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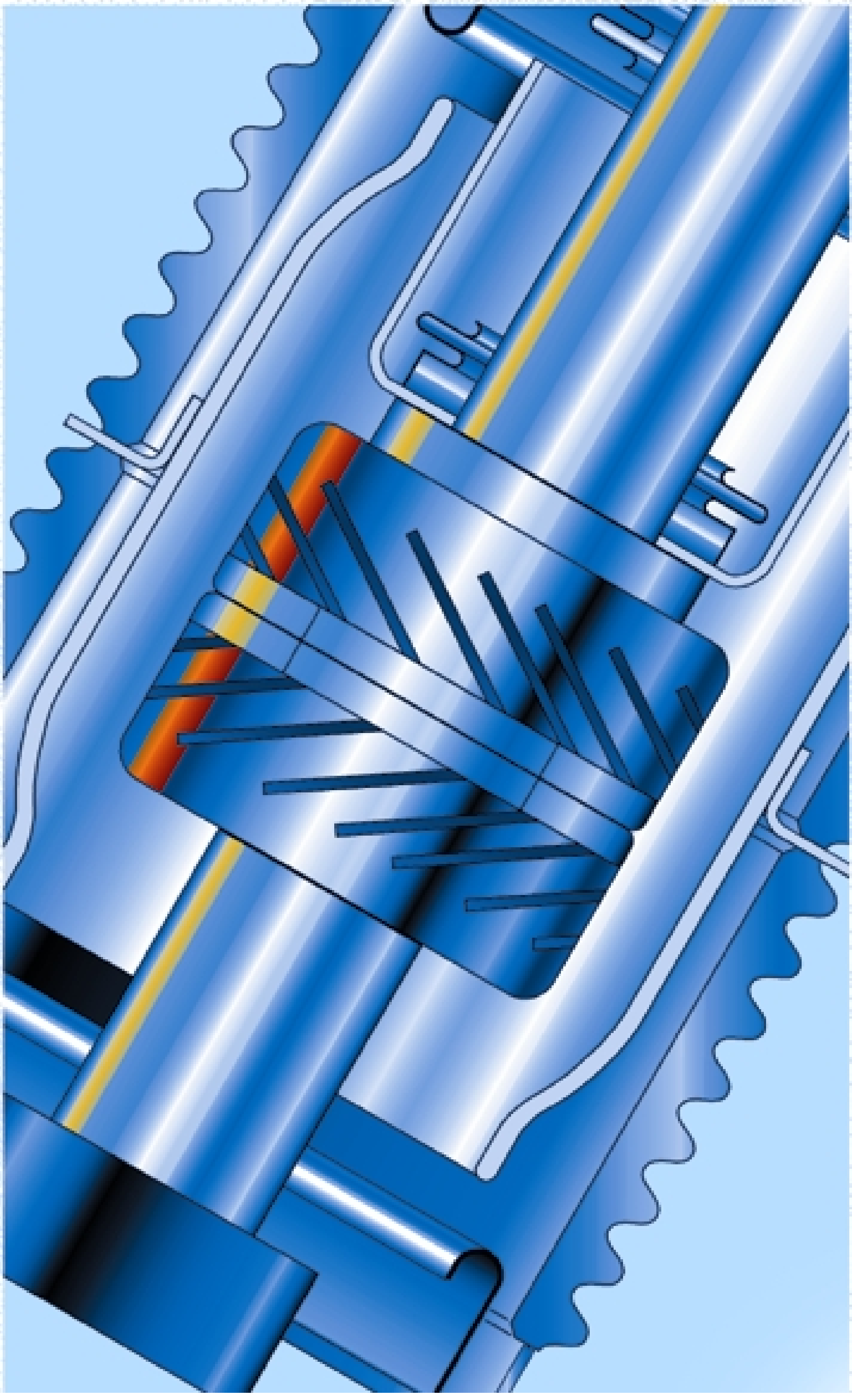
Medium Voltage

Switching Devices and Switchgear



July 2005

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Switching Devices and Switchgear

Fundamental Characteristics of Switching Devices

Types and Application of Switching Devices

Planning of Switchgear Installations

Designs and Application of Switchgear

Accessories for Switchgear

Materials

Standards

Further Reading

Dipl. Ing. Ansgar Müller
Siemens AG
P.O. Box 3220
91050 Erlangen, Germany
E-Mail: ansgar.mueller@siemens.com

Edition 19E0 • 2005-07

CONTENT

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A MEDIUM VOLTAGE

Medium voltage is defined as the range above 1 kV up to and including 52 kV (AC). It is really a sub-range of high voltage, for according to international rules there are initially only two voltage groups:

- Low voltage: up to and including 1000 $V_{\sim}$ (or 1500 $V_{=}$)
- High voltage: above 1 $kV_{\sim}$ (or 1500 $V_{=}$)

It is with low voltage that most electrical devices in the household and industrial spheres work. High voltage is used for very long-distance transmission of electrical energy, as well as for distributing it (on a more finely branched regional basis) to the load centers. These processes of transmission and regional distribution involve differently high voltages, because the duties and demands imposed on switching devices and substations themselves differ substantially. That is why for those voltages with which electrical energy is distributed regionally the term <u>medium voltage</u> came into being.

- Medium voltage: above 1 $kV_{\sim}$ up to and including 52 $kV_{\sim}$
  Most network operating voltages are in the range 3 to 40,5 kV

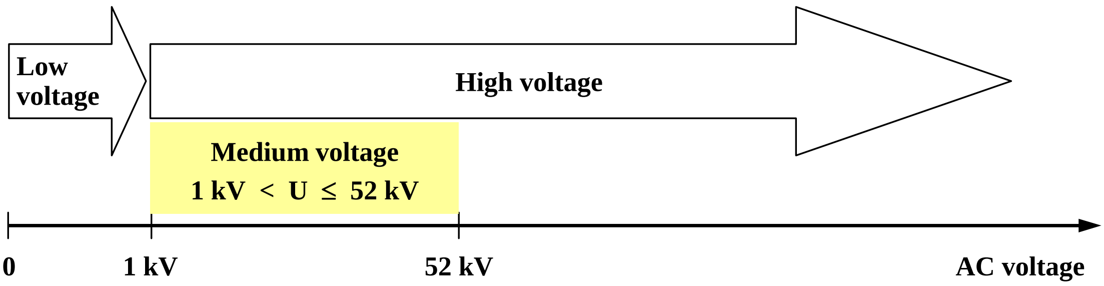

Figure A-1: Voltage designation according to international rules

Why do the operating voltages have to vary so much? Generating plants are located depending on the presence of primary energy sources, on the availability of cooling systems and on other ambient conditions, and are usually therefore at some distance from the centers of consumption. The power transmission and distribution networks do not just link generating plants with consumers; they also form a supra-regional backbone with reserve capacity to ensure a dependable supply and for balancing out load fluctuations. So as to minimize transmission losses, high operating voltages (and lower currents) are preferred. Only when the energy reaches the load centers near the consumers is the high voltage transformed down to the values customary in the low-voltage network.

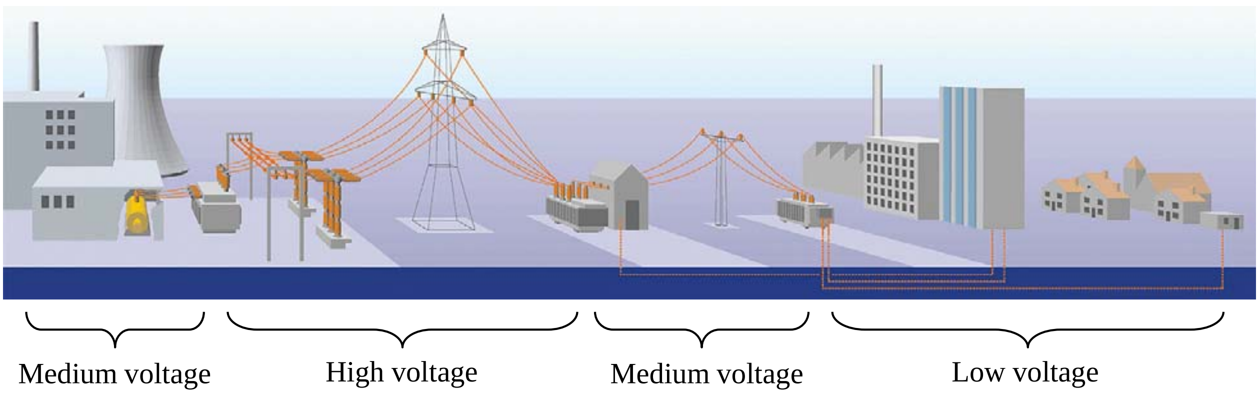

Figure A-2: Voltage levels from the generating plant to the consumer

In public electricity supplies, most medium-voltage networks are operated at between 10 kV and 30 kV. These figures can vary tremendously from country to country, influenced by how technology has developed historically and by local conditions. The spatial supply radius of a medium-voltage network is in an urban area (operating at 10 kV) about 5 to 10 km, and in a rural area (operating voltage 20 kV) in the order of 10 to 20 km. These figures serve just as a guide; in practice the region supplied can depend significantly on local factors, e.g. consumer structure (load) and the geographical situation.

In industrial plants with medium-voltage networks there are – apart from the infeed from the public power supply– other voltages that depend on the loads; usually the operating voltages of the installed motors are the decisive factor. Operating voltages between 3 kV and 15 kV are frequently found in industrial networks.

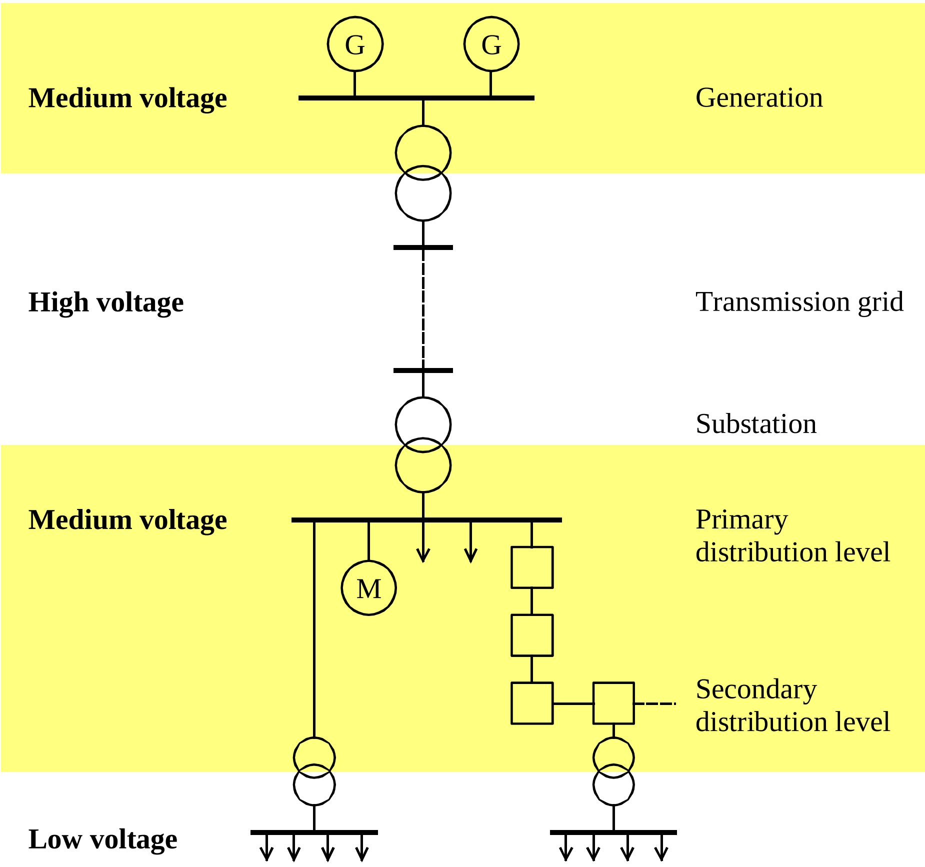

Figure A-3: Medium voltage in an electricity supply network

Figure A-3 shows schematically where medium-voltage equipment is found in the network structure:

- In the generating station (generators and auxiliaries),
- In transformer substations (public power supply networks or in large industrial plants) on the primary distribution level, where the energy is fed in from the HV network, transformed down to the MV level, and taken from there to
- In secondary unit substations, transformer substations or main substations for larger-scale loads – the so-called secondary distribution level where the energy is stepped down from medium to low voltage and distributed to the ultimate consumer.

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B FUNDAMENTAL CHARACTERISTICS OF SWITCHING DEVICES

B 1 What is switchgear?

Switchgear is a generic term meaning all that equipment which is used for distributing, interrupting and disconnecting voltage and current in electrical circuits. Specifically, switching devices for connecting and interrupting electrical circuits are subject to three basic duties:

- current-free switching (when negligible current is flowing)
- interruption of operating currents
- interruption of short-circuit and other fault currents

B 2 What are the individual devices and what can they do?

- **Circuit-breakers**
  Can switch on and off (make or break) all values of current within their rated capability, from small inductive or capacitive currents, up to full short circuit currents, under all possible fault conditions in the network; earth fault, phase opposition etc.
- **Switches**
  Can switch on and off operating currents up to their rated interrupting capability and may be able close onto existing short circuits up to a rated fault making current.
- **Disconnectors** (Isolators**)**
  Have the purpose of opening or closing an electrical circuit and providing a specifically safe isolating distance so that equipment downstream can be worked on in safety. They are designed to open and close only under voltage or current-free conditions.
- **Switch-disconnectors**
  Combine the functions of switches and disconnectors or, put another way, they are switches with the specific safety gap required of disconnectors.
- **Contactors**
  These are load switching devices with limited short circuit making and breaking capacity. They are electrically operated and are used for high switching rates, eg. for motor control.
- **Earthing switches**
  Are used for earthing circuits, or parts of circuits, which have already been disconnected.
- **Make-proof earthing switches**
  Are used for the safe earthing of circuits, or parts of circuits, even if these may be live, that is, also for the case where the circuit to be earthed has accidentally not been disconnected.
- **Fuses**
  Consist of a fuse base and a fuse link for short circuit current interruption. The fuse base will provide a safe disconnection gap when the fuse link is removed under volt-free conditions (as with a disconnector). The fuse link will interrupt a short circuit current once only, then it must be replaced.
- **Surge arresters**
  Conduct excessive electrical charges, caused by lightning strikes (external overvoltages) or switching operations and earth faults (internal overvoltages), to earth, thus protecting the connected equipment against voltages which it is not designed to withstand.

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B 3 Selection of switching devices

Switching devices are selected according to their rated values as well as according to their switching duties. The following tables list the selection criteria. Table B-1 shows selection according to rated data, Table B-2 to Table B-4 show selection according to switching duties in normal service and Table B-5 to Table B-7 the same for abnormal service (fault conditions).

B 3.1 Selection according to rated data

The network characteristics, that is, the features of the primary circuits, determine the necessary values. The most important are:

a) **Rated voltage**
is the upper limit of the highest system voltage, for which the device has been dimensioned. Since all high voltage switching devices interrupt the circuit at current zero (see chapter C 1.1) - with the exception of certain types of fuses - the network voltage is the most important dimensional criterion. It determines the dielectric stress on the device, caused by recovery and restriking voltage, especially when opening.

b) **Rated insulation level**
is the insulating capability of the phases against earth, between the phases and across the open gap or disconnecting distance. The insulation level is the measure of the capability of a device to withstand all voltages to which it is subjected, from normal network fluctuations to those which may occur during network operation. These latter may be operational or high frequency overvoltages, caused by switching, earth faults (internal overvoltages), or lightning (external overvoltages). The insulation level is proven by the application of a standard impulse voltage 1.2/50 µs and an alternating current voltage (50 Hz for 1 minute).

c) **Rated (normal) current**
is the current which the main circuit of the device can carry continuously, under defined conditions. The temperature of components - particularly contacts - shall not exceed specified values. Permissible temperature rises always relate to the surrounding temperature. If a device is fitted into an enclosure, its current carrying capacity may be reduced - dependent upon the quality of heat transfer.

d) **Rated peak withstand current**
is the highest value of the first major loop of current during the transient period following the beginning of current flow, which the device can carry when in the closed position. This is a measure of the electro-dynamic (mechanical) stress on a device. For equipment which has a full closing capability (see rated short circuit making current), this value is of no importance.

e) **Rated peak making current**
is the peak prospective current which the device is proven to close onto with safety, anticipating the condition of short circuit close to the terminals at the instant of closing. Stress is greater than for peak withstand current because mechanical forces may act against the closing movement of the contacts.

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f) **Rated (normal) breaking current**
is the current which can be safely and repeatedly interrupted during normal operation. For equipment which has a full closing capability (see rated short circuit breaking current), this value is of no importance).

g) **Rated short-circuit breaking current**
is the maximum short circuit current which can be safely interrupted, even if the short circuit is at the terminals of the device.

The characteristics of the secondary equipment are not taken into account here.

Device	Withstand capability: rated …				Switching capability: rated …		
	Insulation level	Voltage	Normal current	Peak withstand current	Breaking current	Short-circuit breaking current	Short-circuit making current
Circuit-breaker	X	X	X			X	X
Switch	X	X	X		X		X
Disconnector	X		X	X			
Earthing switch	X			X			
Make-proof earth. switch	X	X					X
Contactor	X	X	X	X		X 1)	X 1)
Fuse link		X	X			X	
Fuse base	X		X				
Surge arrester *)	X 2)	X 3)		X 4)		X 5)	
Current limiting reactor	X		X	X			
Bushing	X		X	X 6)			
Post insulator	X			X 6)			

X Selection criterion

1) Limited short-circuit switching capability

2) Selection criterion only in special cases, e.g. extraordinary stress due to pollution layer

3) For spark gap arresters = recovery voltage

4) Rated discharge current of surge arresters

*) See also chapter B 3.4

5) For surge arresters: fault withstand capability in case of overload

6) For post insulators and bushings: specified failing load

Table B-1: Selection according to switching duties

B 3.2 Selection according to switching duty

Table B-2 and Table B-4 list the switching duties which may apply in actual system service, and indicate the economically most suitable switching devices ("rational application"). Every switching operation has characteristics which stress the switching device in different ways. These characteristics are described in detail in chapters B 4 to B 6. A distinction is made between normal, undisturbed service (load currents) and abnormal, disturbed service (fault currents).

B 3.2 a Normal service (Undisturbed service)

No.	Switching duty	Switching device (rational application)				
		Circuit-breaker	Switch / switch-disconnector			Contactor
			Vacuum	SF_6	Air, hard-gas	
1	Unloaded transformer (neutral earthing transformer)	X	X	X	X	X
2	Loaded transformer	X	X	X	X	X
3	Overloaded transformer	X	X	X	X	X
4	Transformer inrush	X	X			X
5	Furnace transformer	X				X
6	Earthing coils	X	X	X		
7	Shunt reactor	X				
8	Motor, normal operation	X	X	X		X
9	Motor, during starting	X	X	X		X

Table B-2: Inductive circuits

No.	Switching duty	Switching device (rational application)				
		Circuit-breaker	Switch / switch-disconnector			Contactor
			Vacuum	SF_6	Air, hard-gas	
10	Capacitor	X	X	X	X	X
11	Back-to-back switching of cappacitors	X	X			X
12	Unloaded cable	X	X	X	X	
13	Unloaded overhead line	X	X	X	X	
14	Filter	X				
15	Ripple control system	X	X	X		

Table B-3: Capacitive circuits

No.	Switching duty	Switching device (rational application)						
		Circuit-breaker	Switch *(vacuum)*	Lasttrenn schalter *(air, SF_6 hard-gas)*	Discon-nector	Earthing switch	Make-proof earthing switch	Surge arrester
16	Ring main sectionalizing	X		X				
17	Busbar transfer			X	X			
18	Earthing and short-circuiting	X	X	X		X	X	
19	Synchronising	X						
20	Isolating			X	X			
21	Diverting overvoltages							X

Table B-4: Other switching duties in normal service

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B 3.2 b Disturbed service

No.	Switching duty	Switching device (rational application)					
		Circuit-breaker	Switch / switch-disconnector			Contac-tor	HRC fuse
			Vavuum	SF_6	Air, hard-gas		
22	Fault making	X	X	X	X	X [1]	
23	Short-circuit across terminals	X					X
24	Auto reclosing	X					
25	Short-circuit downstream generator	X					
26	Short-circuit downstream reactor	X					
27	Short-circuit downstream transformer	X					X
28	Locked motor rotor	X	X	X		X	X
29	Double earth fault	X					X
30	Out-of-phase condition	X					

Table B-5: Switching in case of short-circuit

No.	Switching duty	Switching device (rational application)		
		Circuit-breaker	Switch-disconnector	
			SF_6	Air, hard-gas
31	Unloaded cables, overhead lines, fault on the supply side	X	X	X [2]
32	Loaded cables, overhead lines, fault on the supply side	X	X	
33	Unloaded cables, overhead lines, fault on the load side	X	X	X
34	Loaded cables, overhead lines, fault on the load side	X	X	X [2]

Table B-6: Switching under earth fault conditions [3]

No.	Switching duty	Switching device (rational application)					
		Circuit-breaker	Switch / switch-disconnector			Make-proof earthing switch	HRC fuse
			Vavuum	SF_6	Air, hard-gas		
35	Protective disconnection (isolating under load)			X	X		
36	Rapid load transfer	X					
37	Transformer with shorted winding	X					X
38	Switching under short-circuit condition	X	X	X	X	X	

Table B-7: Other fault conditions

[1] Limited short-circuit making capacity
[2] Limited short-circuit breaking capacity; take data of manufacturer into account!
[3] Earth fault in networks with isolated or resistive earthed neutral, and in networks with earth fault neutralization

B 3.3 Selection according to switching frequency

If a number of devices meet the electrical requirements and no other criteria take precedence, the required switching frequency can constitute a further selection criterion. The following tables show the service lifetime of switching devices and give recommendations for use. The respective standards make a distinction between classes of electrical and mechanical service lifetime. A “mixture” of classes is possible; for example a switching device can belong mechanically to Class M1 and in electrical terms to Class E3.

B 3.3 a Switches to IEC 60265-1

The standard defines classes only for the so-called multi-purpose switches, although, besides these, there are also "special purpose switches" and "limited purpose switches"[4].

As the name suggests, multi-purpose switches must be capable of switching different kinds of operating currents, for example load currents, ring currents, currents of unloaded transformers, charging currents of unloaded cables and overhead lines, and also of making short-circuit currents. Multi-purpose switches intended for use in networks with an isolated star point or with earth fault compensation must also be capable of switching under earth fault conditions. Their diversity is reflected in the fairly exact designations for the E classes.

<table>
<tr><th colspan="2">Class</th><th>Switching cycles</th><th colspan="2">Description</th></tr>
<tr><td rowspan="2">M</td><td>M1</td><td>1000</td><td colspan="2">Mechanical endurance</td></tr>
<tr><td>M2</td><td>5000</td><td colspan="2">Increased mechanical endurance</td></tr>
<tr><td rowspan="3">E</td><td>E1</td><td>10 x I_1
10 x I_{2a}
2 x I_{ma}</td><td rowspan="3">20 x 0.05 · I_1
10 x I_{4a}
10 x 0.2 to 0.4 · I_{4a}
10 x I_{4b}
10 x I_{6a}
10 x I_{6b}</td><td rowspan="3">I_1 active load-breaking current
I_{2a} closed-loop breaking current
I_{4a} cable-charging breaking current
I_{4b} line-charging breaking current
I_{6a} earth fault breaking current
I_{6b} cable- and line-charging breaking current under earth fault conditions
I_{ma} Short-circuit making current</td></tr>
<tr><td>E2</td><td>30 x I_1
20 x I_{2a}
3 x I_{ma}</td></tr>
<tr><td>E3</td><td>100 x I_1
20 x I_{2a}
5 x I_{ma}</td></tr>
</table>

Table B-8: Classes for multi-purpose switches

SF_6 switches are advisable if the switching frequency averages ≤ 1 / month. Regarding the electrical endurance those switches mostly are rated for class E3.

