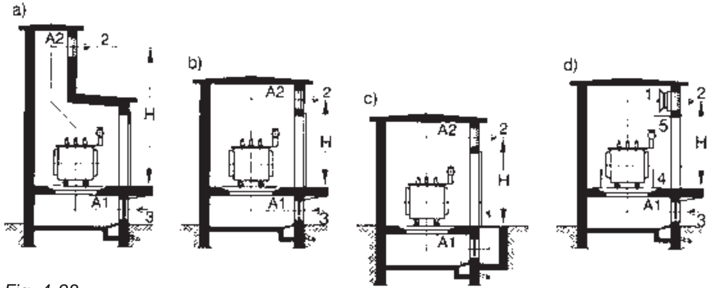


Fig. 4-28

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, $g = 9.81 \frac{m}{s^2}$,
H_0 = height above sea level,
R_L = gas constant of the air, $R_L = 0.287 \frac{kJ}{kg \cdot K}$,
c_{pL} = specific heat capacity of the air, $c_{pL} = 1.298 \frac{kJ}{m^3 \cdot K}$,
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

$$\dot{V}_1 = \frac{P_V}{c_{pL}\,(T_2 - T_1)} \cdot \frac{T_1}{T_0} \cdot e^{-g \cdot H / (R_L \cdot T_0)} = 2{,}4 \frac{m^3}{s} = 8640 \frac{m^3}{h}$$

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 m².

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.

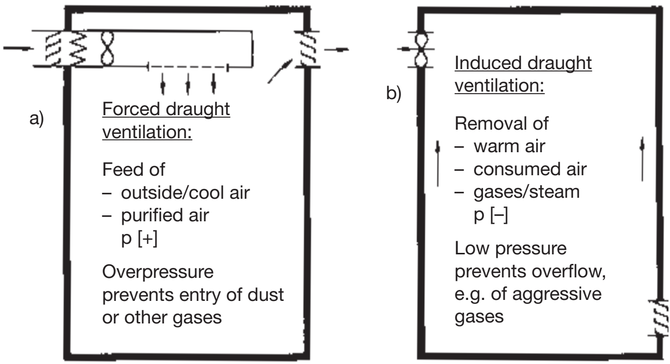


Fig. 4-29

Schematic view of a ventilation system: a) forced draught ventilation, b) Induced draught ventilation

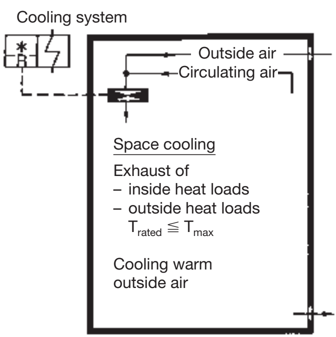


Fig. 4-30
Schematic view of a cooling system

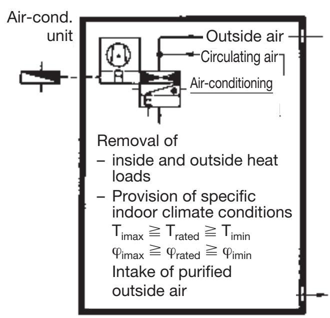


Fig. 4-31
Schematic view of an air-conditioning system

- *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 (m^2) · k (W/m^2 · 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 (m^2)*

k = heat transmission coefficient (W/m^2)

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.

4

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:

$$P_S = \alpha_S \cdot A_S \cdot \Delta \vartheta \text{ or } R_S = \frac{1}{\alpha_S \cdot A_S}$$

$$= C_{13} \cdot A_s \cdot (T_1^4 - T_3^4) \qquad \text{where } \alpha_s = \frac{C_{13}\,(T_1^4 - T_3^4)}{\Delta \vartheta}$$

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.