Air or hard-gas switches are advisable if the switching frequency averages ≤ 1 / year. The design of these devices is simpler and in the majority they belong to class E1, however, also class E2 switches are available.

Vacuum switches constitute a special case. Their performance distinctly exceeds the M2 / E3 classes. They are used for special purposes only, for example in industrial systems or if switching rates ≥ 1 / week are required.

[4] Limited purpose switches need only master a selection of a multi-purpose switch's duties. Special purpose switches are intended for switching tasks such as those of single capacitor banks, parallel switching of capacitor banks, ring circuits formed by parallel-connected transformers or motors (in the normal or braked state).

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B 3.3 b Circuit-breakers

While the numbers of mechanical switching cycles of the M classes are expressly mentioned, the circuit-breaker standard does not define the electrical endurance of the E classes with specific numbers of switching cycles, but unfortunately only vaguely with a verbal description.

The type test switching sequences of the short-circuit type tests provide some orientation as to what is to be understood by "normal electrical endurance" and "extended electrical endurance". The numbers of making and breaking operations are specified in the gray-highlighted boxes in the table.

It must also be said that modern vacuum circuit-breakers are generally capable of making and breaking the rated normal current with the number of mechanical switching cycles.

<table>
<tr><th colspan="2">Class</th><th colspan="3">Description</th></tr>
<tr><td rowspan="2">M</td><td>M1</td><td>2,000 switching cycles</td><td colspan="2">Normal mechanical endurance</td></tr>
<tr><td>M2</td><td>10,000 switching cycles</td><td colspan="2">Extended mechanical endurance, low maintenance</td></tr>
<tr><td rowspan="3">E</td><td>E1</td><td>2 x C and 3 x O with 10%, 30%, 60% and 100% I_{sc}</td><td colspan="2">Normal electrical endurance (circuit-breaker not covered by E2)</td></tr>
<tr><td rowspan="2">E2</td><td>2 x C and 3 x O with 10%, 30%, 60% and 100% I_{sc}</td><td><u>Without</u>
auto-reclosing duty</td><td rowspan="2">Extended electrical endurance without maintenance of the arcing chamber</td></tr>
<tr><td>26 x C 130 x O 10% I_{sc}
26 x C 130 x O 30% I_{sc}
4 x C 8 x O 60% I_{sc}
4 x C 6 x O 100% I_{sc}</td><td><u>With</u>
auto-reclosing duty</td></tr>
</table>

C = closing, O = opening; I_{sc} = rated short-circuit breaking current

Table B-9: Circuit-breaker classes

B 3.3 c Disconnectors

Disconnectors do not have any switching capacity[5], and so classes have only been defined for the number of mechanical switching cycles.

Class		Switching cycles	Description
M	M0	1,000	For general requirements
	M1	2,000	Extended mechanical endurance
	M2	10,000	

Table B-10: Disconnector classes

5 Disconnectors up to 52 kV are only allowed to switch negligible currents up to 500 mA (e.g. voltage transformers) or higher currents only if the voltage difference is insignificant (e.g. when changing busbars with the bus coupling activated).

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B 3.3 d Earthing switches

In the case of earthing switches, the classes designate their short-circuit making capacity (earthing to an applied voltage). E0 corresponds to a normal earthing switch and switches belonging to classes E1 and E2 are also referred to as "make-proof earthing switches".

<table>
<tr><th colspan="2">Class</th><th>Switching cycles</th><th colspan="2">Description</th></tr>
<tr><td rowspan="3">E</td><td>E0</td><td>0 x I_{ma}</td><td>No short-circuit making capacity</td><td rowspan="2">For general requirements</td></tr>
<tr><td>E1</td><td>2 x I_{ma}</td><td rowspan="2">Short-circuit making capacity</td></tr>
<tr><td>E2</td><td>5 x I_{ma}</td><td>Reduced need for maintenance</td></tr>
</table>

Table B-11: Classes for earthing switches

The standard does not define how often an earthing switch can be actuated mechanically. There are no M classes for these switches.

B 3.3 e Contactors

The standard for contactors has not yet defined endurance classes. Customary designs feature mechanical and electrical endurance in the order of 250,000 and 1,000,000 operation cycles. The can be encountered where extremely high switching rates occur; e.g. > 1 / hour.

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B 3.4 Selection of surge arresters

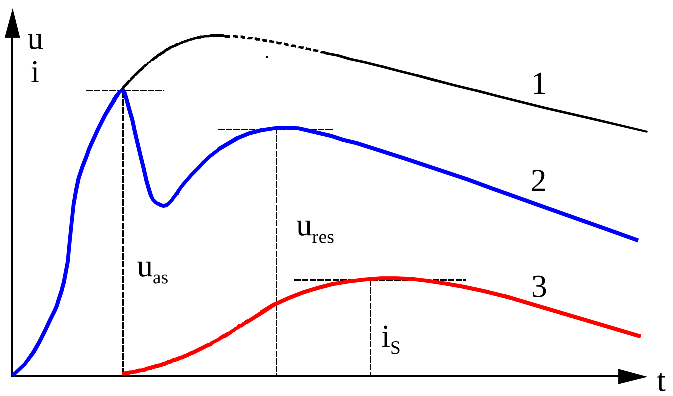
For surge arresters, partially different selection criteria apply than for switchgear in the normal sense of the word. The most important characteristics are described hereafter. Additional explanations are given in Figure B-1.

a) **Rated voltage** (arresters with spark gap)
is the highest system voltage, at which the surge arrester can still recover after it has operated. In the case of metal-oxide arresters (MO-arresters), this corresponds to the rated voltage and the continuous operating voltage.

b) **Rated voltage** (Metal-Oxide-Arresters)
is the highest permissible voltage at which the arrester, under the condition of a temporary rise in voltage (maximum 10 s), will still function correctly; i.e. there is no residual current which causes an impermissible rise in high temperature.

c) **Continuous operating voltage** (Metal-Oxide-Arresters)
is the highest permissible network voltage which may be continuously applied to the arrester.

d) **Sparkover voltage**
is the voltage which causes the arrester to operate, that is, to cause flashover of its spark gap(s). The wave shape determines the response time and the limiting level. The sparkover voltage (sometimes also called the limiting voltage) is more accurately defined by the:



1 = Prospective impulse voltage (without operation of the arrester)
2 = Impulse voltage at the surge arrester
3 = Discharge current
u_{as} = Lightning impulse sparkover voltage
u_{res} = residual voltage
i_S = Discharge current

Figure B-1: Characteristics of surge arresters

Switching impulse sparkover voltage which is the peak value of the lowest switching impulse voltage that causes the arrester to operate.

Front of wave sparkover voltage, i.e. the value at which the arresters discharges at the front-of-wave of a very steep impulse voltage (representative for close lightning).

100% lightning impulse voltage which is the peak value of the lowest impulse voltage that always causes the arrester to operate (representative for remote lightning).

Power frequency sparkover voltage which is the r.m.s. value of a power-frequency voltage (50 Hz or 60 Hz) that causes the arrester to operate (this characteristic is of no importance for the insulation coordination, power-frequency voltages of this value must not appear at the arrester).

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e) **Residual voltage**
is the voltage across the arrester terminals when the discharge current flows. Sparkover and residual voltage define the level of protection given by the arrester and are thus the critical magnitudes for coordination of the system's insulation levels.

f) **Rated discharge current**
is the peak value of the impulse current which will not cause the permissible residual voltage to be exceeded.

g) **Energy absorption capacity**
is the permissible energy which may be converted in the resistances of the arrester during discharge.

h) **Fault withstand capability**
is the capacity of an arrester to carry short circuit currents of specified magnitude and duration after sparkover, without endangering the surroundings by bursting.

Additionally, other aspects can be important for selection, such as the insulating capacity of the housing (with heavy pollution at the site of installation, surface contamination stress), altitude above sea level and special installation conditions (enclosure in insulating gas, SF_6).

Just as other devices, arresters are also selected according to the application. Depending on the method of connection, the characteristics mentioned above may have different priorities.

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B 4 Switching duties and their characteristics

When selecting switching devices, not only the rated data, but also the switching duties arising during normal service must be considered, in order to use the best switching device for each application. The following tables list the most important switching duties again and indicate the characteristic criteria.

Explanations:

① This column indicates whether the stress condition concerned occurs during closing or opening.

② Column 2 indicates normally expected values for the power factor.

③ Column 3 lists the currents to be switched in the worst case, with the following definitions:

I_r = Rated current of the load

I_F = Follow current (only for surge arresters)

I_{sc} = Rated short-circuit breaking current

I_p = Peak short-circuit current of the system

④ Column 4 lists the possible transient recovery voltages. The value in parenthesis, e.g. $(1.5 \cdot U / \sqrt{3})$, indicates the power-frequency recovery voltage in the first-quenching pole (first pole to clear); U is the maximum phase-to-phase voltage (operating voltage).

The factors used are:

1.4 = Amplitude factor γ

$\sqrt{2}$ = Conversion from r.m.s. value to peak value

1.5 = Factor for the voltage displacement in the first pole-to-clear (pole factor)

$\sqrt{3}$ = Conversion delta voltage to star (phase-to-earth) voltage

⑤ Column 5 indicates the maximum rate of rise of the transient recovery voltage after the instant of current interruption.

⑥ Column 6 shows the main problems that could present special difficulty for the switching device. If nothing is indicated, this switching duty does not present a problem for the switching devices selected.

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B 4.1 Normal service (undisturbed service)

No	Switching duty	Load condition encountered					
		Off = O On = C	cos φ	Cur- rent{1}	Transient recovery voltage (TRV)	Rate of rise of TRV	Nature of duty
		①	②	③	④	⑤	⑥
1	Unloaded transformer	O	0.15 to 0.30	$\leq 0.03 \cdot I_r$	$1{,}4 \cdot \sqrt{2} \cdot \left(1{,}5 \cdot \frac{U}{\sqrt{3}}\right)$	≤ 0.1 kV/μs	Overvoltages due to chopping of small currents are possible
2	Loaded transformer {2}	O	0.7 to 1.0	$\leq I_r$		≤ 0.2 kV/μs	---
3	Overloaded transformer {2}	O	0.7 to 1.0	$\leq 1.2 \cdot I_r$		≤ 0.2 kV/μs	---
4	Transformer inrush	O	0.15	$\leq 15 \cdot I_r$	$1{,}4 \cdot \sqrt{2} \cdot \left(1{,}5 \cdot \frac{U}{\sqrt{3}}\right)$	≤ 0.2 kV/μs	Switching off $15 \cdot I_r$ at cos φ = 0.15; overvoltage possible
5	Furnace transformer	C; O	0.2 to 0.9	$\leq 2 \cdot I_r$		≤ 0.2 kV/μs	High switching frequency, overvoltage possible, individual surge protection
6	Earthing coils	O {3}	0.15	≤ 10 A	etwa $0.1 \cdot U$ {4}	≤ 0.2 kV/μs	---
		O {5}		≤ 60 A (300 A)	$1{,}4 \cdot \sqrt{2} \cdot \frac{U}{\sqrt{3}}$	≤ 4 kV/μs	Overvoltages possible when switching off during earth fault
7	Shunt reactor	O	0.15	≤ 2000 A	$1{,}4 \cdot \sqrt{2} \cdot \left(1{,}5 \cdot \frac{U}{\sqrt{3}}\right)$	≤ 6 kV/μs	High rate of rise of TRV
8	Motor, normal operation	O	0.8 to 0.9	$\leq I_r$	$1{,}4 \cdot \sqrt{2} \cdot \left(1{,}5 \cdot \frac{U}{\sqrt{3}}\right)$	≤ 0.2 kV/μs	---
9	Motor, during starting	O	0.2 to 0.3	$\leq 7 \cdot I_r$	$1{,}4 \cdot \sqrt{2} \cdot \left(2 \cdot \frac{U}{\sqrt{3}}\right)$ {6}	≤ 0.2 kV/μs	Interruption of $7 \cdot I_r$ at cos φ = 0.2; high recovery voltage due to residual motor voltage

{1} I_r is the rated normal current of each load.

{2} This means distribution transformers
(not included are unit transformers with with spezial loads, such as motors, furnaces etc.)

{3} Usually earthing coils are not switched off during an earth fault in the network.

{4} The voltage indicated with $0.1 \cdot U$ ist he maximum voltage which occurs during normal service. In case of an earth fault the full rated voltage can appear across the break distance when the device is open.

{5} During an earth fault in the network the current can amount up to 60 A in normal cases, however, exceptionally it may reach 300 A as well.

{6} The factor 2 considers the residual motor voltage, which can increase the transient recovery voltage by this factor in case of phase opposition (180°).

Table B-12: Characteristics of inductive circuits

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No	Switching duty	Load condition encountered					
		Off = O On = C ①	cos φ ②	Cur- rent{1} ③	Transient recovery voltage (TRV) ④	Rate of rise of TRV ⑤	Nature of duty ⑥
10	Capacitor	O	lead- ing	up to $1.4 \cdot I_r$ {2}	$\sqrt{2}\cdot\left([1+1,5]\cdot\frac{U}{\sqrt{3}}\right)$	Power frequency	High recovery voltage
11	Back-to-back switching of cappacitors	C	lead- ing	up to $100 \cdot I_r$ {2}	---	---	High value and rate of rise of inrush current (f up to 50 kHz)
12	Unloaded cable	O	lead- ing	up to 100 A	$\sqrt{2}\cdot\left([1+1,5]\cdot\frac{U}{\sqrt{3}}\right)$	Power frequency	High recovery voltage
13	Unloaded overhead line	O	lead- ing	up to 10 A			
14	Filter	O	lead- ing	up to 2000 A			
15	Ripple control system	O	lead- ing	up to 20 A			High recovery voltage; audio-frequency current (160 Hz up to 1.6 kHz) is superimposed to the p.f. current (50 Hz / 60 Hz)

{1} The first value 1·U/√3 which results from the calculation of the brackets, indicates the voltage at which the capacitance of the device remains charged under worst case conditions. The value 1.5·U/√3 is the power-frequency recovery voltage, including the first pole-to-clear factor 1.5.

{2} I_r is the rated normal current (50- or 60-Hz power-frequency current) of the capacitor.

Table B-13: Characteristics of capacitive circuits

No	Switching duty	Load condition encountered					
		Off = O On = C ①	cos φ ②	Current{1} ③	Transient recovery voltage (TRV) ④	Rate of rise of TRV ⑤	Nature of duty ⑥
16	Ring main sectionalizing	O	0.3 i.	up to I_r	ca. 0.3 · U	≤ 1.0 kV/μs	---
17	Busbar transfer	C; O	0.7- 1.0 i.	up to I_r	up to 20 V	Power frequency	---
18	Earthing and short-circuiting	C	---	---	---	---	---
19	Synchronising	C	---	---	---	---	---
20	Isolating	O	---	---	---	---	---
21	Diverting overvoltages	O	---	I_F	U {2}	Power frequency	Interruption of follow current at U

{1} I_r is the rated normal current of each load.

{2} Since the follow current through an arrester is resistive, the operating voltage appears without high-frequency transient components.

Table B-14: Characteristics of other duties in normal service

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B 4.2 Disturbed service

No	Switching duty	Load condition encountered					
		Off = O On = C ①	cos φ ②	Cur- rent{1} ③	Transient recovery voltage (TRV) ④	Rate of rise of TRV ⑤	Nature of duty ⑥
22	Fault making	C	0.15 lag.	I_p	----	---	Peak short-circuit current during closing
23	Short-circuit across terminals	O	0.15 lag.	I_K	$1{,}4 \cdot \sqrt{2} \cdot \left(1{,}5 \cdot \frac{U}{\sqrt{3}}\right)$	≤ 1.0 kV/µs	Full breaking current
24	Auto reclosing {2}	O-t_u-C-O	0.15 lag.	I_K		≤ 1.0 kV/µs	2 x Off, 1 x On within 300 ms
25	Short-circuit downstream generator	O	0.15 lag.	I_K		≤ 6.0 kV/µs	Interruption at high initial rate of rise of TRV
26	Short-circuit downstream reactor	O	0.15 lag.	I_K		≤ 10.0 kV/µs	Interruption at high initial rate of rise of TRV
27	Short-circuit downstream transformer	O	0.15 lag.	I_K		≤ 4.0 kV/µs	Interruption at high initial rate of rise of TRV
28	Locked motor rotor	O	0.2 lag.	$\leq 7 \cdot I_r$ {3}	$1{,}4 \cdot \sqrt{2} \cdot \left(1{,}5 \cdot \frac{U}{\sqrt{3}}\right)$	≤ 1.0 kV/µs	Interruption $7 \cdot I_r$ at $\cos \phi = 0.2$
29	Double earth fault	O	0.15 lag.	$0.87 \cdot I_K$	$1.2 \cdot \sqrt{2} \cdot U$ {4}	≤ 1.0 kV/µs	High recovery voltage
30	Out-of-phase condition	O	0.15 lag.	$0.25 \cdot I_K$	$2 \cdot 1{,}4 \cdot \sqrt{2} \cdot \left(1{,}5 \cdot \frac{U}{\sqrt{3}}\right)$ {5}	≤ 2.0 kV/µs	Very high TRV and high initial rate of rise

{1} I_K is the short-circuit current of the system, I_p is the corresponding peak current.

{2} Dead time t_u = 300 ms

{3} I_r is the rated normal current of the motor.

{4} The amplitude factor is only $\gamma = 1.2$ in the case of double earth fault.

{5} The factor 2 takes into consideration the least favourable switching conditions under which the two system part are out of phase by 180°.

Table B-15: Switching in case of short-circuit

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No	Switching duty	Off = O On = C ①	cos φ ②	Current{1} ③	Transient recovery voltage (TRV) ④	Rate of rise of TRV ⑤	Nature of duty ⑥
31	Unloaded cables, overhead lines, fault on the supply side	O	leading	up to 5 A	$\sqrt{2}\cdot[U+(U)]$ {1}	Power frequency	High recovery voltage
32	Loaded cables, overhead lines, fault on the supply side	O	leading, lag. >0.7	up to 5 A + up to 300 A			
33	Unloaded cables, overhead lines, fault on the load side	O	leading	up to 400 A	$\sqrt{2}\cdot\left(1{,}5\cdot\frac{U}{\sqrt{3}}\right)$	Power frequency	High capacitive current (charging current of network) + load current
34	Loaded cables, overhead lines, fault on the load side	O	leading, lag. >0.7	up to 400A + up to 300 A			

{1} The first value U in square brackets indicates the voltage at which the capacitance of the device remains charged under worst case conditions. The value in parenthesis represents the power frequency recovery voltage.

Table B-16: Switching under earth fault conditions

No	Switching duty	Off = O On = C ①	cos φ ②	Current{1} ③	Transient recovery voltage (TRV) ④	Rate of rise of TRV ⑤	Nature of duty ⑥
35	Protective disconnection (isolating under load)	O	0.7-1.0 lag.	up to I_r	$1{,}4\cdot\sqrt{2}\cdot\left(1{,}5\cdot\frac{U}{\sqrt{3}}\right)$	≤ 0.2 kV/µs	---
36	Rapid load transfer	O	0.15-1.0 lag.	up to I_K	$1{,}4\cdot\sqrt{2}\cdot\left(1{,}5\cdot\frac{U}{\sqrt{3}}\right)$	≤ 0.2 kV/µs	Load transfer in less than 150 ms
		C	0.7-1.0 lag.	up to I_r	---	---	
37	Transformer with shorted winding	O	0.15-0.3 lag.	I_r up to I_{sc}	$1{,}4\cdot\sqrt{2}\cdot\left(1{,}5\cdot\frac{U}{\sqrt{3}}\right)$	≤ 2.0 kV/µs	Interruption at high rate of rise of TRV. Currents between I_r and I_{min} for fuses
38	Switching under short-circuit condition	C	0.15 lag.	I_p	---	---	Peak short-circuit current during closing

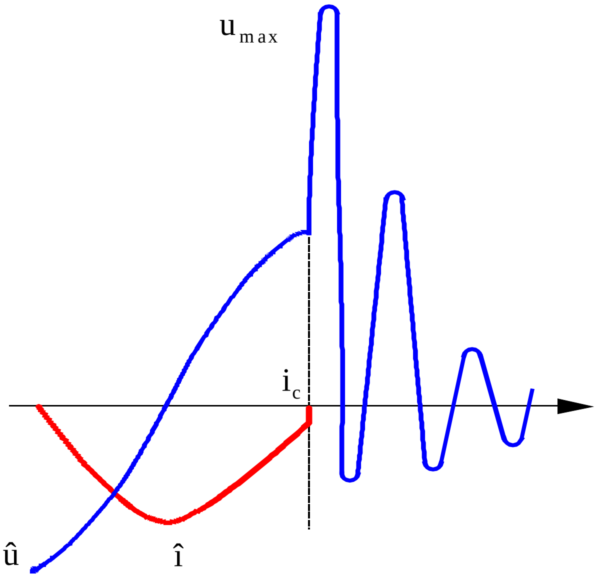
Table B-17: Other fault conditions

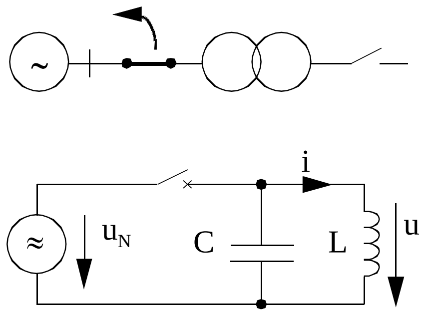
B 5 Normal system service (Undisturbed service)

B 5.1 Switching operations in inductive circuits

The main problem when switching inductive circuits is the possibility that switching overvoltages can occur. These are overvoltages generated by the switching device during switching on and especially during switching off. There are three possible causes to be considered:

B 5.1 a Current chopping





$$\frac{1}{2} \cdot L \cdot I^2 = \frac{1}{2} \cdot C \cdot U^2 \qquad \{1\}$$

$$U_{\max} \cong \sqrt{\frac{L}{C}} \cdot I_a \qquad \{2\}$$

Figure B-2: Current chopping during inductive switching

If the current is suddenly interrupted before the natural current zero (i_c in Figure B-2) when switching very small inductive currents (up to approx. 20 A), magnetic energy remains in the iron of the circuit on the disconnected side, proportional to the chopped current. This magnetic energy is discharged through the capacitance on the disconnected side (mainly the cable capacity) {1}. Transposing formula {1} gives formula {2}. The maximum overvoltage is $U_{max} \approx \sqrt{(L / C)} \cdot i_c$. As L and C are defined by the system, the only item that can be influenced is the magnitude of the chopped current i_c. So, one objective is to develop switching devices with small chopping currents. However, the chopping effect cannot be reduced at will, because intensive arc quenching is required for other switching duties, such as switching of capacitive currents.

B 5.1 b Multiple re-ignitions

When switching small inductive currents (approx. 20 A up to some hundred amps), higher overvoltages can be generated if the arc reignites after the first interruption of the current, and if the device is then able to interrupt the high-frequency transient current i, which appears after the reignition. This process always includes a transient reaction between the capacitance on the system side and that on the load side. If it occurs repetitively, it is defined as multiple reignition. The voltage ampli-

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tude increases with each reignition (voltage escalation), so that extremely high overvoltages can result.

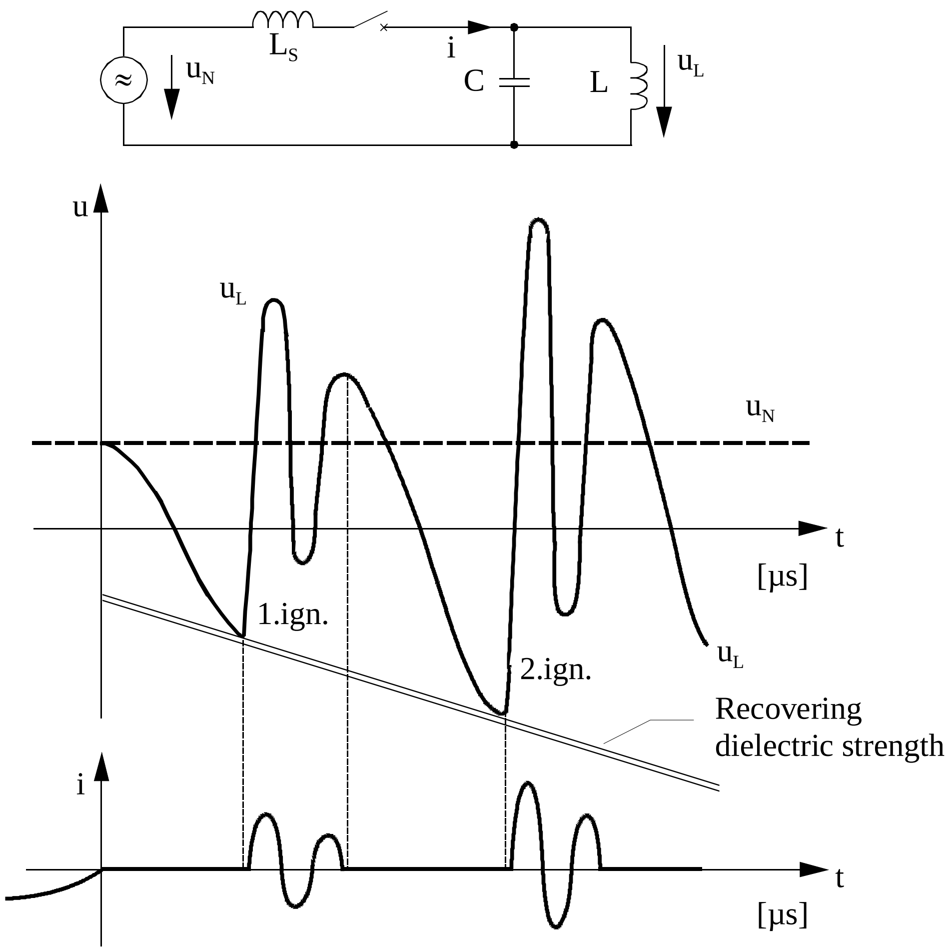
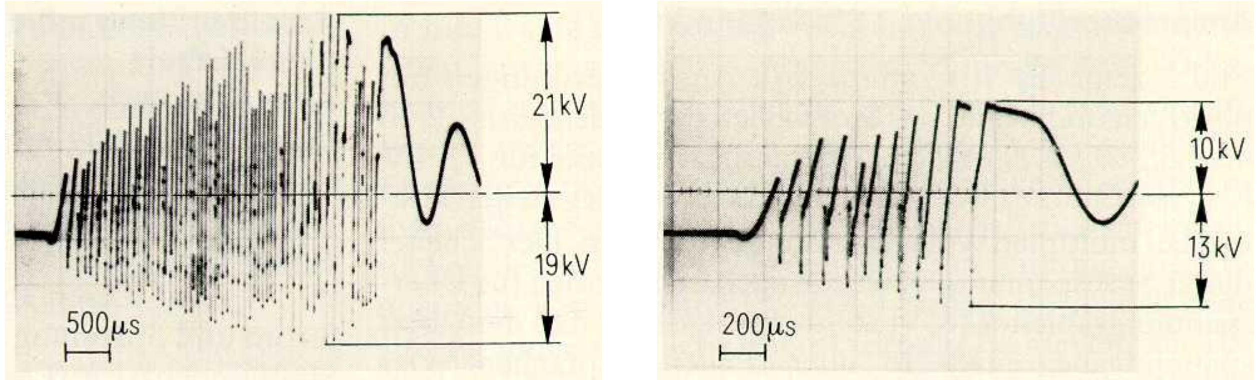


Figure B-3: Reignitions during inductive switching (principle)



Multiple reignitions in the breaking of a purely inductive 6 kV circuit;
without voltage limiting (left) and with voltage limiting (right).

Figure B-4: Oscillogram of multiple reignitions

B 5.1 c Virtual current chopping

With an increasing voltage amplitude, caused by reignition, the correspondingly high frequency transient current rises with each reignition. If this transient current (i_T in the figure) is coupled inductively / capacitively into the other two phases, which are still carrying the power-frequency current at this time, high-frequency current zeros (i_S, i_R) may also appear there. If the breaker interrupts in one of these current zeros, this is called virtual (= induced) current chopping. This high-frequency current only flows in the immediate vicinity of the switchgear, whereas the load still carries the 50-Hz-current. Current interruption at a high-frequency current zero described above has the same effect on the 50-Hz current as real current chopping at this time. So, formula {2} $U_{max} \approx \sqrt{(L / C)} \cdot i_c$ mentioned in a) will also give the height of this possible overvoltage.

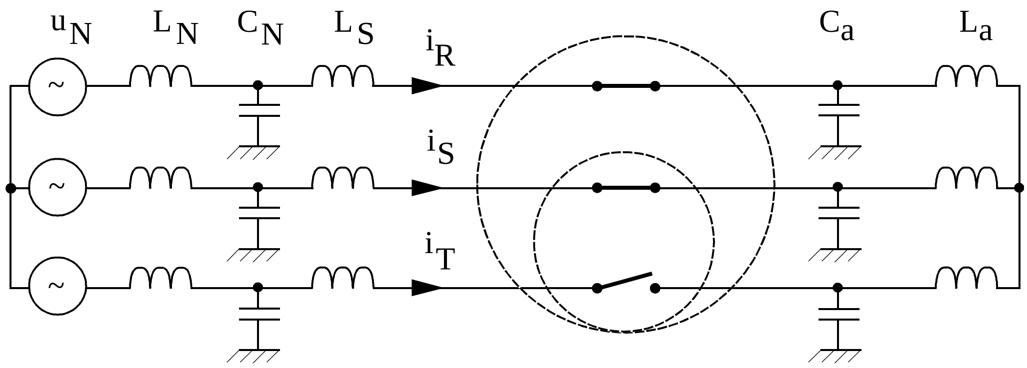


Figure B-5: Coupling to the phases S and R due to multiple reignitions in phase T

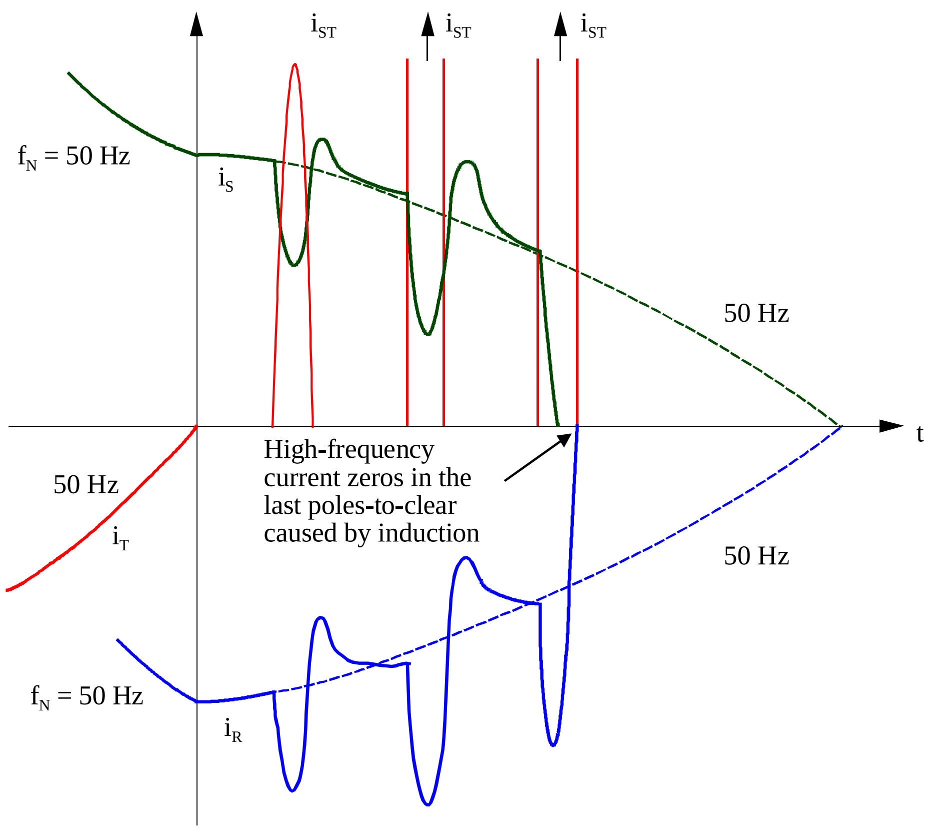


Figure B-6: Virtual (induced) current chopping in the phases S and R

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As this virtual current chopping can occur at comparatively high instantaneous values of the 50-Hz current, correspondingly high overvoltages are possible. These overvoltages can be controlled by surge arresters (surge limiters).

B 5.1 d Transient closing voltages

Every closing of an electrical circuit in high voltage systems will cause pre-arcing with transient oscillations. The following theoretical treatment describes the closing conditions in the most unfavourable case, in which the maximum transients occur. Damping and other effects are neglected.

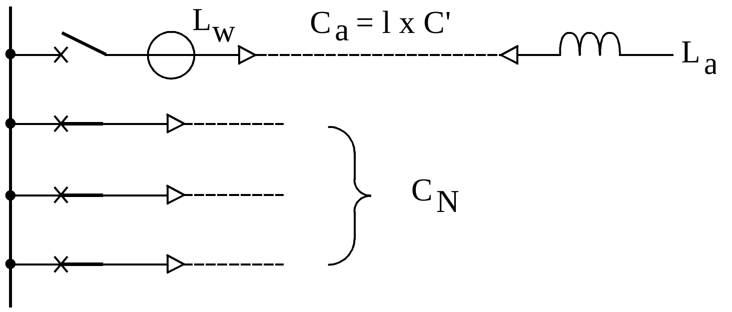
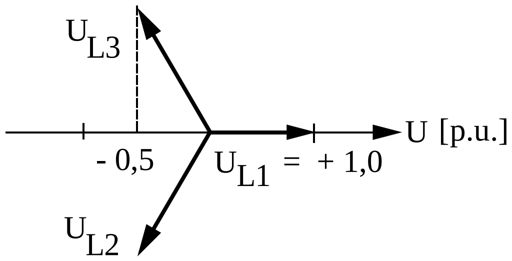


Figure B-7: Network and load capacitances on closing

The arrangement in Figure B-7 shows an inductive load, which is connected to the switchgear by a cable. The load capacitance C_a results from the cable, whereas the inherent capacitance of the load (e.g. transformer, motor) is some mutiples of ten less, so it can be neglected in this treatment. Many cables are connected to the busbars, so the network capacitance is very large ($C_N \rightarrow \propto$). Thus full transient voltage appears at the load side of the breaker.



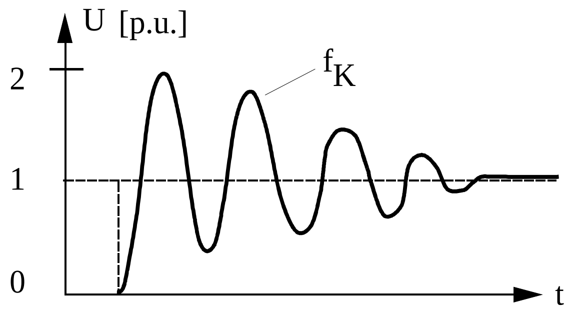


Figure B-8: Voltages at time t_1 and voltage trace in first pole to close

In the time scale of the oscillations described here, the operating frequency voltage remains almost constant. Up to time t1, consider the line to earth voltage $U_{L1}$to be at the maximum + 1 p.u. (Figure B-8 left). Also, consider the first closing pole to be in line L1. The breakdown of voltage over the switch contacts L1 (due to pre-arcing or galvanic contact) causes, as a result of the sudden voltage change, a travelling wave which runs periodically along the cable. In the first pole to close, L1, this builds an oscillating voltage with an overvoltage factor k = 2 (Figure B-8 right). The travelling wave sees the inductive load as a quasi open cable end, since the wave resistance of, for example, motors and transformers lies in the region of Z_{load} = 1000 Ω, in contrast to Z_{cable} = 10 Ω. At the switch, the cable connection has a wave resistance approaching Z = 0. Thus the cable natural frequency $f_K = \nu / (4 \cdot l)$; where ν = wave velocity, approx. 150 m/µs.

Simultaneously with the closing of the first pole, an equalising oscillation of frequency fa is set up in the two last closing poles L2 and L3. This is represented by the circuit in Figure B-9. Through the bridging of the contact gaps in the last poles to close, the oscillation fa moderates into an oscillation with the natural frequency of the cable f_K (Figure B-10), which then oscillates into the instantaneous value of the operating frequency voltage (half line-to-earth voltage. Overvoltages up to k = 3 result.

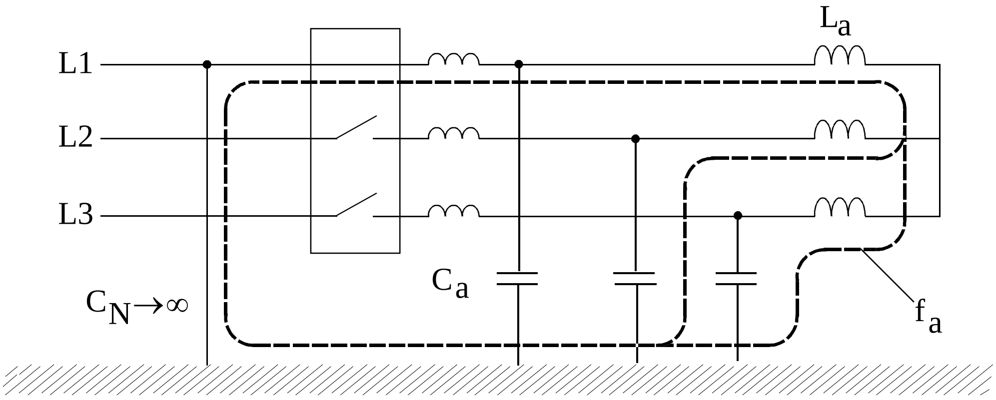


Figure B-9: Oscillations in last poles to close before contacts touch

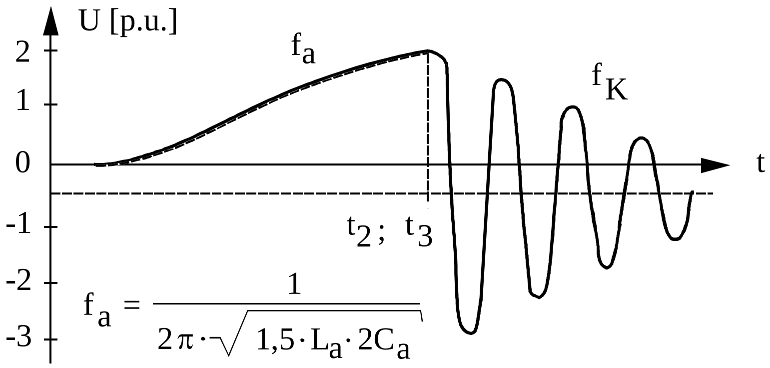


Figure B-10: Voltage trace in last poles to close

Related to the peak value of the line-to-earth voltage, overvoltages with factor k = 2 can occur in the conductor of the first pole to close and, in the conductors of the last poles to close, with k = 3 resp. k' = 5 (bipolar). Theoretically, a value of k = 6 is possible for the overvoltage between the phases of the last poles to close. In practice, the stresses are less than the theoretical maximum values, because of the statistical distribution of the overvoltages.

The described phenomena can occur in all switching devices, regardless of the method of arc extinction and arc quenching medium used.

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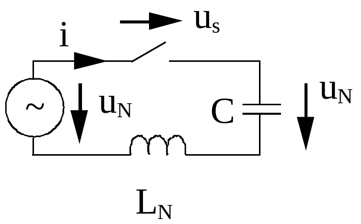
B 5.2 Switching operations in capacitive circuits

A distinction has to be made here between switching off and switching on capacitive consumers. Different stresses may arise:

B 5.2 a Switching off

When switching off at a current zero (time t1), the capacitor remains charged at the peak value of the source voltage (u_C). The system voltage (u_N) continues changing sinusoidally and reaches its opposite peak value after 10 ms. The recovery voltage (difference between u_C and u_N) now starts rising slowly. In this case, the stress is not caused by the rate of rise, but by the absolute value of the voltage. If there is a new ignition within 5 ms after arc quenching, this is called a reignition. This type of new ignition is not dangerous. If the new ignitions take place after a de-energized pause of more than 5 ms, they are called restrikes. However, if they appear after approx. 10 ms, these restrikes can be the origin of high switching overvoltages for the following reason: The restrike recharges the residual energy of the capacitor. Due to this, the voltage theoretically oscillates to a value corresponding to the capacitor voltage + the instantaneous system voltage (Figure B-11, time t2), but this value is not fully reached due to the existing system damping. Multiple recharging (more reignitions) can generate very high switching overvoltages, so that the switchgear insulation may be overstressed and flashover may occur.



u_N	System voltage
u_C	Capacitor voltage
u_S	Voltage at the breaker
i_C	Capacitor current
L_N	System inductance
C	Capacitance of load side

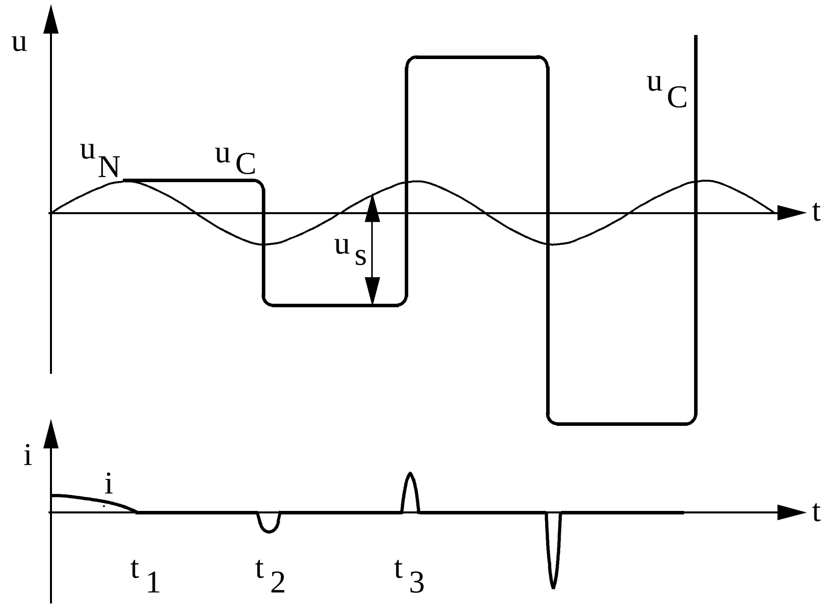
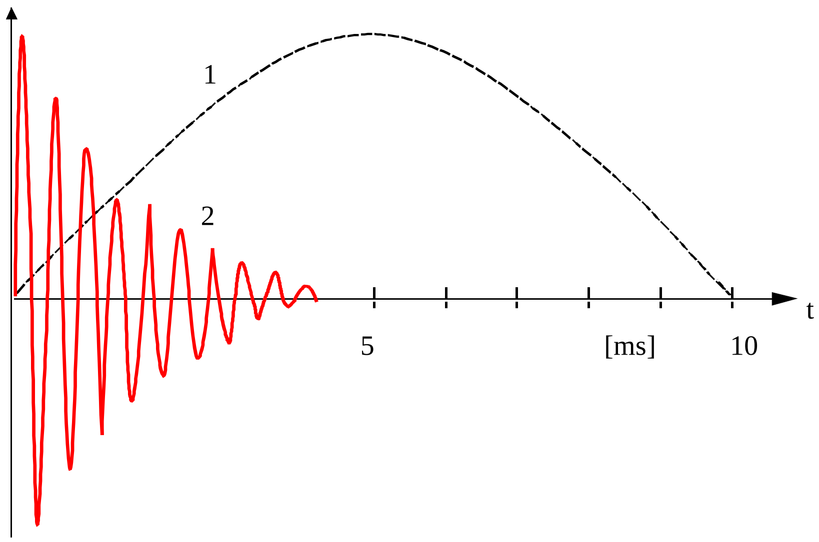


Figure B-11: Restrikes during capacitive switching

B 5.2 b Closing onto and parallel switching of capacitors

When the switch contacts approach each other, pre-arcing occurs across the open gap before galvanic contact. At this moment, a transient process takes place between the system and the capacitor, in which making currents up to some 10 kA with frequencies up to several kHz can appear. As pre-arcing occurs approx. 1 to 2 ms prior to galvanic contact, the full transient current (2) flows through the arc when switching on capacitors. In contrast to this, when making onto a short-circuit (1) the instantaneous current value at this time is much smaller. This means that switching on capacitors is a much harder duty than making onto a short-circuit with the same values of current amplitude.



1 Current variation during making on a short-circuit (50 Hz system); fault making on voltage maximum, i.e. maximum rate of rise of making current

2 Current variation during closing on a capacitor

Figure B-12: Current variation when switching on a capacitor

B 5.3 Switching duties in inductive circuits

These are the switching duties listed in Table B-2 and Table B-12.

1 **Unloaded transformers and network earthing transformers**: switching devices must have very low current chopping characteristics so that unacceptable overvoltages do not arise from current chopping during switch-off.

2, 3 **Loaded and over-loaded transformers**: present no critical problems for any switching device.

4 **Transformer inrush**: when interrupting a transformer inrush current, its value can be up to approx. 15 times the rated transformer current with a power factor of 0.15 and additionally it can be superimposed with harmonic components. Therefore, for example, switches or disconnectors are not suitable

5 **Furnace transformers**: when switching furnace transformers up to 100 operating cycles are possible per day. The currents range from no-load operation up to twice the rated transformer current (rated transformer current up to 2000 A). For this switching duty, only circuit-breakers with a high electrical and mechanical service life are adequate, such as vacuum circuit-breakers. Furnace transformers should always be equipped with an individually matched protective circuit to avoid the danger of overvoltages arising from virtual current chopping after multiple reignitions.

6 **Earthing (Petersen) coils**: under normal conditions only a very small current flows through the coil because the network is loaded symmetrically. Air or hard gas switch (disconnectors) are not suitable. Switching devices must have very low current chopping characteristics to avoid overvoltages during switch-off. A special case occurs when a Petersen coil is disconnected under earth fault conditions. Then an inductive current flows which can have the same magnitude as the capacitive earth fault current of the network (normally

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up to 60 A, in exceptional cases up to 300 A). For this switching duty only circuit-breakers, vacuum switches and some SF_6 switches are suitable. Additionally, multiple reignitions can occur, necessitating a special protective circuit.

7 **Shunt reactors**: the current switched are mostly very large. since such coils are frequently used to offset the reactive power of extensive h. v. networks. Thus only circuit-breaker are suitable for this duty. The previously mentioned multiple reignitions, which can occur during switch-off, lead to resonance excitation in many networks. Compensation coils also, therefore, require an individually matched overvoltage protection circuit.

8 **Motors in normal operation**: switching devices must have very low current chopping characteristics to avoid excessive overvoltages during switch-off. Small motors are often switched very frequently, therefore, contacors are most economical but circuit-brakers and vacuum switches may also be used.

9 **Motor starting**: the current may be as high as 7 times the rated full load current, at very low power factor. Over a specific current range, multiple reignitions and virtual current chopping may occur during switch-off.

B 5.4 Switching duties in capacitive circuits

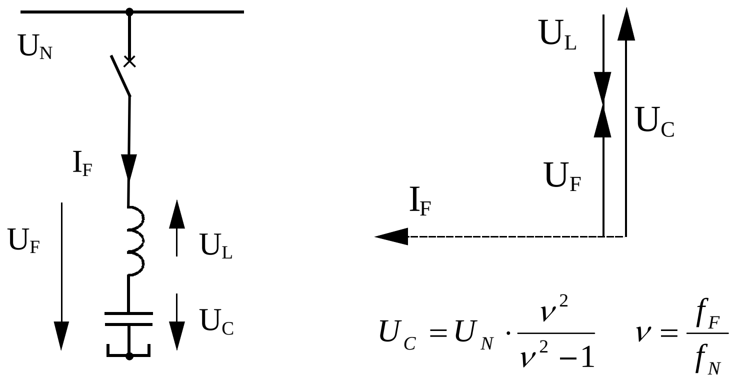
Switching duties according to Table B-3 and Table B-13. Switching duties 10 and 12 to 15 require unconditionally a restrike-free disconnection, in order to avoid overvoltages. In contrast to inductive switching, the transient currents during capacitive switching can be very high. It is then very difficult or even impossible to limit the overvoltages by surge arresters. It must be the aim to use reignition-free breakers, in order to avoid overvoltages right from the beginning, even if these breakers should possibly generate higher overvoltages during inductive switching. But, as already mentioned, those latter overvoltages can be controlled by surge arresters.