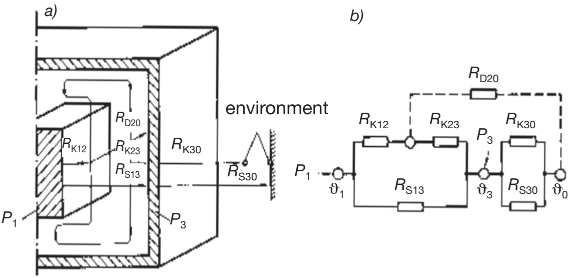


Fig. 4-32

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

$P_c = c \cdot \gamma \cdot A \frac{d}{dt} \Delta \vartheta$ 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/(m² K))
c = specific heat (384.38 Ws/K · kg for copper)
γ = density ($8.92 \cdot 10^{-3}$ kg/cm³ for copper)
ρ = specific resistance (0.0178 Ωmm²/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	mm²
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.

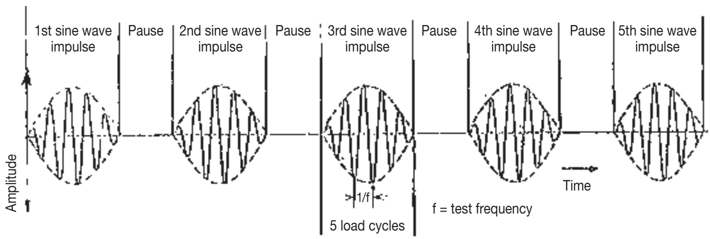


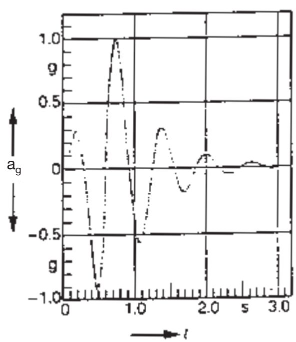
Fig. 4-33

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



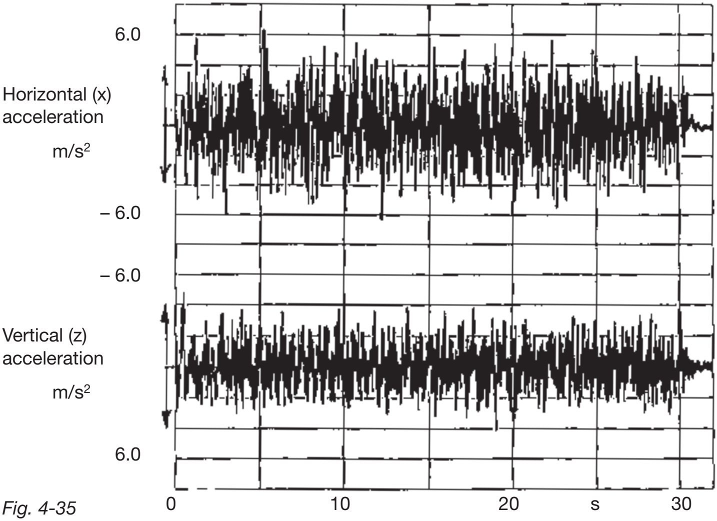


Fig. 4-35

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 $U_m \geq 300$ 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 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, Indoor installation mm	Outdoor installation 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
		185 [4]	450	900
132	145	230	550	1100
		275	650	1300
		230 [4]	550	1100
150 [1]	170	275	650	1300
		325	750	1500
		325 [4]	750	1500
220	245 [5]	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 U_n kV	Maximum voltage for apparatus U_m kV	Rated switching impulse withstand voltage phase-to-earth 250/2500 µs U_{rS} kV	Minimum clearance (*N*) phase-to-earth: Conductor/design mm	Minimum clearance (*N*) phase-to-earth: Bar/design mm	Rated switching impulse withstand voltage phase-to-phase 250/2500 µs kV	Minimum clearance phase-to-phase: Conductor/conductor parallel mm	Minimum clearance phase-to-phase: Bar/conductor 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).