10 **Capacitors**: the r.m.s. value of the operating current is larger than the value of the rated current of the capacitor bank because harmonic current is superimposed on the basic 50 Hz current. Harmonics add frequency-proportionally to the current (inversely to the frequency dependant impedance of the capacitors - $1/\omega C$). In normal networks one anticipates a maximum total addition of 40 %, so the switching device must be able to carry 140 % of the rated current of the capacitors. For rectifier or furnace transformer installations, even larger harmonic content will sometimes appear.

11 **Parallelling of capacitors**: stresses the breaker contacts especially due to the rate of rise and the magnitude of the current flowing during pre-arcing. Depending on the type of contact system, the following problems can arise. In the case of tulip contacts (for example, minimum-oil, air-blast and SF_6 circuit-breakers) the contraction of the contact fingers makes it more difficult for the moving contact to enter the tulip. The moving contact brakes and this reduces the closing speed, perhaps to an unacceptable extent. In the case of flat contacts (as in the vacuum circuit-breaker) pre-arcing can melt parts of the contact surfaces, and this may lead to contact welding. If the making current exceeds the permissible breaker value due to the system arrangement, damping measures are required (e.g. reactors). However, it must be mentioned, that only limited making currents are allowed for any form of capacitor switching ($I_e < 100 \cdot I_{Cr}$).

12, 13 **Cables and overhead lines**: present no critical problem for any switching device.

14 **Filter circuits**: when switching off filter circuits or reactor-capacitor banks, the breaker is even more stressed by the recovery voltage than when switching capacitors only. This is due to the electric behaviour of the series connection of an inductance and a capacitance: if the same current flows through both elements, the voltages at the capacitor and at the inductor are in phase opposition. Thus, the capacitor voltage U_C exceeds the source system voltage by the value of the inductor voltage u_L. After switching off, the breaker has the voltage u_C, as the capacitor stores the electric charge. The capacitor voltage - and thus, the breaker stress - depends on the natural frequency of the filter circuit. If necessary, a breaker of a higher rated voltage class must be chosen.



$$U_C = U_N \cdot \frac{\nu^2}{\nu^2 - 1} \qquad \nu = \frac{f_F}{f_N}$$

U_N = System voltage
U_L = Voltage at reactor
U_C = Capacitor voltage
U_F = Voltage at the filter

F_F = Filter freqency
f_N = Power frequency

Figure B-13: Voltages of a filter circuit

15 **Ripple control systems**: If switching takes place during transmission, a capacitive current flows, consisting of superposed portions at network and at audio frequency (160 to 1600 Hz). This results in steep current zero crossings, which can be critical for hard gas and air switch-disconnectors. Such devices are therefore not suitable for this switching duty.

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B 5.5 Other switching duties in normal service

Switching duties of Table B-4 and Table B-14. These operations cannot be clearly assigned to the switching duties in inductive and capacitive circuits mentioned above.

16 **Ring main sectionalising**: a typical example is the sectionalizing of a cable which interlinks substations. At the main switchboard at the primary substation, the ring is connected to a circuit-breaker whilst at the switchboards at the distribution transformer units, the ring can be sectionalized by switches.

19 Synchronizing: the switching device must have a short and defined closing time (i.e. from instant of closing command to contact make in all poles). Manually closed, spring assisted devices are unsuitable. Stored energy spring operated devices are used.

20 **Isolation**: isolating (disconnecting) devices must have higher gap voltage withstand capability than other parts of the installation (120 %). Additionally it shall not be possible for leakage current to cross the gap and the gap may be bridged by insulating material only when there is effective protection against surface pollution (gas encapsulation) or when it is ensured that any leakage current is conducted to earth. Circuit-breakers do not fulfil these conditions because they are designed for high electrodynamic stresses and frequent switching. It is more economical to use a separate disconnecting device. In contrast, in secondary distribution switchboards, where lower currents and switching frequency are the rule, it is practical and economical to combine both functions in one device.

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B 6 Disturbed service

B 6.1 Characteristics of the short-circuit current

The characteristic values of the short-circuit currents for the different fault types are described below (see IEC 60909 / VDE 0102).

Generally, phase displacement between current and voltage before the short-circuit is small (cos ≥ 0.9), since the loads are mainly ohmic, or power factor corrected if highy inductive.

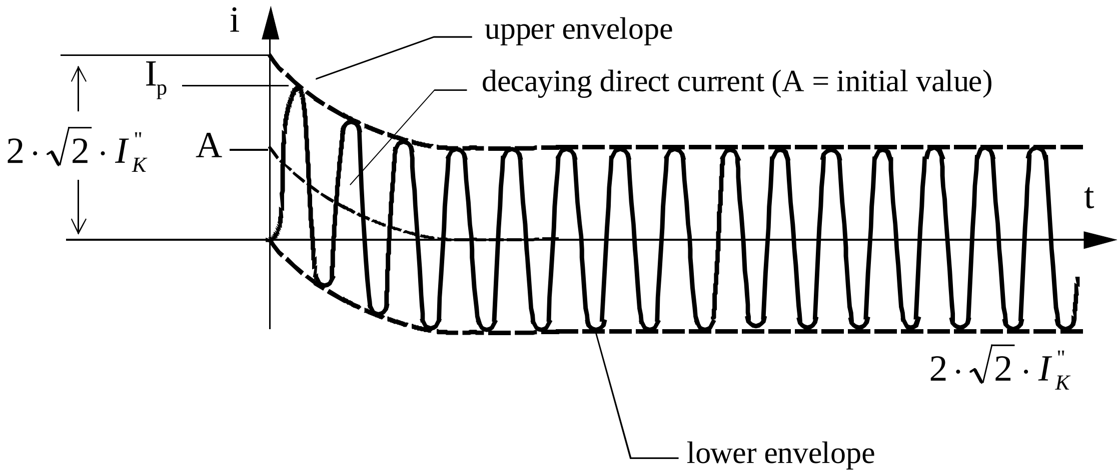

Figure B-14: Short-circuit remote from generator (short-circuit in the system)

If a short-circuit occurs, the phase angle is determined by the nature of the short-circuit. Since the inductive content is much greater than the ohmic content in the case of cables, transformers and generators, short-circuit calculations generally only consider the inductive part of the circuit. This means, that when a short-circuit occurs, the almost ohmic current prior to fault converts into an almost inductive current. Taking the worst case for the magnitude of the short-circuit current as a basis, that is, when the short-circuit occurs at a voltage zero, the current would have to jump to the peak value of the initial symmetrical short-circuit current (I_k''), due to the phase displacement which results. But this is not possible due to the inductivity of the circuit; the short-circuit current must start with a finite rate of rise and reaches its peak value after one halfwave. The displacement of the current from the zero line and the subsequent decaying-to-zero process is called the direct current displacement (A) or the DC component of the short-circuit current (Figure B-14 to Figure B-16). The alternating current decays from the initial symmetrical short-circuit current I_k'' to the sustained short-circuit current I_k. The peak value of the initial symmetrical short-circuit current with the superimposed DC component is called the peak short-circuit current I_p. This is the highest instantaneous value of the short-circuit current.

B 6.1 a DC component

The direct current decays according to the relation between the inductivity and the ohmic resistance (X/R) of the circuit. Generally, this occurs within a few cycles. Only if the fault is close to the generator (generator circuit-breaker) may the direct current decay very slowly, since the ohmic resistance of generators is very small and thus the relation X/R is very large.

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B 6.1 b Short-circuit close to generator

If the short-circuit is close to a generator, then not only the DC component, but also the AC component decreases. IEC 60909: ”A short-circuit is close to a generator, when in a three-pole short-circuit the contribution to the initial symmetrical short-circuit current from a synchronous machine exceeds at least twice its rated current ”(Figure B-15).

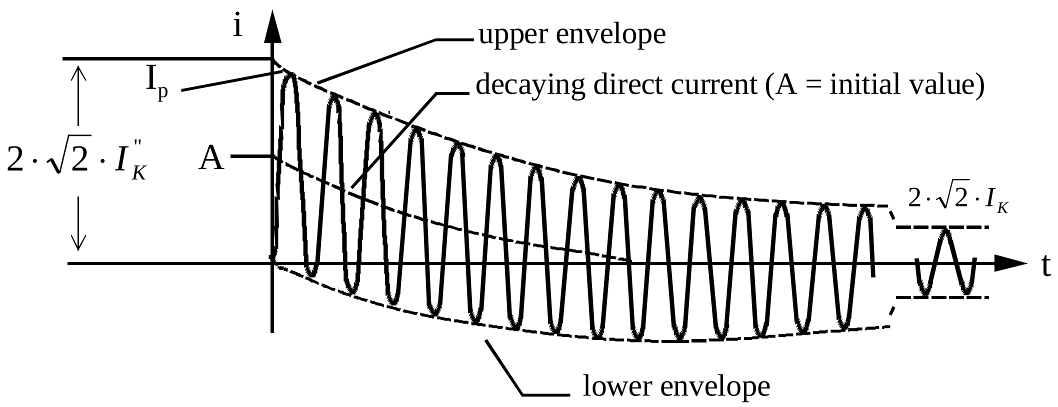

Figure B-15: Short-circuit close to generator

In the case of short-circuits close to generator terminals, it is possible under extreme conditions, that the AC component of the short-circuit current decays faster than the DC component, so that there are no current zeros for some cycles (Figure B-16).

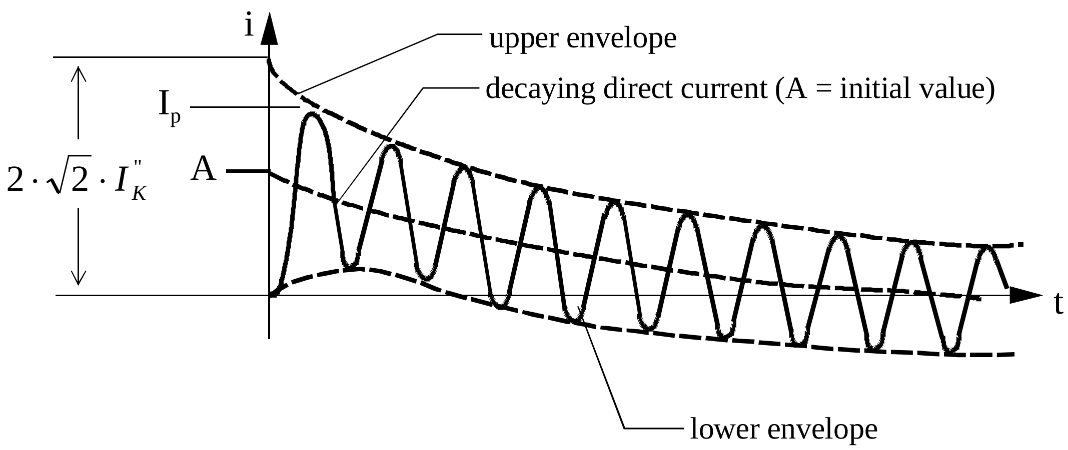

Figure B-16: Short-circuit close to generator woth missing current zeros

B 6.1 c Short-circuit remote from generator (in the system)

If a short-circuit is remote from the generator, then the AC component of the short-circuit practically does not decay, that is, the symmetrical current remains almost constant throughout the total short-circuit duration ($I_k''=I_k$), see Figure B-14.

B 6.1 d Initial symmetrical short-circuit current

The initial symmetrical short-circuit current (r.m.s. value) of the symmetrical short-circuit current at the instant that the short-circuit occurs.

B 6.1 e Peak short-circuit current

The peak short-circuit current (I_p) is the highest instantaneous value of the current after the instant of fault inception.

B 6.1 f Sustained short-circuit current

The sustained short-circuit current (I_k) is the r.m.s. value of the symmetrical short-circuit current that remains after all the transient processes are over.

B 6.1 g Breaking current

The breaking current is the current that flows through the breaker at the time of the first contact separation. It consists of the AC component at this time, and the possibly still existing DC component at this time. The AC component of the breaking current is the symmetrical current I_a.

In the case of a short-circuit close to generator terminals, $I_k'' > I_a > I_k$. In the case of a short-circuit remote from the generator, $I_k'' = I_a = I_k$. That means, that depending on the

- short-circuit location (close to/remote from the generator)
- beginning of the short-circuit (e.g. at voltage zero)
- time of interruption (relay time and breaking time)

the breaker must be able to switch off a current, which can possibly still run asymmetrically to the zero line (DC component), and whose AC component has not yet decayed to the sustained short-circuit current.

B 6.2 Recovery voltage and transient recovery voltage

Figure B-17 shows how the voltage recovers across the break distance after the short-circuit current has been interrupted. It is assumed that contact separation takes place at the time t_1. The short-circuit current i_K now flows through an arc and is first interrupted at the next current zero (time t2) in one of the three poles. (In Figure B-18, L1 is the first pole to clear). In the other two poles, the current continues flowing for approx. 5 ms until it is interrupted at a common current zero. (L2' and L3'). As shown in Figure B-18, the recovery voltage in the first pole to clear (L1) in the isolated neutral system jumps to the delta vector between L2 and L3, and exceeds the phase-to-earth voltage by a factor of 1.5 ($1.5 \cdot U / \sqrt{3}$). A high-frequency component is superimposed upon this power-frequency recovery voltage. The standards assume that this transient recovery voltage, which is indicated as a peak value ($\sqrt{2}$), overshoots the power-frequency recovery voltage by the factor 1.4. Thus, the transient recovery voltage u_C in the first pole to clear has a total value of
$1.4 \cdot 1.5 \cdot \sqrt{2} \cdot U / \sqrt{3} = u_C$ (see IEC 62271-100 / VDE 0671-100).

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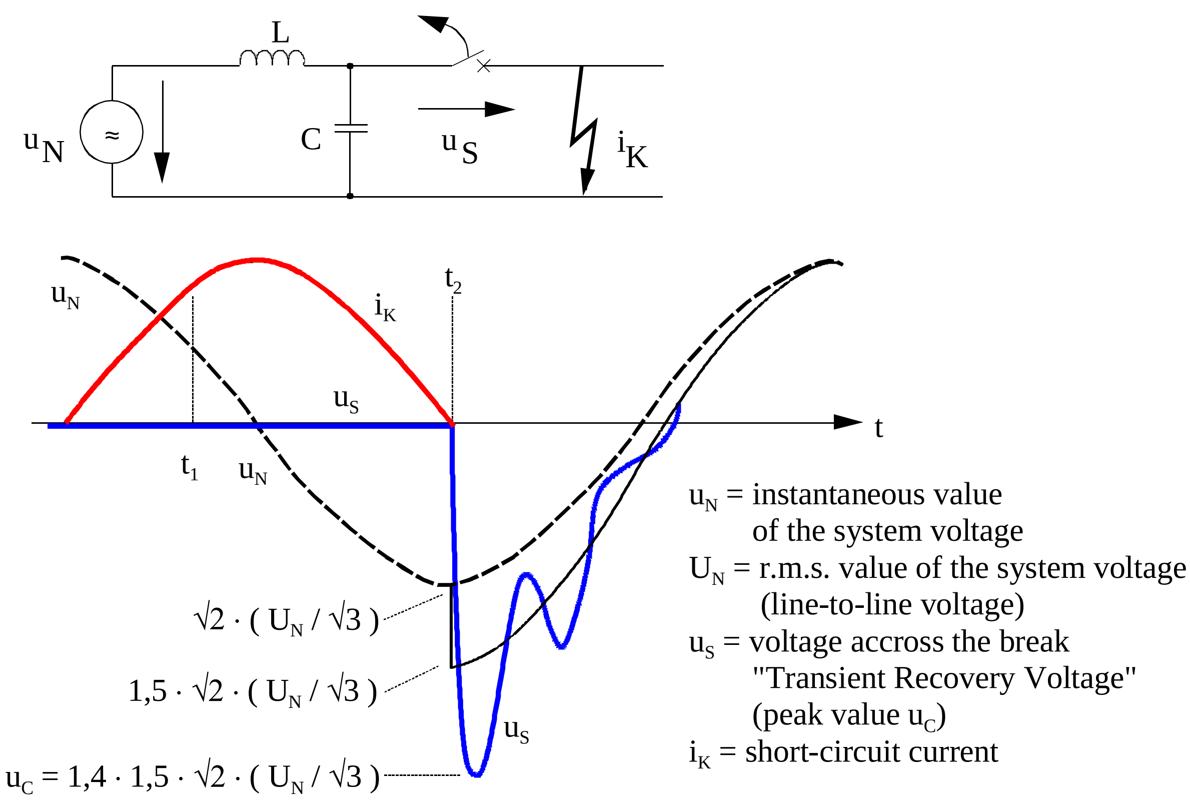

Figure B-17: Transient recovery voltage after short-circuit in the system

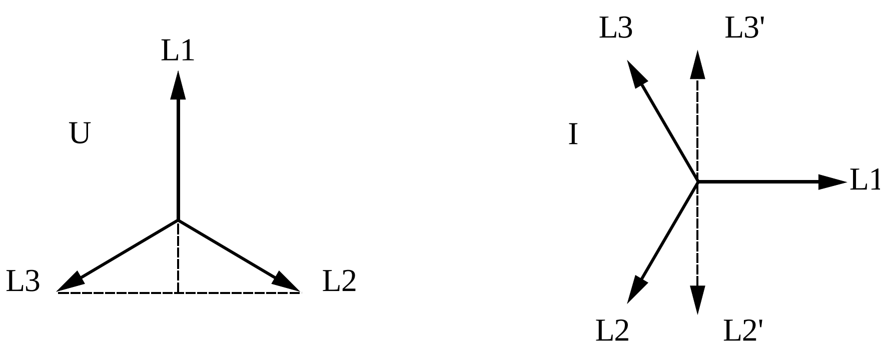

Figure B-18: Vector diagram of a short-circuit in the system

B 6.3 Making onto a short-circuit

When making onto an existing short-circuit (switching duty 22 of Table B-15), the making current is the peak assymetrical current I_p (Figure B-14, Figure B-15). That means, the current at this time is much higher than for the breaking duty. For short-circuits remote from the generator, the standards for AC switching devices of more than 1 kV (IEC 62271-100) indicate a value of 2.5 for the relation between the rated short-circuit making current and the AC component of the rated short-circuit breaking current. The ratio 2.5 comprises two factors. Factor $\kappa = 1.8$: effect of the DC component at the time of the first peak of the short-circuit current. It is assumed that, from the inception of short-circuit up to this time, the DC component has decayed from 2 to 1.8. Factor $\sqrt{2}$: Ratio of the r.m.s. value of the AC component of the short-circuit breaking current to the peak value. Thus we have $\kappa \cdot \sqrt{2} = 1.8 \cdot \sqrt{2} = 2.5$.

Figure B-15 shows that for short-circuits close to generator terminals, the ratio of the making current to the AC component of the breaking current can become much higher than 2.5, because, as mentioned above, the symmetrical short-circuit current also decays.

In systems with asynchronous motors, the short-circuit current can present a similar characteristic to that of the case of short-circuits close to generator terminals. Here, the ratio of the making current to the AC component of the breaking current can also considerably exceed the value 2.5. This is due to the fact that asynchronous motors can seriously increase the peak short-circuit current of the system in the case of short-circuit, whereas their effect can be neglected regarding the breaking current.

IEC 60909 / VDE 0102 "Calculation of short-circuit currents in three-phase systems" considers the different system conditions when calculating the peak short-circuit current. For a short-circuit being singly fed from many sides, the withstand ratio κ is defined as $\kappa = 1.15 \cdot \kappa_b$. κ_b is the partial factor resulting from the ratio R/X at the fault location. 1.15 is a safety factor for consideration of inaccuracies resulting from different R/X ratios in parallel system branches. However, the withstand ratio κ is limited to a total of $1.15 \cdot \kappa_b = 2.0$. This results in a relation of the making current to the AC component of the breaking current of up to $\kappa \cdot \sqrt{2} = 2.0 \cdot \sqrt{2} = 2.8$.

B 6.4 Breaking of short-circuit currents

Switching duties of Table B-5 und Table B-15

23 **Terminal short circuit**: on occurrence of short circuit close to the terminals of the device, the full prospective short circuit current must be interrupted.

24 **Auto-reclosing** (AR) or **delayed auto reclose** (delayed AR): means that when a short circuit occurs, the circuit-breaker immediately upstream of the fault, when controlled by an appropriate auto-reclose relay, first interrupts the current. Then, to avoid the need for a manual fault location exercise (e.g. by using a voltage tester), the circuit is automatically reclosed after a short time interval - approx. 300 ms - in the hope that the fault will have cleared itself. However, this procedure is only reasonable in overhead systems, where more than 50% of all faults are transitory. This offers a chance to reduce the number of long short-circuit interruptions, increases the reliability of the power supply and avoids the necessity to locate the point of fault.

On the other hand, not all faults on an overhead system can be cleared by auto-reclosing, even after multiple attempts (unsuccessful auto-reclose). Some faults are permanent short-circuits, which must be definitely disconnected by the circuit-breaker. This means, that during an unsuccessful auto-reclose attempt (and in the worst case this may be a terminal short-circuit), the circuit-breaker must open twice and close once in a few hundred milliseconds. Therefore the testing sequence for a single shot A/R breaker is:
O - 300 ms - C - O.

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25 - 27 **Short circuit at generator, reactor or transformer**:
when switching off a short-circuit directly behind (downstream of) a generator, a reactor or a transformer, the problem for the circuit-breaker is that the transient recovery voltage increases with a very high rate of rise. If dielectric recovery in the gap is not fast enough, there is the risk that the circuit-breaker may not break the current safely.

Figure B-19 to Figure B-21 show the network configuration and the corresponding equivalent circuit diagram.

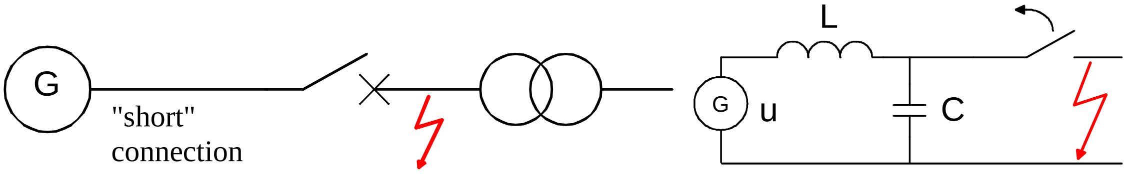

Figure B-19: Short-circuit downstream generator

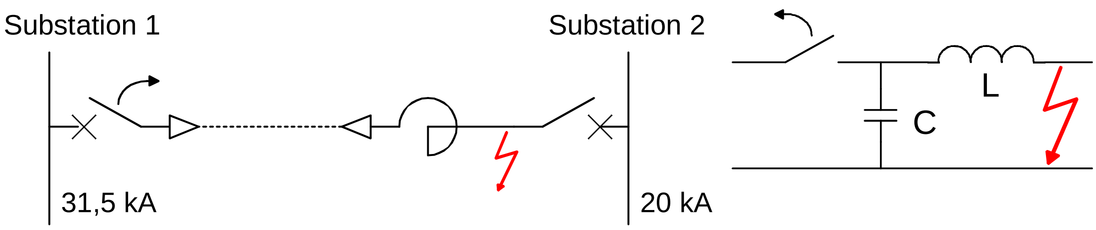

Figure B-20: Short-circuit downstream current limiting reactor

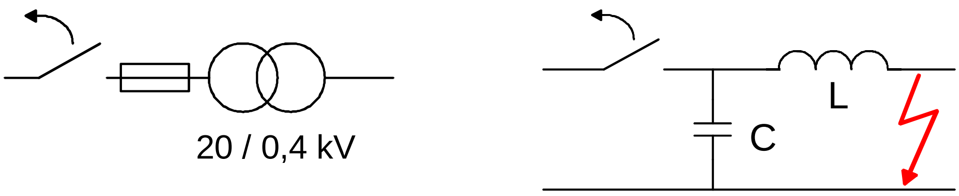

Figure B-21: Short-circuit downstream transformer

28 **Stalled motors**: when switching off stalled motors, the device must interrupt a comparatively high current (approx. 5 to 7 times the rated motor current). Further, there is the risk of causing overvoltages as described above if a motor is switched off during starting (switching duty 9**)**.

29 **Double earth fault**: when clearing a double earth fault with one fault location before the breaker and one after the breaker, the recovery voltage (after breaking the short-circuit current) is higher than in the case of a three-phase short-circuit. Figure B-22 shows, that in the case of such a double earth fault, the power-frequency recovery voltage is the phase-to-phase voltage (L2 in the fig.), whereas in the case of a three-phase short-circuit there is only the phase-to-earth voltage. If both faults of the double earth fault are located downstream of the breaker, there is the same stress in the two last poles to clear as in the case of a three-phase short-circuit.

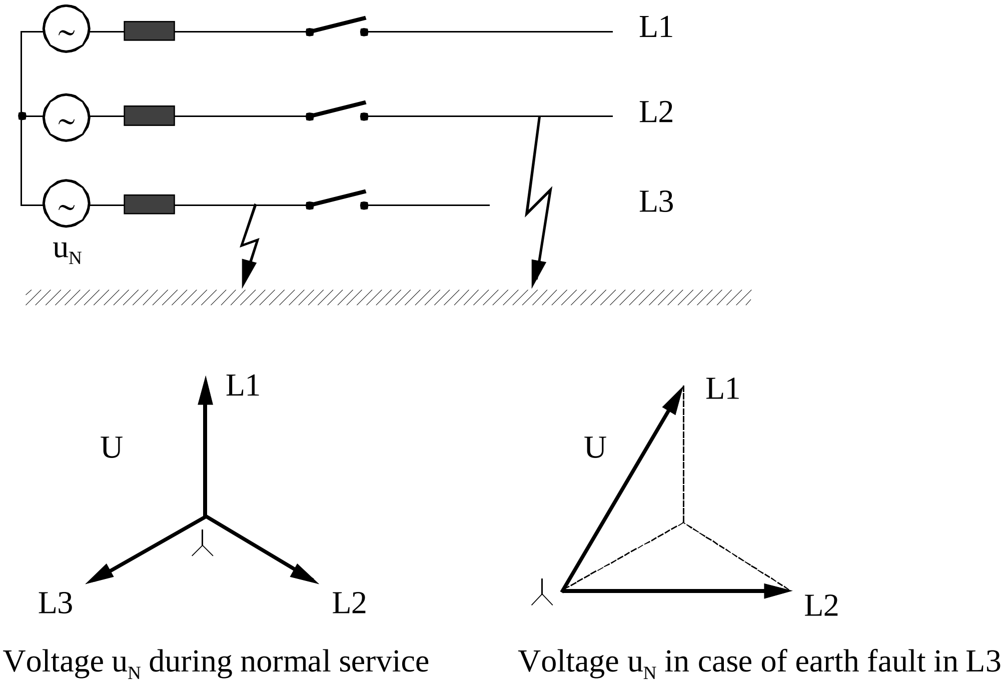

Figure B-22: Double earth fault

30 **Out of phase**: switching off under out-of-phase conditions (phase opposition) means a high voltage stress for the circuit-breaker (circuit-breaker b in Figure B-23). In the branch a three-phase short-circuit occurs in the feeder after breaker a. The systems N' and N" with the supply impedances Z' and Z" become asynchronous. In medium voltage systems, this case can occur, if there is on site power generation (system “N”) and an external supply (system N'). As soon as breaker a breaks the short-circuit, a transient current flows between N' and N", since the two systems will have fallen out of synchronism. As a consequence, when circuit-breaker b is tripped by its overcurrent protection, it opens under an out-of-phase condition, and the voltage stress is much higher than during switching off under normal short-circuit conditions. In the worst case (phase opposition by 180°), the voltages can double the value, as shown in Figure B-23: the power-frequency recovery voltage can reach the value $2 \cdot 1.5 \cdot U / \sqrt{3}$, and the transient recovery voltage can reach the value $2 \cdot 1.4 \cdot 1.5 \cdot \sqrt{2} \cdot U / \sqrt{3}$.

Where the factors are as follows:

- Amplitude factor 1.4
- Conversion to the peak value of the phase-to-earth voltage $\sqrt{2}$
- Factor for the voltage displacement in the first pole to clear (abbreviated as first-pole-to-clear factor) 1.5

In the worst case and when the system impedances Z' and Z" have the same value, the transient current flowing after switching off the short-circuit can be 0.5 times the short-circuit current of the feeder (breaker a). Assuming different system impedances Z' and Z", and taking as a basis that the appearance of the most unfavourable phase relation is rather improbable, the transient current is much smaller in most practical cases. This has also been taken into account in the standards, which define the transient current in the case of phase opposition as 25% of the rated short-circuit breaking current.

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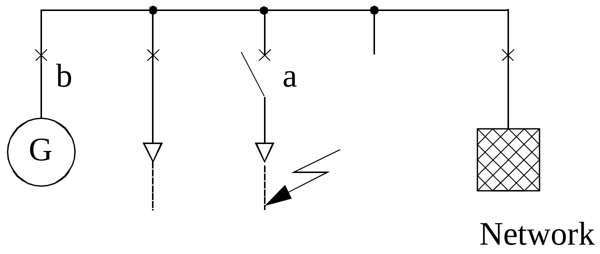
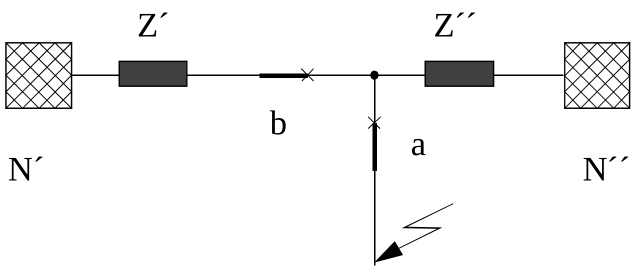


Example with own and external supply



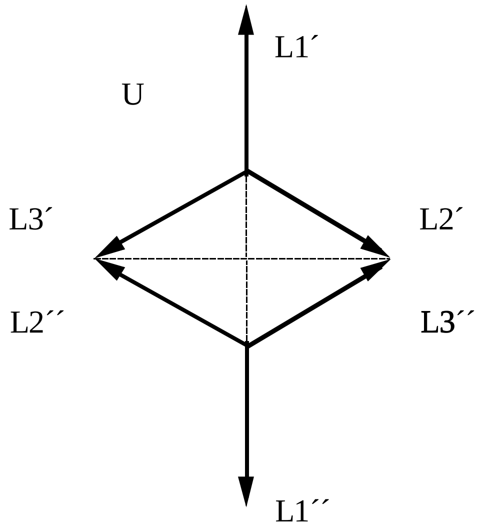


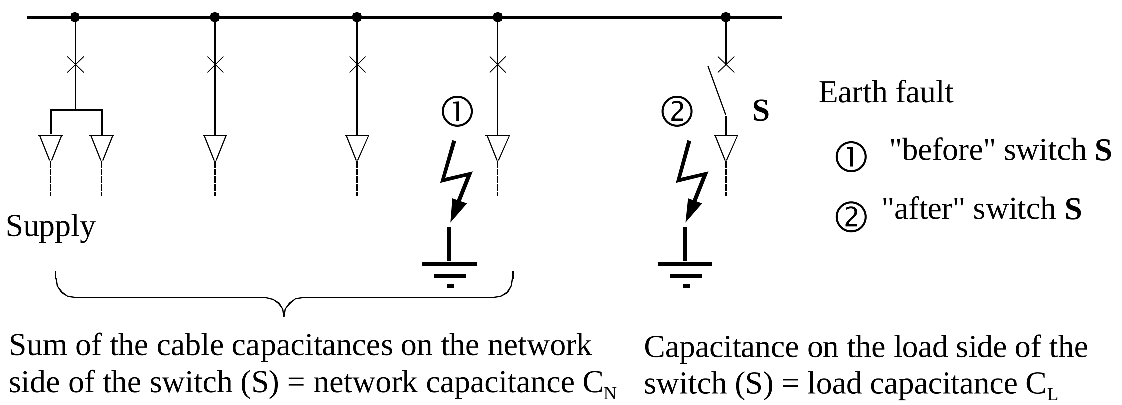
Figure B-23: Switching off under out-of-phase condition

B 6.5 Switching in the case of earth fault

Switching duties of Table B-6 and Table B-16.

When an earth fault occurs on one phase of a system with an isolated neutral or with an arc suppression coil (Petersen coil), the voltage to earth of the two healthy phases will rise to the phase-to-phase voltage. Switching operations at any point of the system then result in an increased current or voltage stress for the switching device. The stress depends on the location of the earth fault (in front of or behind the breaker), and whether there is a load current or not. Figure B-24 shows the network conditions related to the breaker which must open immediately.

In a switchboard (Figure B-24), breaker S now opens. Viewed from the network side, the disconnected circuit is after the breaker (load side), all other circuits on the switchboard lie before the breaker (network side). The conductor/earth capacitance of all the cables on the network side can be summated as C_N, which includes all cables electrically connected to the network. On the load side of the breaker, the cable gives the load capacitance C_L. In extensive networks, the capacitance can reach very high values, whereas the load capacitance is very small by comparison. In meshed networks, on the other hand, even the load capacitance can be comparatively large.



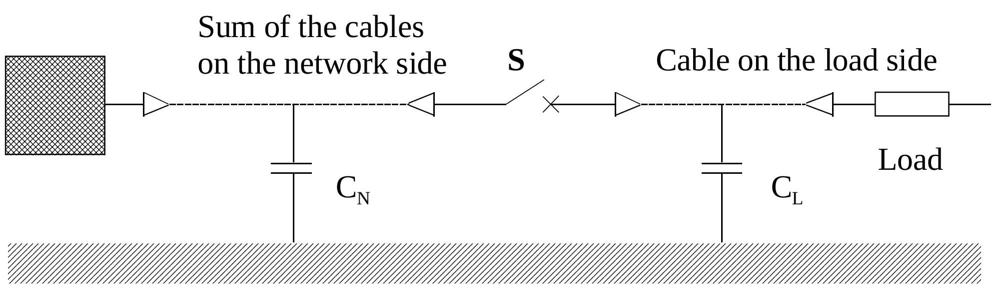


Figure B-24: Network conditions or earth fault before and after a breaker

B 6.5 a Fault on the system side

Here, the critical breaker stress is the high transient recovery voltage. The fault is not cleared if it is on the system side (e.g. in L3). The earth fault and also the displaced higher voltage in the healthy phases remain present. The transient recovery voltage is therefore much higher in the poles L1 and

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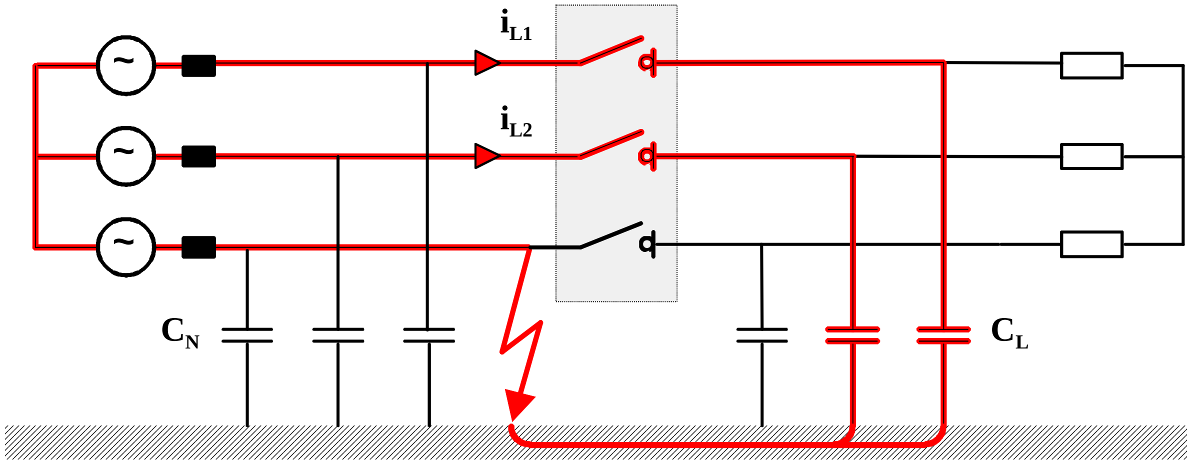
L2. The breaker must interrupt the charging current of an unloaded cable or overhead line at an increased transient recovery voltage (duty 31), or additionally, the superimposed load current (duty 32).



Route of the capacitive load current, e.g. in the healthy phase L2, that must be switched off by the breaker.

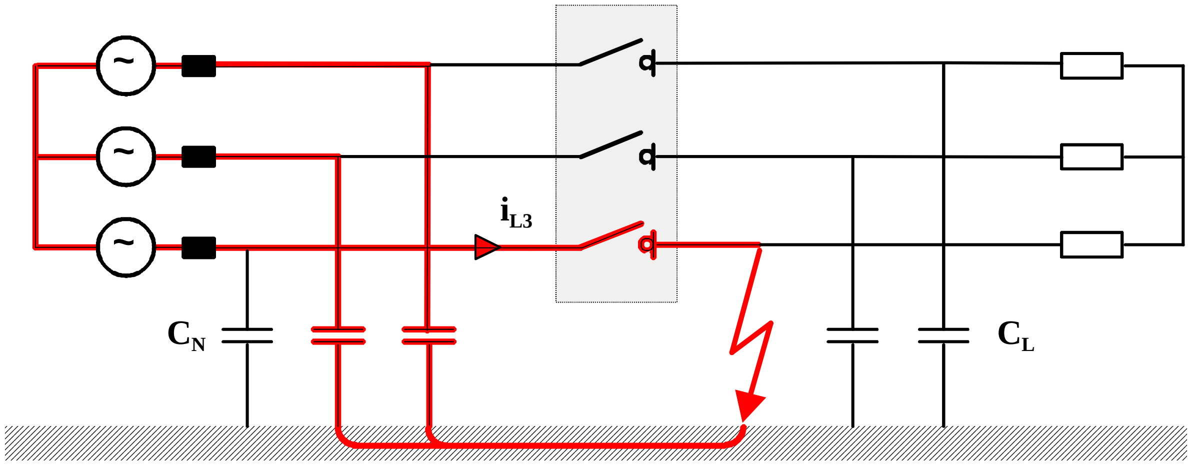
Switching duty 31: without load
Switching duty 32: with load

C_L = Capacitances on the load side
C_N = Capacitances on the network side

Figure B-25: Earth fault in L3 on the system side (supply side)

B 6.5 b Fault on the load side

Here, the critical breaker stress is the large capacitive current. If the earth fault is located on the load side of the breaker, pole L3 must switch off the capacitive load current of the whole system (duty 33). This capacitive current can reach very large values, depending on the extent of the galvanically connected cable or overhead-line system. In addition, it is possible that another capacitive current is superimposed (duty 34). Here, the transient recovery voltage is normal, because the fault is cleared by the breaker concerned.



Route of the capacitive load current of the entire galvanically connected system, that must be switched off by pole L3 of the breaker.

Switching duty 33: without load
Switching duty 34: with load

C_L = Capacitances on the load side
C_N = Capacitances on the network side

Figure B-26: Earth fault in L3 on the load side

B 6.5 c Location of earth faults in unearthed systems

In distribution systems, with substations connected to cable rings, the location of an earth fault is often traced by opening switch-disconnectors and not, as recommended, by means of circuit-breakers. One switches out cable sections in sequence and thus seeks to find the fault. As the fault location is unknown at first, any of the switching duties 31 to 34 described can appear at any of the operated switching devices. Depending on the extent of the system, the capacitive currents to be switched can reach such large values, that conventional switch disconnectors are overstressed.

The reason why the fault is searched by opening the switch-disconnectors is the ease of opening and the comparatively short power outage time for the consumer - as long as this method works. Using switch-disconnectors for this purpose is only safe, when the switching devices are able to control all four switching duties 31 to 34, with all the currents and voltages of the associated system. However, it is not easy to precalculate these values. For the safe location of earth faults, it is recommended:

- first, to switch off parts of the system with the circuit-breaker, then to isolate individual cables or overhead-lines, off load, using the switch-disconnectors. This means however, that the consumer must suffer longer power outages during the process.
- to limit the extension of galvanically connected cable systems, and thus, to limit the load currents to be switched.

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B 6.6 Other switching duties under fault conditions

Switching duties of Table B-7 und Table B-17.

35 **Protective isolation**: in this case, switch-disconnectors are used instead of simple disconnectors, in order to be sure that accidental operation under load will not cause danger for the operating personnel. Remember: disconnectors are only suitable for de-energized switching. Chapter D 9.1 will examine whether it is useful to adopt the protective isolation concept or to use other protective measures, such as the installation of switchgear interlocking systems.

36 **Rapid load transfer**: for rapid load transfer, switching devices with short making and breaking times, with accurately reproducible switching times are required, in order to transfer important consumers safely from one power supply to another without long de-energized pauses (≤ 150 ms).

37 **Transformer with shorted winding**: when switching a transformer with a shorted winding, or when switching off similar inductive currents with small cos φ, comparatively high rates of rise of transient recovery voltage appear. For fuses, this can cause the problem that the currents lie between the rated fuse current In and the smallest permissible breaking current Imin. In this area, fuses must not operate, because safe quenching cannot be ensured (see chap. C 5 Fuses and C 7 transformer protection).

38 **Switching on under short-circuit condition**:
when short-circuiting an applied voltage, the peak short-circuit current rises during the closing operation (compare with switching duty 22: making on a short-circuit). That is the reason why only switching devices with the corresponding short-circuit making capacity can be used.

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C TYPES AND APPLICATION OF SWITCHING DEVICES

C 1 Circuit-breakers

C 1.1 Arc-quenching

AC arcs are interrupted by taking advantage of the natural sinusoidal current zeros (current-zero quenching) – in contrast to DC arc-quenching. Accordingly, the main duty of the arc-quenching system is to deionize the gap between the contacts at the instant of current zero in order to restore the dielectric strength of the gap as quickly as possible. An additional aim of every arc-quenching principle must be to keep the arc energy low, so that the arc chambers are stressed as little as possible by the effects of heat and pressure.

Before describing the different arc-quenching principles in detail, let us summarize the processes in "conventional" circuit-breakers. We define conventional circuit breakers as all those except the vacuum circuit-breaker. For arc-quenching, all these circuit-breakers rely upon a relative movement between the arc and the arc-quenching medium. In most of these breakers, the arc-quenching medium is set in motion and flows into the arc in order to de-ionize the contact gap as fast as possible at the instant of the first current zero after contact separation. But there are also circuit-breakers where the arc is made to move in the arc-quenching medium. These are called rotating arc breakers. SF_6 circuit-breakers often operate according to this principle.

However, homogeneous arc cooling throughout the total duration of current flow, i.e. also during the maximum, automatically increases arc power and arc energy, and thus the chamber stress. The reason for this is:

Depending on the current intensity and on the medium in which it is burning, every arc has a specific temperature and, accordingly, a specific internal arc resistance. Intensive cooling reduces the arc temperature but increases the resistance. In its attempt to maintain the current flow the arc voltage rises. This results in increased arc power.

Other arc-quenching principles use the energy of the arc itself to assist the flow of the arc-quenching medium. This is called a current-dependent arc-quenching effect. The problem with these arc-quenching principles is, however, to attain the correct balance between the flow of the arc-quenching medium and the strength of the arc in order not to increase the quantity of energy unnecessarily. However, in practice, there is no time-relation between the moment of contact separation and a current zero which coincides with sufficiently large contact separation (tripping is not synchronized with the current half-wave). Thus, for most break operations, the flow of the arc-quenching medium is larger than necessary. As mentioned above, this leads to unnecessarily high arc energy.

The strength of flow of the arc-quenching medium is particularly critical when switching small inductive and capacitive currents:

C 1.1 a Current-dependent arc-quenching

Current-dependent flow of the arc-quenching medium is particularly suitable for switching small inductive currents (soft switching). However, when switching capacitive currents, there is the risk of restrikes, because the dielectric strength of the contact gap cannot be restored fast enough, resulting in restrikes Figure B-11 with the corresponding explanations.

Moreover, unnecessarily long arcing times may occur when switching small currents, because there is insignificant or even no flow of the arc-quenching medium.

C 1.1 b Current-independent arc-quenching

Current-independent flow of the arc-quenching medium must be very strong if it is to achieve interruption of short-circuit currents and therefore, in most cases it will also interrupt capacitive currents without restrikes ("hard" switching). On the other hand, it gives the advantage that small inductive currents may be chopped so harshly, that high switching overvoltages result (see Figure B-2).

C 1.1 c Combined arc-quenching

For these reasons, experience has shown that a combined flow is the most suitable solution for all switching duties. The current- independent flow is kept at a comparatively low level, thus reducing the risk of high switching overvoltages when switching small inductive currents but, on the other hand, the flow can be designed to be sufficient to interrupt capacitive currents without restrikes and arcing times can be kept short even when breaking small currents. The strong flow of the arc-quenching medium required for interrupting short-circuit currents is generated by the current itself, and is superimposed upon the forced flow, which has a constant value.

Our minimum-oil circuit-breakers 3AC (T-breakers), for example, used the principle of combined flow of the arc-quenching medium.

The processes in vacuum circuit-breakers are fundamentally different and are described in detail later.

C 1.1 d Designs of circuit-breakers

At present, circuit-breakers with the following arc-quenching principles are in operation in medium voltage distribution systems:

- Bulk-oil circuit-breaker
- Minimum-oil circuit-breaker
- Expansion circuit-breaker
- Air-blast (compressed air circuit-breaker)
- SF_6 circuit-breaker
- Air-magnetic (air circuit-breaker)
- Vacuum circuit-breaker

The first 5 types (bulk-oil to SF_6), all have the common feature that the arc is extinguished by gas, because the high arc temperatures develop gases or vapours from the liquid, even in the first three types. In bulk-oil circuit-breakers, hydrogen develops from the oil. Hydrogen has very good arc-quenching properties due to its high thermal conductivity and a good dielectric behaviour because of its high arc resistance (13.5 times higher than air). These features are also called the hydrogen effect.

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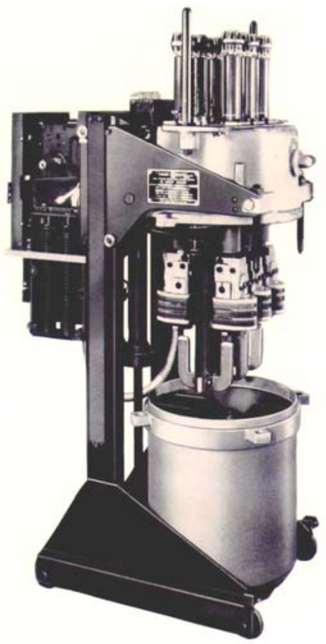
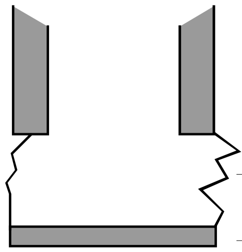
C 1.2 Bulk-oil circuit-breaker

A typical feature of bulk-oil circuit-breakers is the two current terminals or isolating contacts per pole, which are brought out of the top of the tank through bushings (they require special switchboard constructions). In the most simple design, there were no arc chambers. The arc is divided into two partial arcs, and is drawn by means of a switching cross-arm. The three phases are installed in one common tank. The general advantages of the bulk-oil circuit breaker are the good dielectric characteristics of the oil. Disadvantages are the large oil volume, the high arc energy (long arc, long arc duration) and the large amount of gas generated, which must be vented from the breaker, often taking oil with it. Another disadvantage is possible tank explosion as, due to the large tank surfaces, it has to withstand very large pressures if the arc is not successfully interrupted.