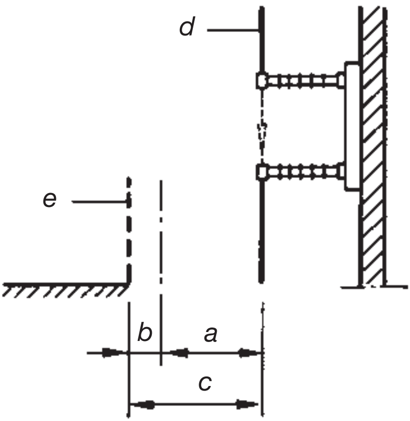


Fig. 4-36

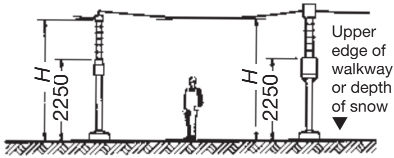
Minimum clearance + safety clearance = protective barrier clearance:
a = minimum clearance,
b = safety clearance,
c = protective barrier clearance,
d = live part,
e = protective barrier

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).

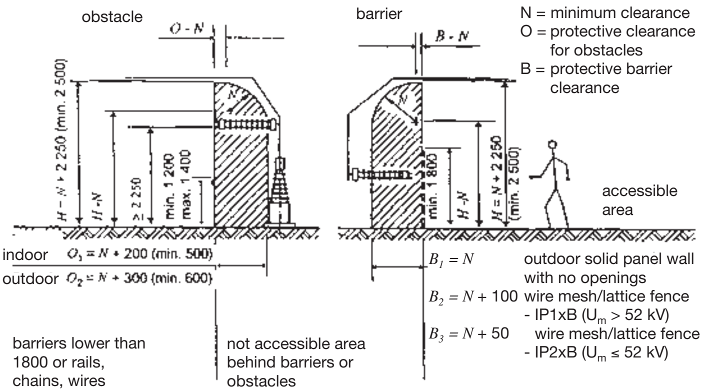


Fig. 4-38

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.

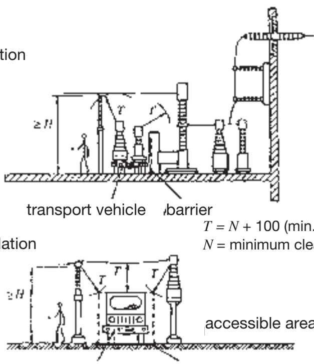
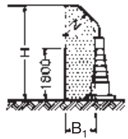


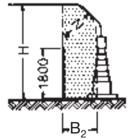
Fig. 4-39

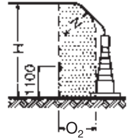
Transport clearances

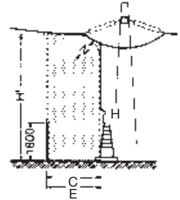
Table 4-11

Minimum height and protective barrier clearances in outdoor installations as per DIN VDE 0101 (H’ as per DIN VDE 0210)





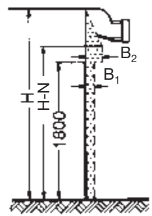




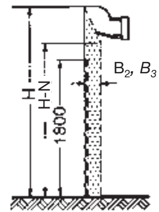
Nominal voltage	Maximum voltage for equipment	Minimum clearances *N* as per Table 4-10	Minimum height	Protective barrier clearances of live parts inside the installation as per Fig. 4-38 Solid-panel wall	Wire mesh, screen	Rail, chain, rope	at the outer fence	Solid wall	Screen	Transport clearances as per Fig. 4-39
U_n kV	U_m kV	N mm	H mm	B_1 mm	B_2, B_3 mm	O_2 mm	H' mm	C mm	E mm	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

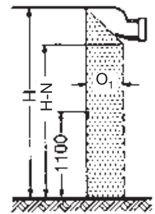
Minimum height and protective barrier clearances in indoor installations as per DIN VDE 0101



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.

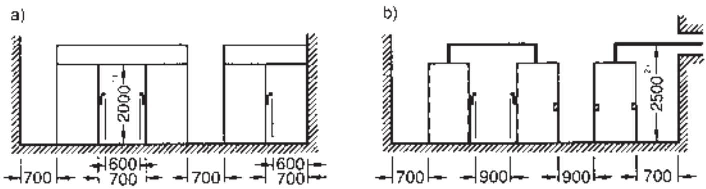


Fig. 4-40

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.