Some of these disadvantages were overcome by the introduction of arc chambers under the oil. The switching characteristics of these designs correspond approximately to those of minimum-oil circuit-breakers with a current-dependent arc-quenching effect.

Bulk-oil circuit-breakers are, however, not very important anymore. Even in the British influenced countries, where they used to predominate, manufacture is declining.

Figure C-1: Bulk-oil circuit-breaker

C 1.3 Minimum-oil circuit-breaker

The minimum-oil circuit-breaker has the advantages of the bulk-oil circuit-breaker, but not its disadvantages. In the minimum-oil circuit-breaker, the arc is extinguished by an oil flow. This oil flow is either initiated by the arc itself or it is forced by the operating mechanism of the breaker with the help of suitable supplementary devices.

Current-dependent oil flow is caused either by a special diversion of the gas bubble or by a differential piston.

Current-independent oil flow is achieved either by pumping devices or by making use of the volume compensation of the moving contact (rigid arc chamber), but this is only possible when the contact moves downwards.

The most favourable result is achieved with a combination of the current-dependent and the current-independent oil flow systems (as in Siemens T-breaker).

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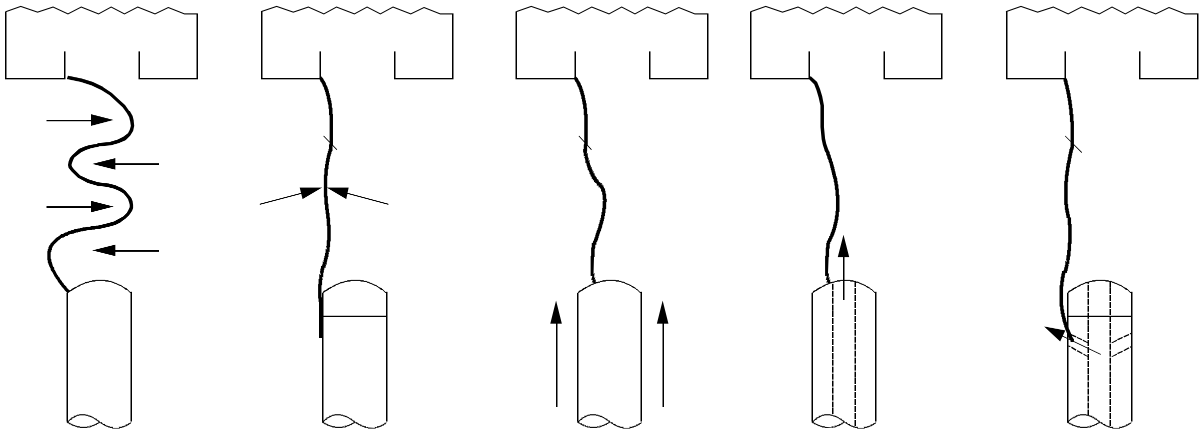
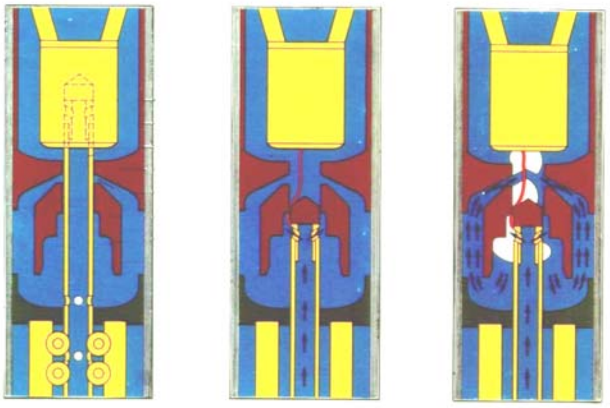
Radial pressure on the arc (transverse flow) is generally more effective than axial pressure (longitudinal flow). However, the radial flow carries the risk that the arc is elongated artificially and that it may be cooled too much before reaching the minimum quenching distance. These two factors lead to a high increase of arc power.



Transverse flow, elongating the arc artificially	Transverse flow, with a sustainable streaming angle in the T-breaker	Longitudinal flow, which has only a small effect when streaming in parallel to the arc	Longitudinal flow in the T-breaker, which cools the arc roots

Figure C-2: Arc-quenching in minimum-oil circuit-breakers



Left: breaker is closed

Middle: breaking a small current

Right: breaking a large current (short-circuit)

Figure C-3: Example of a minimum-oil circuit-breaker with combined oil flow

C 1.4 Expansion circuit-breaker

In the expansion circuit-breaker, the arc develops hydrogen from water. The arc therefore burns in the same arc-quenching medium as in the oil circuit-breaker.

Most expansion circuit-breakers operate according to the expansion principle, i.e the arc produces gas, which surrounds the arc under high pressure. Due to this effect, the arc chamber lifts up from its seat. The pressure is compensated through a resulting annular gap. As new gas is produced con-

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tinuously, a high pressure is maintained. But when the current approaches its current zero, the gas development is reduced, the pressure decreases suddenly. The water around the arc evaporates abruptly and de-ionizes the gap.

Due to the residual conductivity and to a certain continuous conductivity of the water, high transient frequencies are controlled safely. There is no sudden chopping of small inductive currents, but re-strikes can easily appear when switching capacitive currents.

Since the water has a residual conductivity, air-break isolators are installed in series with the gap.

The conductivity is also a disadvantage when making onto a short-circuit, as the pre-arcing time and thus the gas development times are very large (leading to burning down of the moving contact). Relief is afforded by high making speeds and switching on in air with the air-break blade. However, the main disadvantage of the expansion circuit-breaker is its costly construction, which also obliged us to give up this product. No expansion circuit-breakers are manufactured anymore.

C 1.5 Air-blast circuit-breaker

Air-blast circuit-breakers always have a current-independent flow of the arc-quenching medium, and so they are especially suitable for switching capacitive currents; but, without supplementary equipment they generate high switching overvoltages when breaking inductive currents. To avoid switching overvoltages, high resistances must be connected in parallel to the break distance.

The main reason why air-blast circuit-breakers do not control high transient frequencies well, is the absence of hydrogen effect. Hydrogen effect is that which results from the good arc-quenching and dielectric features of hydrogen, whose thermal conductivity is 17 times that of air, and whose arc drop-voltage is 13.5 times that of air. For better control of the recovery voltage, low resistances are often connected in parallel to the break distance. These resistances reduce the amplitude.

In air-blast circuit-breakers there is one value of contact separation by which the arc must have been extinguished, because the pressure available may have been reduced to such an extent that the difference between it and the back pressure from the arc is insufficient to extinguish the arc. Additionally, contact travel may not be adequate to establish an isolating distance and an additional isolating contact or stroke may be necessary.

As the air-blast circuit-breaker always has to store a large volume of air, which must be lead abruptly to the break distance through complicated valve arrangements, and for the above mentioned reasons (parallel resistances, two-step contact stroke, or air-break blade respectively), this circuit-breaker type is rather expensive. At medium voltage, it is only economic for high breaking capacities and high rated currents.

Other disadvantages of air-blast circuit-breakers are:

- the circuit-breakers cannot be operated if the compressed air supply fails;
- additional safety distances must be observed, because of the exhausting switching gases;
- the circuit-breakers can only be manufactured with pneumatic operating mechanisms;
- due to the large amounts of air required within an extremly short time, high operating pressures and large pipe sections are required, which, combined with the required safe design of the compressed-air supply, lead to a costly compressed-air system;
- due to the open contact system, there may be insulation or corrosion problems if air humidity is high;
- the loud switching noise.

Regarding the high costs (for the breaker itself as well as for the corresponding compressed-air system and for maintenance) and since there are now other non-oil circuit-breakers on the market which are able to control the different switching duties in a better way, the air-blast circuit-breaker is not very important today. It is still used for special applications, e.g. as generator circuit-breakers (high short-circuit and operating currents).

C 1.6 Air-magnetic circuit-breaker

The air-magnetic circuit-breakers operate with the so called direct current arc-quenching effect, i.e. the arc voltage is increased until it is higher than the source voltage. The following arc-quenching methods are used:

a) The arc is blown between insulating plates by magnetic forces and arc extinction is improved by wall cooling.

b) The arc is divided into many partial arcs by means of conductive steel plates, making use of the cathode drop effect. Cathode drop is a process in which, immediately after arc extinction, a space is created in front of the cathode, free of charge carriers, which immediately has a dielectric strength of approx. 250 V. This is caused by the faster movement of electrons to the anode in contrast to the slower movement of ions to the cathode.

As the dielectric strength of the break distance is restored rather slowly after the current is interrupted, air-magnetic circuit-breakers are not restrike-free when interrupting capacitive currents (see also Figure B-11). As they are also very expensive (production costs, maintenance costs), they are increasingly being replaced by other non-oil circuit-breakers (vacuum circuit-breakers, SF_6 circuit-breakers).

C 1.7 SF_6 circuit-breaker

SF_6 has very good arc-quenching and dielectric properties. Compared with nitrogen, (on which the arc-quenching effect of air-blast circuit-breakers is based), the thermal conductivity at high temperatures (3,000 up to 10,000 K), such as those arising in the arc, is much lower. Therefore, the radial temperature slope is much steeper and the arc radius smaller. Thus, the arcing time-constant near current zero is also much smaller. The arcing time-constant is a measure for the increase in arc resistance when that energy flow ceases. For SF_6 it is only approx. 1/100 that of nitrogen. The dielectric recovery after cessation of current flow is therefore much better.

On the other hand, below 3,000 K, the thermal conductivity of SF_6 much exceeds that of nitrogen, and this is favourable for heat dissipation (see also chapter G 1).

As SF_6 is expensive, it is used only in circuit-breakers with a closed gas system.

Basically, there are 3 types:

- Dual-pressure type
- Puffer type
- Circuit-breakers with self-generated arc-quenching

Dual-pressure circuit-breakers are not in production anymore (they were manufactured e.g. by Siemens from 1963 to 1970). They were followed by puffer type circuit-breakers. In these circuit-

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breakers, the flow of the arc-quenching medium is produced by the operating mechanism. As the strength of this flow is designed for breaking the full short-circuit current, SF_6 puffer type circuit-breakers belong to the so-called hard breakers. That means when switching small inductive currents, they produce high switching overvoltages by current chopping and/or by multiple re-ignitions (see also Figure B-2 to Figure B-6 with the corresponding explanations). In contrast to this, they are very suitable for capacitive switching.

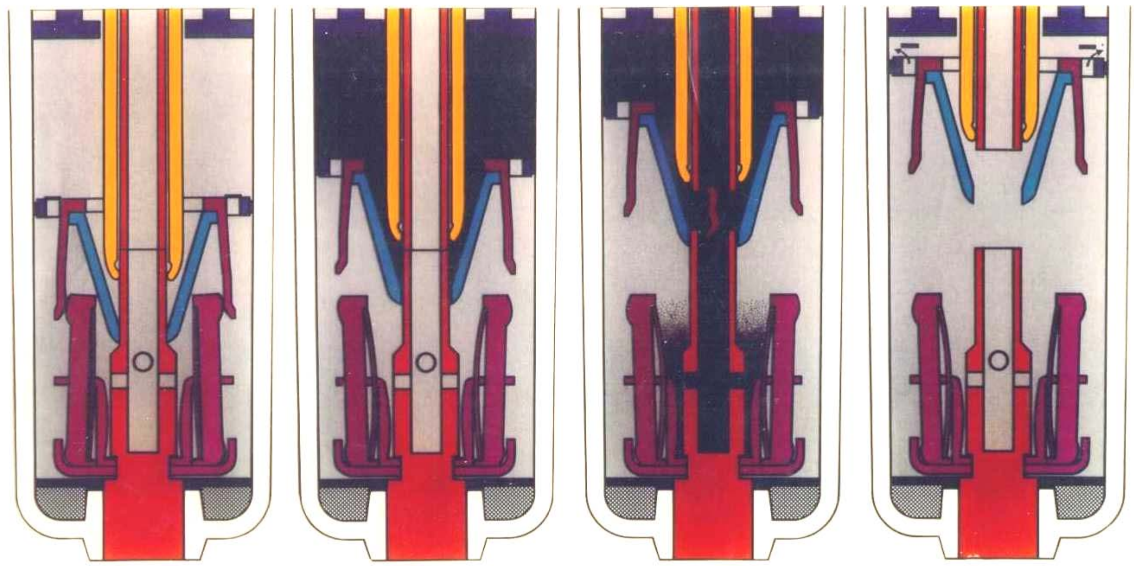


Figure C-4: Arc-quenching principle of an SF_6-puffer type circuit-breaker

Now, puffer type circuit-breakers are increasingly being succeeded by SF_6 circuit-breakers with self-generated arc-quenching (especially for cost reasons and because of the above mentioned switching overvoltages). In these circuit-breakers, the arc-quenching effect depends on the primary current. There are two different methods:

- a gas flow is initiated by the arc, depending on the current magnitude
- the arc is forced by the magnetic effect of the current to move in the SF_6 filled space (rotating-arc or roll-arc circuit-breaker).

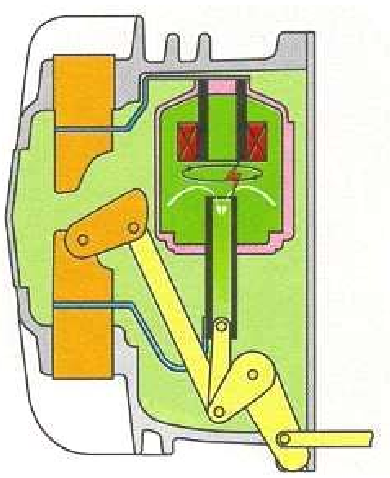


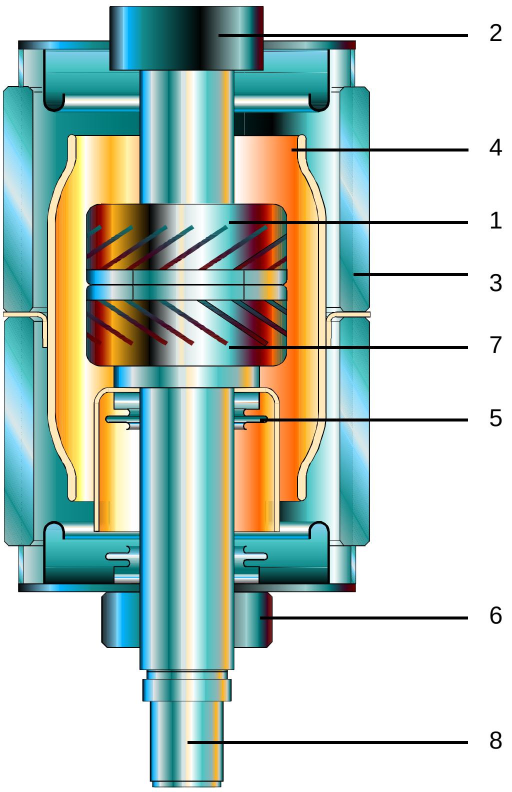
Figure C-5: Example of an self-extinguishing SF_6 circuit-breaker

These circuit-breakers are "soft" breakers because of the current-dependent arc-quenching, i.e. they produce only minor switching overvoltages when switching small inductive currents. However, as they may have problems when switching capacitive currents (very long arcing times with the risk of switching failures as a consequence of the absence of or only very small gas flow), they may be equipped with supplementary pistons in order to ensure perfect capacitive switching capability. On the other hand, this leads to high overvoltages when switching very small inductive currents (switching of unloaded transformers).

C 1.8 Vacuum circuit-breaker

In vacuum, the arc is extinguished in a totally different way than in gas. This arc-quenching principle is therefore described here in more detail.

The switching element of the vacuum circuit-breaker (V-breaker) is the vacuum interrupter (Figure C-6). It consists of an arc chamber, which is located between two ceramic insulators. Terminal studs connect the contacts to the external terminals. One contact is fixed within the housing, the other one is moveable. The metal bellows enable the contact movement and provide a hermetic connection to the interrupter housing. The contact stroke is only a few millimeters. The internal pressure in the vacuum interrupter is less than 10^{-7} bar. The vacuum circuit-breaker has no arc-quenching medium. The properties of the contact material and the contact geometry define the switching behaviour and the switching capacity.



1 Fixed contact piece

2 Connection disc

3 Ceramic insulator

4 Arc chamber

5 Metal bellows

6 Guide

7 Moving contact piece

8 Moving contact piece terminal

Figure C-6: Structure of a vacuum interrupter

After contact separation, the resultant arc evaporates contact material from the contact surfaces. The arc current thus flows through a metal vapour plasma until the next current zero. Near the current zero, the arc is extinguished, and the metal vapour looses its conductivity within a few microseconds as a consequence of the recombination of the charge carrier ions. In this way, the contact gap is de-ionized and the dielectric strength restored very fast. The metal vapour condenses on the contact surfaces. Only a very small portion condenses on the arc chamber wall. The arc chamber

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wall has the function of a vapour shield, to prevent condensation of the metallic vapour onto the insulators.

The dielectric strength in vacuum is very high. Figure C-7 shows a laboratory comparison of the dielectric strength of flat plate contacts (slightly inhomogeneous field) in different arc-quenching media. The characteristic for vacuum has the steepest front: with a contact gap of only a few millimeters, a very high voltage impulse strength is achieved. Then the curve flattens, that means that from a specified value on, a larger contact stroke scarcely increases the dielectric strength. Vacuum circuit breakers for rated voltages from 7.2 kV up to 36 kV have contact gaps between 5 mm and 25 mm.

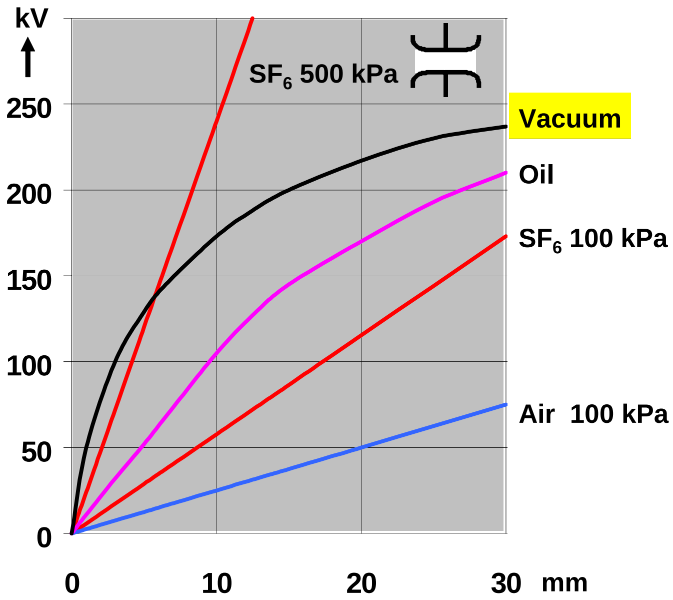

Figure C-7: Discharge voltages as a function of the contact stroke in different media

When interrupting normal currents and short-circuit currents with momentary values below 10 kA, the current flows through a diffuse arc. When breaking currents of more than 10 kA, the arc contracts, compressed by its own magnetic field. If not prevented this would excessively heat the contacts at the arc roots. In order to prevent such local overheating of the contact surfaces, the arc is either forced to rotate, or kept as a diffuse arc even above 10 kA. This can be achieved, for example, by special contact geometries: radial magnetic field contacts and axial magnetic field contacts (Figure C-8).

The radial magnetic field contact prevents local overheating of the contacts by forcing the arc to rotate.

Two inversely slotted contact carriers form a loop-shaped current circuit, thus generating a supplementary radial magnetic field. Together with the current flowing through the arc, a force is developed which makes the arc rotate on the arcing rings of the contacts. Thus, erosion at the arc roots is distributed over the whole ring surface.

If the instantaneous value in the course of a current half-wave drops below 10 kA, the arc becomes diffuse again, i.e. it flows again through many parallel single arcs (when breaking currents <10 kA, the arc generally remains diffuse). A current of approx. 100 A flows through each partial arc. When the current diminishes within a half-wave, increasingly more partial arcs are extinguished, until there is only one single arc left.

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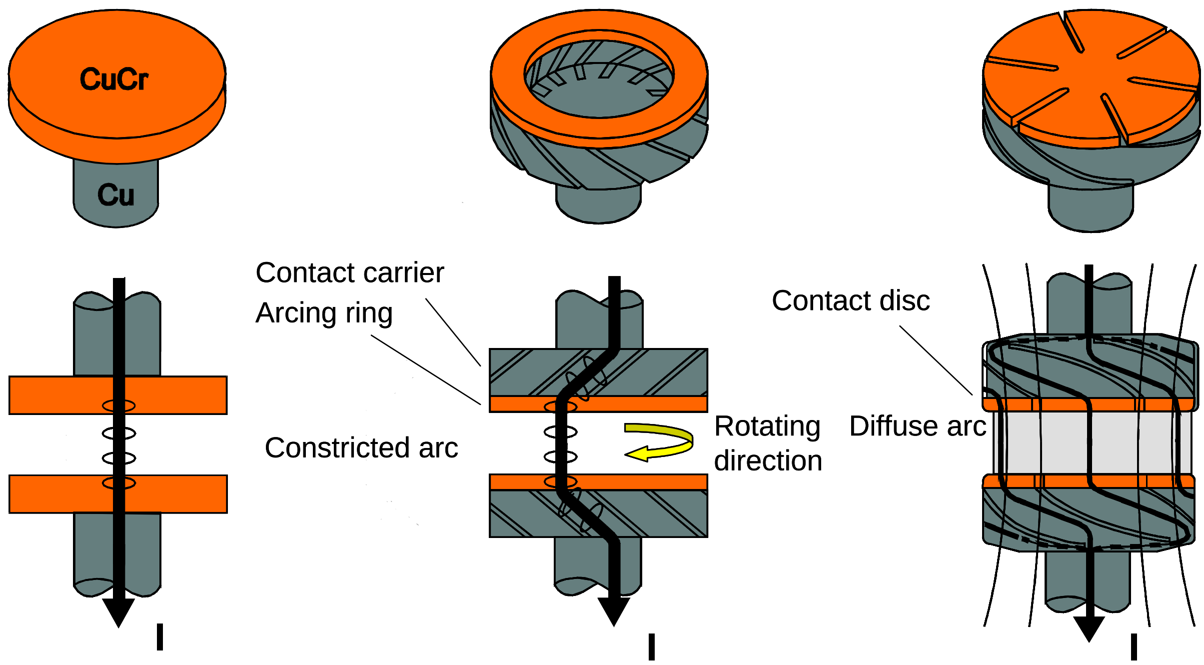

Flat contact **Radial magnetic field contakt** **Axial magnetic field contakt**

Figure C-8: Contact types for vaccum circuit-breakers

To handle the largest short-circuit currents met in practice, another method is used. Two equally slotted contact carriers form a coil-shaped current circuit. This generates a supplementary axial magnetic field, which keeps the arc diffuse even in the case of very large currents. The arc is distributed regularly over the whole contact area, so that there are no undue local stresses.

The energy produced during arc-quenching is low. The reasons for this are the short arc duration, the small contact gap, and the fact that the arc is not cooled. This results in a long electrical service life of the contacts, far beyond that which is attained by any other arc-quenching principle. This is the main reason, why today the V-breaker is the circuit-breaker with the minimum maintenance requirements, with long maintenance intervals and little maintenance costs.

As the dielectric strength of the contact gap is restored very quickly, the V-breakers interrupt capacitive currents without restrikes (see Figure B-11). The fast recovery of the dielectric strength of the contact gap is not achieved by a strong flow of the arc-quenching medium, but by the contact properties. So, in contrast to conventional breakers, higher overvoltages are not an inevitable consequence when switching inductive currents. In V-breakers, the magnitude of the chopping current depends on the contact material. Today, modern V-breakers have such small chopping currents, that no unduly high overvoltages arise, even when switching unloaded transformers (see also Figure B-2).