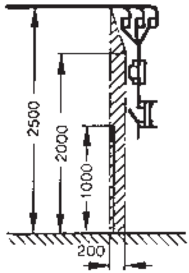


Fig. 4-41

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.

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.

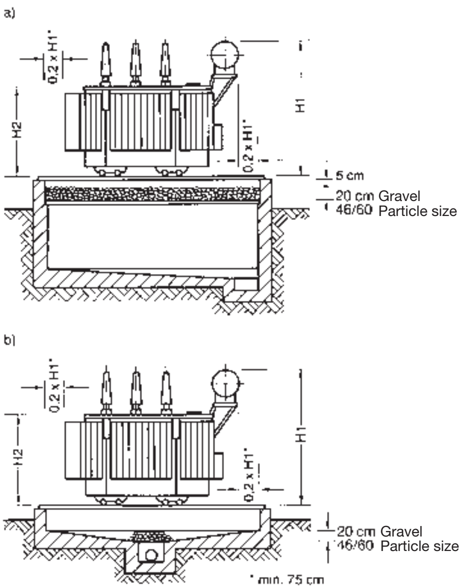


Fig. 4-42

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.

4

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.

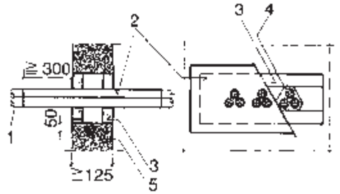


Fig. 4-43

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

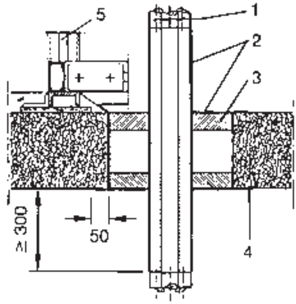


Fig. 4-44

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

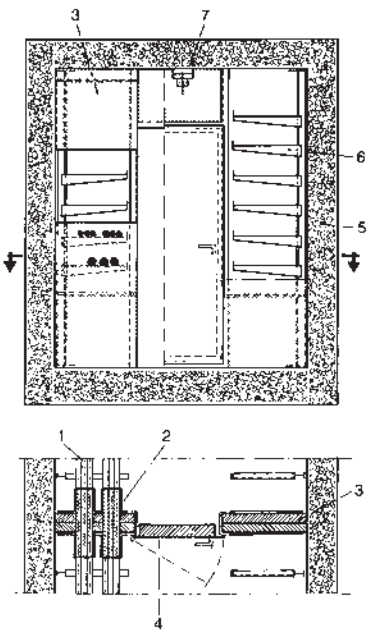
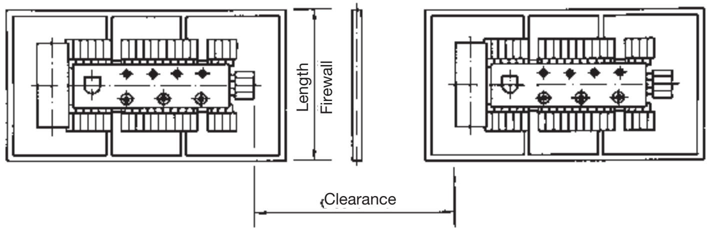


Fig. 4-45

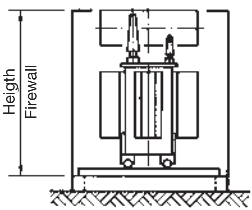
Partition construction of an accessible cable duct:

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

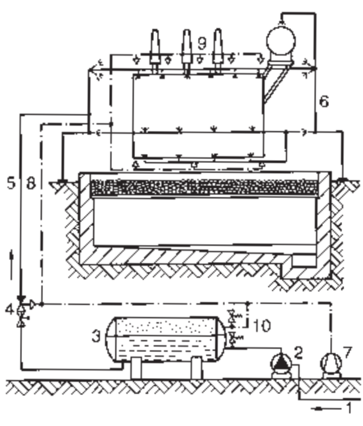


Fig. 4-47

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.