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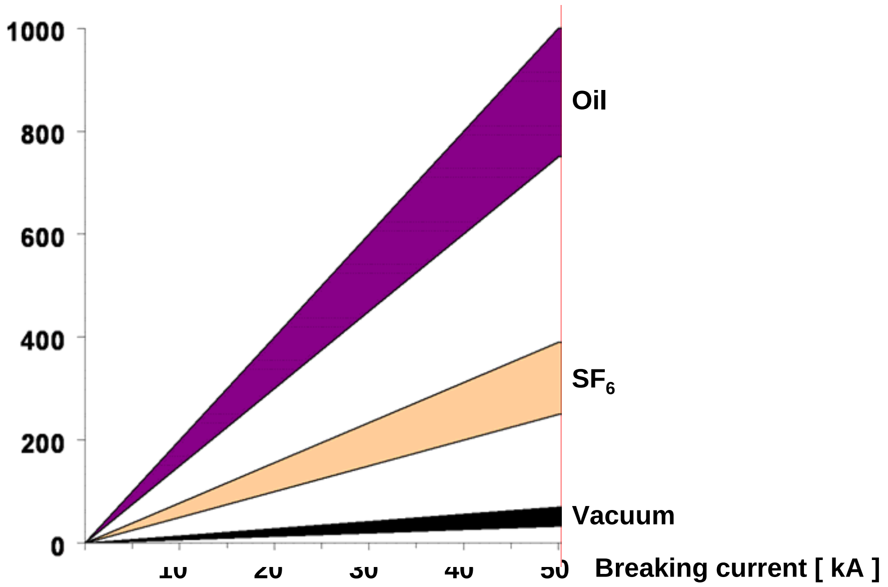

Figure C-9: Arc energy in different quenching media in the comparison

However, in some special switching duties and due to their good arc-quenching capability, vacuum circuit-breakers tend to generate overvoltages as a consequence of multiple reignitions (see Figure B-3 to Figure B-6 with the corresponding text), but these overvoltages can be controlled without any problems with suitable protective elements (e.g. surge limiters).

As modern vacuum circuit-breakers present the best balanced arc- quenching capability regarding the sum of all switching duties to be controlled, they have become the most frequently installed breakers. Today, their share of the world-wide market is far more than 50 %.

C 2 Switches and Switch-Disconnectors

Switches are used for opening and closing electrical circuits carrying any current up to their rated operating current. Since, when closing a circuit, making onto an existing short-circuit cannot be excluded, switches and switch-disconnectors generally have fault closing capability nowadays. If a switch has the required safety insulation levels across the open gap and to earth, it becomes a switch disconnector.

In combination with fuses, the combination can also be used for breaking short-circuit currents. The short-circuit is interrupted by the fuses. Afterwards, striker pins in the fuses trip the switch in all three poles, thus separating the faulty circuit from the system.

According to the standards, switches and switch-disconnectors are divided into definite-purpose and general-purpose switches. Definite-purpose switches are used for special applications, e.g. as capacitor switches. Tables A2 and A3 show which switching duties can be controlled by these devices.

At present, the following arc-quenching principles are used at medium voltage levels:

- Hard-gas
- Air (switches)
- SF_6
- Vacuum

For general switchgear construction, practically only the first two arc-quenching principles are used. SF_6 and vacuum switches are mostly used in switchgear that is especially designed for these devices.

C 2.1 Gas evolving switch ("hard-gas switch")

In the hard-gas switch, the arc develops gas from an insulating material which surrounds the arcing contacts. The arc-quenching effect corresponds approximately to that of bulk-oil breakers, where gas (hydrogen) is developed from the oil.

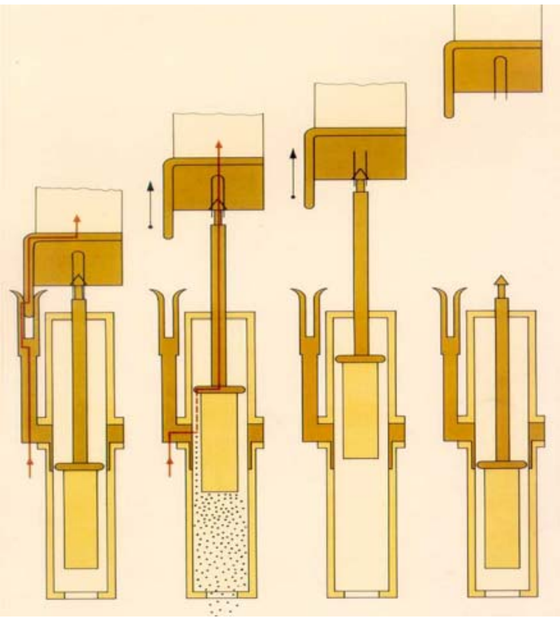

Figure C-10 shows a diagram of the breaking operation with main and quenching contact (Siemens Type 3CF).

As the material for the gas cannot renew itself as the oil can (by circulation and replacement) the service life is not long. These switches or switch-disconnectors are therefore only used for low switching rates, e.g. in distribution substations. In spite of this, hard-gas switches or switch-disconnectors are very popular because they have a good cost/performance ratio.

Figure C-10: Arc quenching with hard-gas

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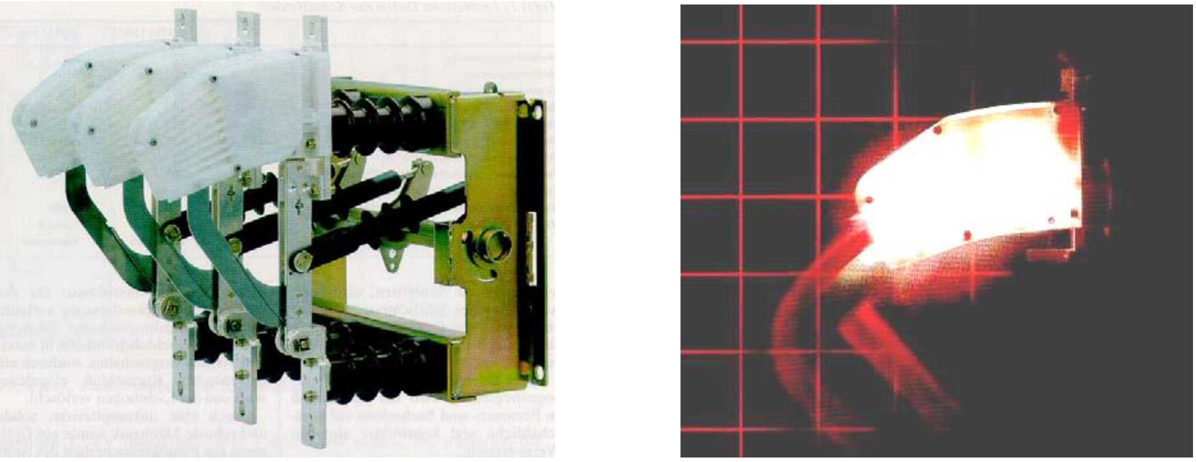

Figure C-11: Typical switch with enclosed arcing chamber (Driescher Type LDTM)

C 2.2 Air-break switch (compression switch)

In air-break switches, the arc is extinguished by air flow initiated by the operating mechanism of the switch during the breaking movement. The air flow is specifically directed to give fast de-ionization of the gap. These switches are especially suitable for switching capacitive currents and for switching under earth fault conditions in unearthed networks. In both of these switching duties, a high recovery voltage appears after interruption of the current, but the gap can withstand it very well due to the fast recovery of dielectric strength.

C 2.3 SF_6 switch

The main properties of SF_6 as a quenching gas can be found in the circuit-breaker section.

In SF_6 switches, the flow of the arc-quenching medium is generally initiated by the operating mechanism. As switches only have to break operating currents, this flow can be comparatively low. When switching small inductive currents the risk of extreme switching overvoltages by current chopping is also low.

The electrical service life and the switching capacity of SF_6 switches are larger than those of the devices described in B 2.1 and B 2.2. This is one of the advantages that justify their higher cost. Other advantages are:

- as SF_6 switches require a closed gas circuit, the switching element can also be installed in a hermetically closed housing filled with SF_6, which makes the whole switchgear unit independent of its environment
- in addition to making and breaking a circuit, the switching elements can perform other functions, such as safe earthing.

C 2.4 Vacuum switch

Vacuum switches offer all the advantages of the vacuum switching principle

- low or zero maintenance vacuum tube
- long service life
- suitable for all duties required of a switch, without restriction.

The use of vacuum switches in a line-up combination with vacuum circuit-breakers allows consistant use of all the advantages mentioned. Vacuum switches have extremly long contact and mechanical life. So it is possible, for example, to switch off unloaded transformers in industrial systems daily, thus minimizing no-load losses and reducing operational costs.

Short-circuit protection is provided by means of fuses, just as for other switches. As a switch-fuse combination, the vacuum switch can be used with all HRC fuses, up to the highest available current ratings.

C 3 Disconnectors, earthing switches and three-position disconnectors

C 3.1 Disconnectors

Disconnectors (isolators) are used to make a safe gap in an electrical system. They are intended to be operated off load but they may switch negligible currents (these are currents up to 500 mA, e.g. capacitive currents of busbars or voltage transformers) or larger currents, when no significant voltage appears between the terminals when switching off, for example during busbar transfer in a duplicate-busbar switchgear when a bus coupler is closed.

Since the duty of disconnectors is to provide an isolating gap, in order to enable safe working on other equipment isolated by these devices, the voltage withstand of the gap is about 15% higher than that to earth, and moreover the isolating distance has also to meet high requirements regarding reliability and recognizability.

Leakage currents

For reasons of safety, disconnectors shall be designed in such a way that no dangerous leakage currents can pass from the terminals of one side to any of the terminals of the other side of the disconnector. This means that the isolating distance may not be bridged by insulating material unless the insulation is effectively protected against pollution in service, for example by hermetic encapsulation as it is used for gas-insulated switchgear. Sometimes an insulant brace cannot be avoided over the isolating distance, for example because of the mechanical stability of the switch. An earth connection then must reliably lead possible leakage currents to the earth in the middle

Indication of the position: for safety reasons the position of a disconnector must always be reliably recognizable; this essential requirement is met either if

- ***the isolating distance is visible***, or
- a ***reliable position indicating device*** is used.

The kinematic chain between the movable contacts and the position indicating device shall be designed with sufficient mechanical strength. The kinematic chain shall be a continuous mechanical

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connection to ensure a positively driven operation. Springs or torque limiters must not be part of the position indicating kinematic chain.

With regard to types of construction there are, in Germany at least, few differences between the manufacturers. In general, they all manufacture knife type disconnectors. In some countries there are other types, e.g. rotary disconnectors in Italy, (also called bushing disconnectors). They have two partial isolating distances and can be installed in the wall between 2 compartments, thus providing the function of bushings as well as the isolating function.

Disconnectors are not required if the isolating distance is provided in another way, such as in the case of truck-type switchgear or withdrawable switchgear.

C 3.2 Earthing switches

Earthing switches are used for earthing and short-circuiting specific parts of switchgear units, cables or lines. They enable safe working on isolated equipment.

In principle, earthing switches are three-pole disconnectors with one side short circuited and earthed. They must be designed to withstand the maximum short-circuit current which is possible at their location. That means, just as all other devices, that they must be designed dynamically for the peak short-circuit current I_p and thermally for the symmetrical short time current (I_k" and I_k according to Figure B-14 and Figure B-15). They must withstand the sustained current I_k until an upstream circuit-breaker (or fuse) clears the circuit if the circuit is energised accidentally.

If make-proof earthing switches are installed, earthing and short-circuiting is safe even if, by mistake, the circuit was not previously isolated.

In this case, the make-proof earthing switch must make onto a live circuit, and it must be able to withstand the peak short-circuit current as a making current and the symmetrical short-circuit current (I_k" and I_k), until the short-circuit is disconnected as described above.

Make-proof earthing switches are constructed like knife disconnectors. Both types are often attached to disconnectors, switches or switch-disconnectors, but they can also be supplied as single devices or integrated into switchgear.

Earthing switches are usually interlocked with the corresponding disconnectors, switch-disconnectors or with the movement of the circuit-breaker truck or the withdrawable circuit-breaker, in order to prevent earthing of live circuits as far as possible. When using make-proof earthing switches, this interlocking may be omitted.

C 3.3 Three-position disconnectors

Three-position disconnectors combine the functions of disconnecting and earthing in one device. As the name implies, there are three possible positions, whereby the device energizes the feeder, disconnects or earths it, and short-circuits it. In circuit-breaker panels the the three-position disconnector usually combines a plain earthing switch without short-circuit making capacity (on left in Figure C-12); it just prepares the feeder for earthing, whereas the circuit-breaker subsequently performs the actual earthing and short-circuiting. In contrast, in load-interrupter switch panels the three-position disconnector is usually designed as as a make-proof earthing switch with short-circuit breaking capacity.

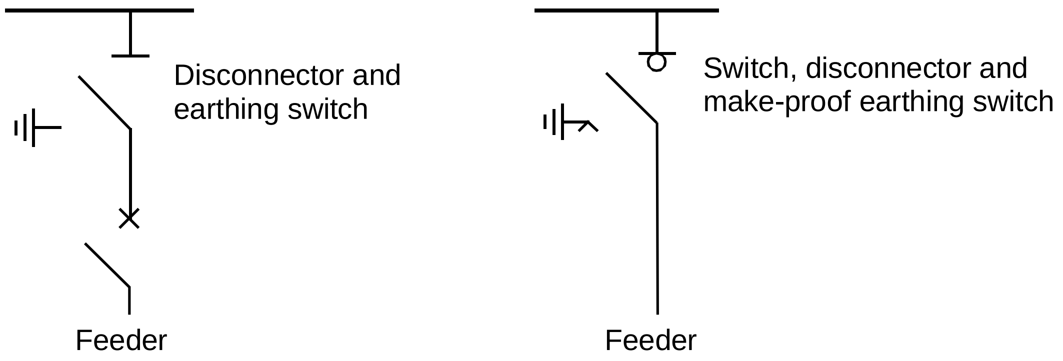

Figure C-12: Pattern of three-position disconnector or switch

Three-position disconnectors are typical of gas-insulated switchgear, because the good insulating characteristics of the SF_6 allow a compact design with short rotary movements (contact travel). SF_6 can also be used as quenching medium for three-position disconnectors.

See also E 8.2 on the use of three-position disconnectors in gas-insulated switchgear.

C 4 Contactors

Contactors are electro-magnetically operated switching devices. They are used for frequent operational switching of consumers, such as motors, transformers and capacitors. They may also have a limited short-circuit switching capacity, but this is generally not enough for the short-circuit stresses appearing at their location. Other devices with a short-circuit switching capacity must be connected in series. Normally, these devices are fuses, but circuit-breakers, particularly moulded case type may also be used.

Contactors have a long electrical and mechanical service life: Magnitudes longer than that of switches. Contactors are mainly used where a high switching rate is required.

The following contactor types are to be considered:

- Air-break
- Vacuum
- SF_6

C 4.1 Air-break contactor

Air-break contactors are switching devices that work in similar fashion to air-magnetic circuit-breakers (see also chap. C 1.6 Air-magnetic circuit-breakers). As air-break contactors are very large and expensive in comparison with modern contactors, they have no significance anymore.

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C 4.2 Vacuum contactor

Vacuum contactors operate with to the same arc-quenching principle as vacuum circuit-breakers (see chap. C 1.8 Circuit-breakers). The electrical and mechanical service life of vacuum contactors is much longer than that of vacuum circuit-breakers.

As the switching forces are low in comparison with those for circuit-breakers (contactors switch normal currents and only onto very low short-circuit currents), contactors have relatively simple solenoid operating mechanisms (Figure C-13). The difference in the interrupter is largely the longer bellows (dimensioned for a higher number of operating cycles). Modern vacuum contactors can for example switch their rated normal current 1 million times. For this reason and for those described under “Circuit-breaker”, the vacuum contactor represents nowadays the most common quenching method worldwide.

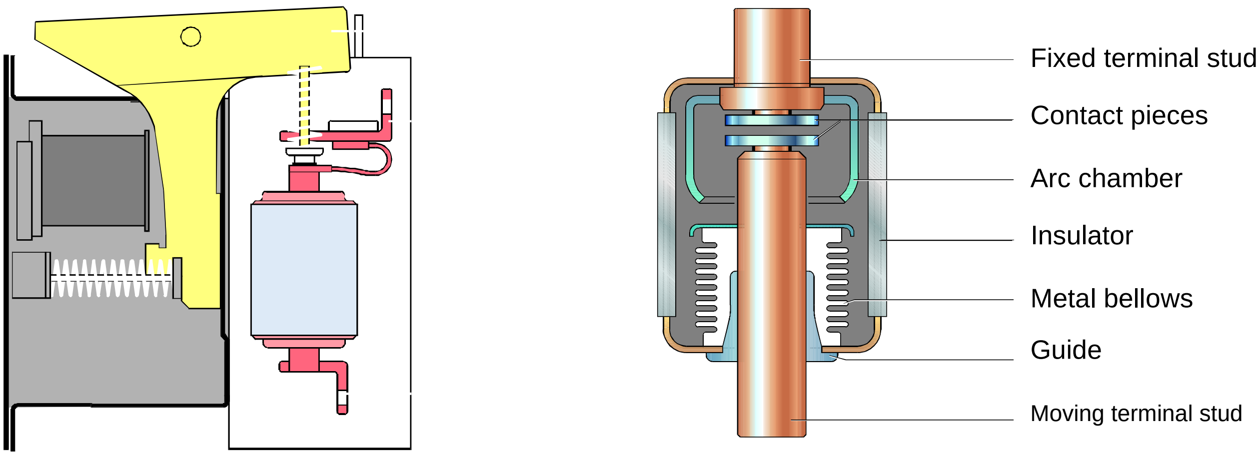

Figure C-13: Principle of a vacuum contactor and an interrupter

C 4.3 SF_6- contactor

SF_6 contactors operate with a self-generated arc-quenching effect, the same as the SF_6 circuit-breakers described in the chapter C 1.7 "Circuit-breakers" (rotating arc). When compared with vacuum contactors, they have advantages when switching inductive currents, but disadvantages regarding capacitive switching. The fundamental difference with SF_6 contactors lies, however in operational factors. The electrical and mechanical life is significantly less than that of vacuum contactors. Furthermore, their construction is more complex and the number of components larger than that of modern vacuum contactors, leading to a higher failure rate possibility.

C 5 Fuses

Fuses consist of the fuse-base and the fuse-link. When the fuse- link is pulled, the fuse-base provides an isolating distance corresponding to disconnector requirements.

Fuse-links are used for breaking overcurrents once-only; afterwards they must be replaced.

Fuses can be designed as switch fuses and as current-limiting fuses. The current-limiting fuses can be divided into back-up fuses and general-purpose fuses.

C 5.1 Gas filled fuse

These fuses are similar to the switching devices described above (circuit-breakers, switches) regarding the arc-quenching principle. They are current zero interrupters, i.e. they make use of the natural current zero in order to break the current. An advantage is that they can break any current that operates them. Gas filled fuses are designed for example as vacuum fuses. The tube structure is similar to the vacuum interrupter. The difference is that the vacuum fuse has two fixed-mounted contacts which are linked by a fusible wire. When a specific overload or short-circuit current is exceeded, the fusible conductor melts, the current flows through an arc until the next current zero and is interrupted in the same way as in the vacuum circuit-breaker. Due to their expensive construction, similar to the vacuum interrupters, such fuses are very costly. Moreover, they are not current limiting, as the current always flows at least until the next current zero, as described above.

C 5.2 Current-limiting fuse

The standard IEC 60282 / VDE 0670-4 distinguishes between the following types of current limiting fuse.

- **General-purpose fuse**
  is capable of breaking, under specified conditions of use and behaviour, all currents from the rated maximum breaking current down to the current that causes melting of the fuse element in 1 h or more. This type is not described in greater detail here.

- **Back-up fuse**
  is capable of breaking, under specified conditions of use and behaviour, all currents from the rated maximum breaking current down to the rated minimum breaking current.

- **Full-range fuse**
  is capable of breaking, under specified conditions of use and behaviour, all currents that cause melting of the fuse element(s), up to its rated maximum breaking current.

The basic function of current-limiting fuses is explained with reference to the back-up fuse (most widespread in operation).

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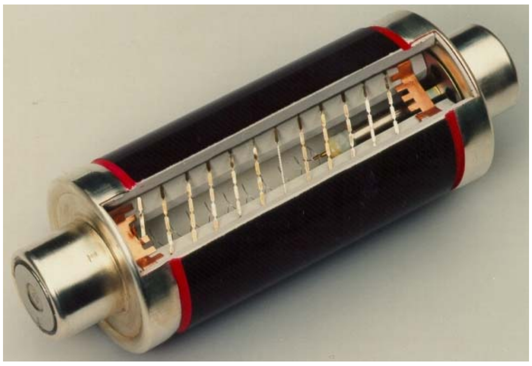

The ceramic body is filled with silica sand as quenching medium. The fusible elements – depending on their rated current, there can be nmore than one connected in parallel – are wound around a ceramic star. The striker with auxiliary fusible element can be seen in the longitudinal axis.

Figure C-14: Sectional view of an HRC fuse

When a short circuit flows through the fuse, the main elements fuse and evaporate at defined points as the current rises. Arcs occur at these confined points; these arcs are cooled so much by the sintering and melting of the quenching medium (silica sand) that the total of their voltages attains the level of the operating voltage. The series connection of a number of arcs produces – owing to the anode and cathode fall of each partial arc – a higher voltage than a single arc, which would be scarcely controllable. Depending on the magnitude of the current to be broken, a minimum number of arcs must burn simultaneously. The auxiliary fusible element is connected in parallel with the main elements; it releases the striker when it (the auxiliary element) melts. The auxiliary element (> 150 Ω) is very thin and of high resistance in comparison to the main fusible element (in the order of a few tens of mΩ). It (the auxiliary element) burns right through and does not contribute to quenching the current.

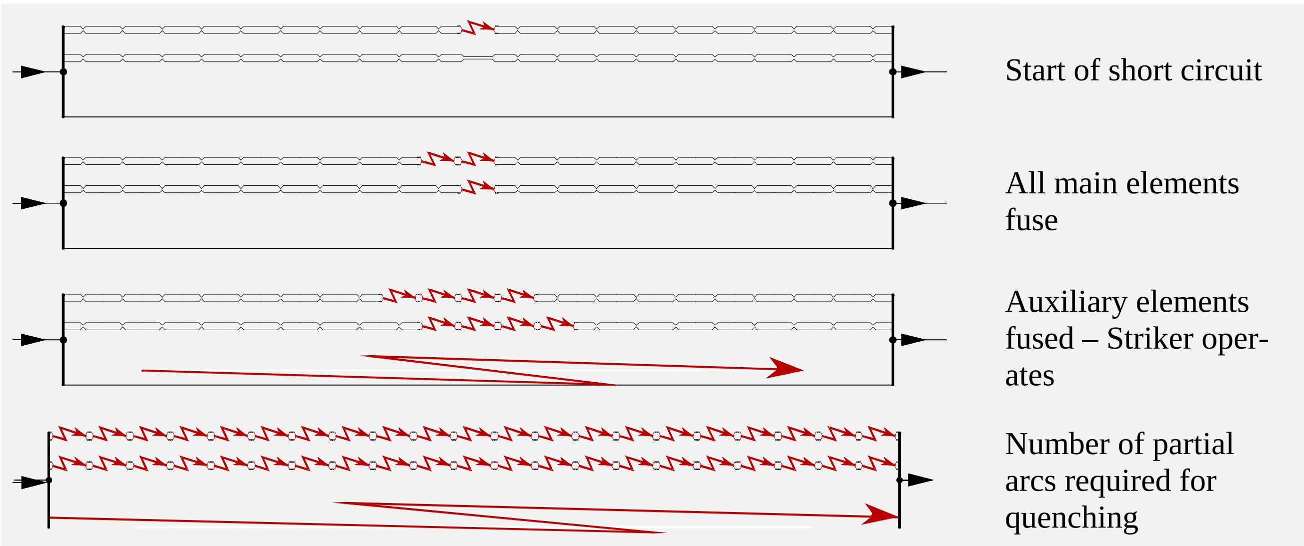

Figure C-15: Phases of breaking

The advantage of this fuse is that in the case of large short-circuit currents, the current is already interrupted as it rises and the peak value of the prospective maximum is not reached at all (Figure C-16). In this way, the connected equipment is protected against high dynamic and thermal effects, and does not have to be dimensioned for the full short-circuit current that can appear in front of the fuse. Cut-off characteristics show the maximum cut-off current I_D as a function of the initial symmetrical short-circuit current and the rated fuse current (Figure C-17).

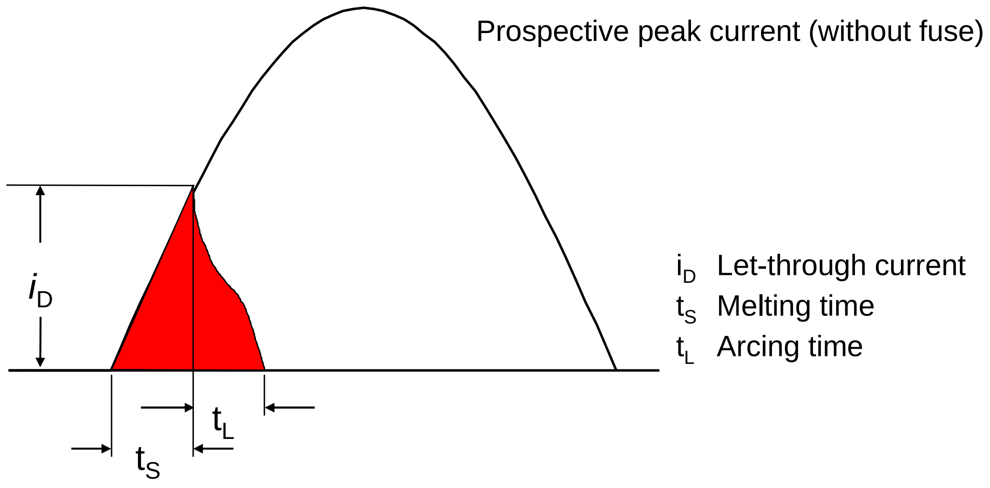

Figure C-16: Breaking operation of an HRC fuse

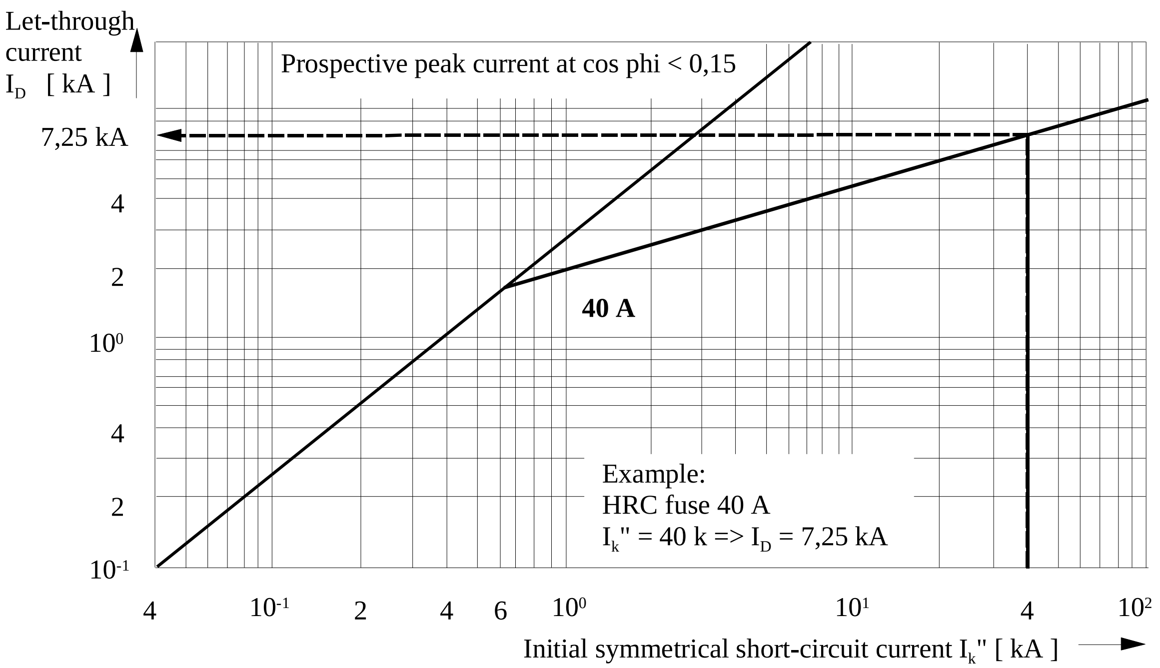

Figure C-17: Cut-off characteristic of an HRC fuse

The current/time characteristic of an HRC fuse gives the pre-arcing time as a function of the 3-phase steady state short circuit current (Figure C-18). The characteristic has a current tolerance. For a specific pre-arcing time, the current may, therefore, deviate from the average value.

The time tolerance in contrast is not firmly defined but depends on the value of the current itself. At a specific current I_x, the pre-arcing time lies between T_{min} and T_{max}, dependant upon where the particular fuse lies in the tolerance band.

In 3-phase circuits with 3 fuses, the fuse with the lowest current/time characteristic will operate first; the two others later. The larger the current, the smaller the time difference between the upper and lower tolerance limits. For currents of kA magnitude, all three fuses operate practically simultaneously.

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Mostly, fuses are combined with load breaking devices (switches or contactors). The current time characteristic is then essential to ensure co-ordination between the fuse and the associated switching device. The first fuse to operate trips the switch with its striker pin (a mechanical component of the fuse, designed to release another device). Whether the current in the other two phases is broken by the fuse or the switch is determined by the time difference between operation of the first and last fuse and the inherent opening time of the switching device. When the opening time is smaller - the switch is faster - it interrupts the current in the other two phases; otherwise the fuses interrupt first. Therefore the HRC fuse must be coordinated with the switching capacity of the switching device. Factors to be considered are standardised in IEC 62271-105 / VDE 0671-105.

Moreover, the characteristics are required for protective grading (selectivity) in combination with low-voltage circuit-breakers and low-voltage fuses for transformers.

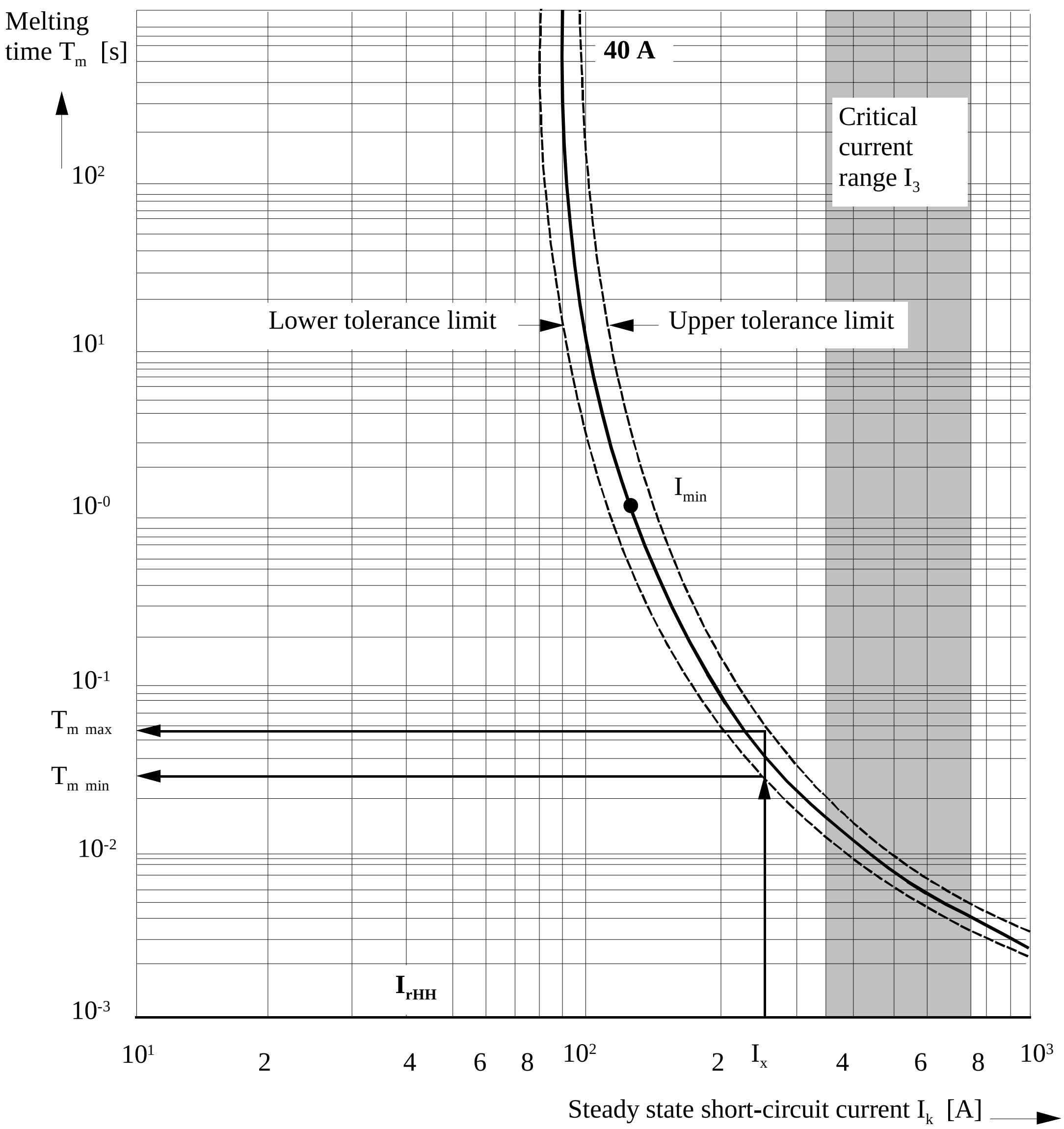

Figure C-18: Current/time characteristic of an HRC fuse

The shaded "critical current range" is the working range of the fuse in which the effort is maximum. At critical current levels, the maximum energy (I^2t) conversion occurs. The fuse must safely interrupt this current and the body of the fuse must remain intact. The critical current lies in the range between 10-times and 20-times fuse rated current.

C 5.3 Back-up fuse

Back-up fuses are current-limiting fuses, which may only be provided for breaking short-circuits. They must not operate in a range between rated current and approx. 3 times rated current (this is the minimum breaking current I_{min} in Figure C-18.

This forbidden range can be sub-divided: up to twice the rated current $I_{rHH} < I < 2 \cdot I_{rHH}$ will cause thermal overload. The fuse becomes too hot and endangers its surroundings. The fusible element does not yet operate! If the fuse has a thermal striker pin ("thermal protection"), the associated switch clears the overload. Thermal striker pin release means that, at excessive temperature, a striker pin is released mechanically; e.g. by melting of a plastic retainer.

Over approx. $2 \cdot I_{rHH}$ the element operates but the fuse cannot clear. Again, the switch must clear the overload; initiated by the striker pin. Operation means: each of the parallel elements in the fuse are galvanically broken at at least one point so that each current has commutated to the neighbour and broken that too.

If currents can occur in the forbidden range, they must be broken by other switching devices, e.g. switches or contactors. Despite this limitation, back-up fuses are those most frequently used, for reasons of cost.

See also C 6.1 for a more detailed explanation of the electrical behavior.

C 5.4 Full-range fuse

Full-range fuses are current-limiting fuses that can interrupt any current that makes them melt. They have no minimum breaking current as the back-up fuses have. Essentially, the full range is covered by superposing a number of time/current characteristics, as shown in Figure C-19.

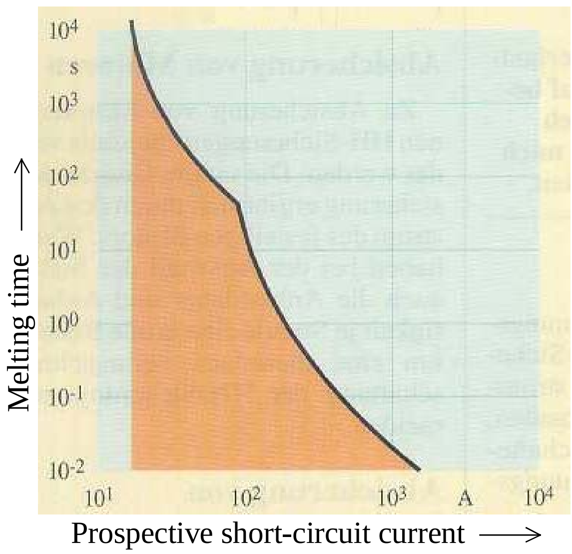

Figure C-19: Current/time characteristic of a full-range fuse

Source: Driescher Wegberg

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Creating a multi-range characteristic was previously no easy matter; for example, various fusible element metals were soldered together. Such designs were subject to aging, fault-prone, expensive and consequently not widespread. Modern designs without these disadvantages have been available for some time. When breaking sizable currents, this fuse works in the same way as the back-up fuse described above.

At low current levels, the fusible element is mechanically forced to break at a suitable number of points. This ensures that there are always enough partial arcs for quenching. Thanks to the mechanical break, the fuse is not dependent (at low levels of current) on many of these confined points having to burn through “electrically”. The switching movement operates a rod that activates a gas generator (similar to the principle of an airbag).

Before tripping

After tripping

Source: Driescher Wegberg

Figure C-20: Full-range fuse before and after tripping

C 6 Switch-fuse combinations

Switch and fuse combinations are used mainly in secondary distribution substations and industrial networks where relatively small currents and switching frequencies occur. The switch switches the normal load current; it has only a specific and limited switching capability. Fault current interruption is the responsibility of the fuses. Between these two values there is an overload current range where the operation of the two devices overlaps. This overlap area will only function properly if the two devices are correctly matched.

The standard IEC 62271-105 / VDE 0671-105 regulates the co-ordination between switch and fuse so clearly, that no grey zones can occur in the over-current range. It applies to combinations of switches and switch-disconnectors and current limiting fuses. They must be able to interrupt:

- any load current up to the rated current of the switch;
- any over-current up to the rated short circuit current of the combination, with automatic release (operation of the striker pin).

The fuses have striker pins which will trip the switch if the fuse attempts to interrupt a current which is less than the minimum interrupting current of the fuse. The switch must be able to clear this current. On the other hand, a correctly chosen fuse protects the switch against currents which it cannot clear. Furthermore, the combination can be fitted with overcurrent or shunt release.

C 6.1 The responsibilities within the combination

At first sight, the responsibilities of the components in a switch-fuse combination are quite clear. The switch switches normal load currents and the fuses take care of short circuit currents. Between normal load and short circuit currents the components share the duty. In all, the combination must safely control any current up to full short circuit.

Note: In the following, only partial range fuses (back-up fuses) are considered.

Figure C-21 shows the division of function between the components, dependant upon current. The current ranges are given as multiples of rated current of the HRC fuse (I_{rHRC}), whereby the given factors are average values.

C 6.1 a Rated current of the combination I_{rK}

This is generally less than the fuse rated current. Because of the thermal conditions at the fuse location (in a cubicle or compartment), heat dissipation is limited in comparison to a fuse in the open. Thus the combination cannot be loaded with the normal rated fuse current.

Up to the value I_{rK} only the switch operates.

C 6.1 b Overload range ($I_{rHH} < I < 3 \cdot I_{rHH}$)

Above its rated current, the fuse is overloaded thermally. Until it reaches the characteristic curve (at roughly $2 \cdot I_{rHH}$) the fuse exhibits no defined behavior. The term “forbidden region” is even used. There is a risk of the ceramic body rupturing and the fuse losing its breaking capacity. To avoid this, some manufacturers offer the option of “thermoprotection” or a “thermostriker”, meaning that the striker pin operates at a defined excess temperature and the load interrupter switch then breaks the circuit.

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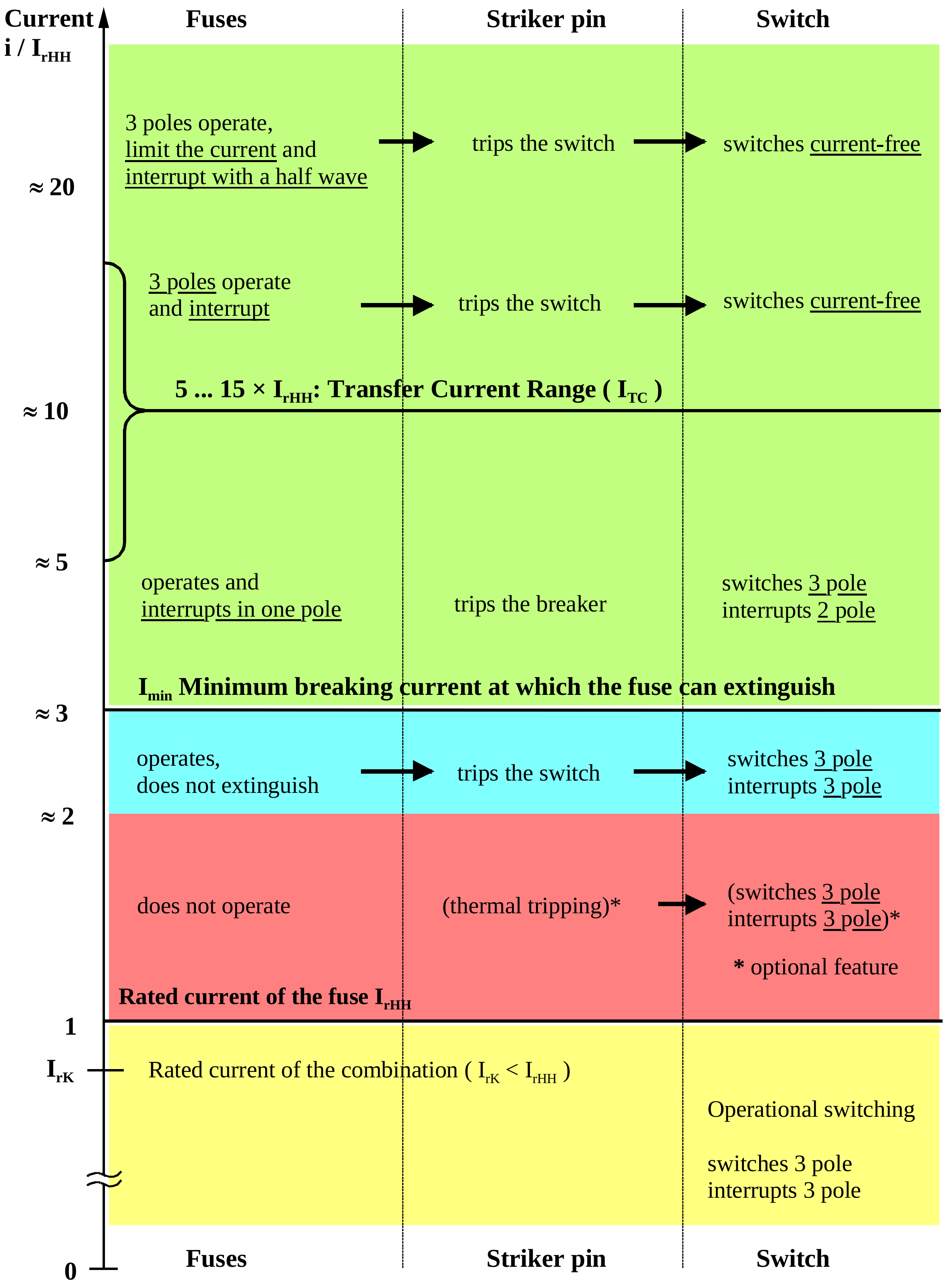

Figure C-21: Interaction between switch and fuses in combination

Over approximately $2 \cdot I_{rHH}$ the elements start to melt but the fuse cannot clear the arc. The striker pin is released and the switch must clear the overcurrent.

"Starts to melt" means: all the main elements (parallel paths) within the fuse become galvanically broken at least one point; the current commutates to the neighbouring element and breaks that too.

C 6.1 c Minimum breaking current $I_3 = I_{min}$

At currents larger than approximately three times rated current, the fuse is also able to clear the fault after release of the striker pin. Above Imin the fuse definitely operates. In a three phase circuit, one of the three fuses will be the first to react, to release its striker pin and clear. The switch clears the fault current in the other two phases; both of the other two fuses may have reacted but the switch will be faster and clears the current first.

Which fuse, in which phase, operates first, depends on the

- type of fault (earth fault, two pole or three pole fault)
- magnitude of the current
- tolerance of the fuse characteristics

C 6.1 d Range of the transfer current (I_{TC})

This extremely important current range is clearly defined in the standard; because incorrect selection of the fuse could lead to the switching capacity of the switch being exceeded.

With increasing fault current, the time difference between operation of the three fuses decreases. Up to the value of the transfer current, the fuse in only one pole operates, the switch clears the other two poles. All currents greater than I_{TC} are cleared by the fuses, the switch operates off load.

The transfer current is the largest current which the switch - at the occurring power factor - must be able to interrupt. It lies between five times (small fuses) and 15 times (large fuses) the rated current of the HRC fuse.

C 6.1 e Current limiting range

With large fault currents, above some 20 times fuse rated current, the fuse operates within the first half loop of fault current and limits the peak current to the value of its let-through current (cut-off current) I_{co}. The current is already cleared after the half loop.

C 6.2 The transfer current

C 6.2 a Definition

Transfer current is the value of the three-phase symmetrical current at which the switch and the fuse exchange switching duty. Immediately below this value, the first pole will be interrupted by one pole of the fuse and the other two by the switch. Immediately above the value, the current is interrupted only by the three fuses.

The transfer current is also the largest current which a series switch must be able to handle. It is given by the opening time of the switch and the tolerance of the current-time characteristic of the fuse. Whereby one must differentiate between:

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- Rated transfer current I_4, which is the maximum interrupting capability of the switch (rated value and maximum value for the combination); that is, this value gives the largest fuse which can be used in the combination
- Transfer current I_{TC}, which is that which relates to the fuse actually used in the combination.

C 6.2 b The maximum breaking current required

A switch can, by definition, interrupt currents in normal operation. Its interruption capability is very limited, especially for pure inductive or capacitive currents. Not every switch will handle the high transient voltages which occur under earth fault conditions. In practice, there are vast differences in capability, depending upon the principle of extinction. For short circuit conditions, the fuses are there. These current limiting part range fuses only interrupt in all three phases with high fault currents. In between, there is a range of overcurrents where the switch must interrupt two phases. The maximum value which the switch must interrupt is the transfer current, which is determined by the fuse.

The most unfavourable condition for the switch: The first fuse to melt operates the switch by its striker pin. In its characteristic time, the switch interrupts the other two phases. The highest switching capacity is demanded of the switch when the last two poles open just before the last two fuses melt. Under that condition, the switch must interrupt the largest possible current. This largest value is attained when

- the current tolerance between the fuses is at a maximum, that is, when one lies on the two on the upper tolerance line,
- the opening time of the switch is short (if it were long, the fuses would have time to melt and interrupt).

C 6.3 The procedure to determine the transfer current

One needs the following data to calculate the transfer current from Figure C-22 the:

- current / time curve of the HRC fuse
- opening time of the switch, T_0
  (for direct striker pin operation or via electrical trip)
- rated transfer current of the switch I_4 (manufacturer's data)

Striker pin initiated opening:

① Draw a line parallel to the current axis, through the point $0.9 \cdot T_0$ on the melting time axis. Continue with ③.

Release initiated opening (Striker pin activates auxiliary switch):

② Draw a line parallel to the current axis, through the point T0 on the melting time axis. If an external relay is in the relase circuit, draw the line through the point T0 + 0.02 s on the melting time axis (the delay of the relay is assumed to be 20 ms).

③ The intersection of this line with the lower time-current characteristic of the fuse gives the associated transfer current I_{TC} (three-phase, symmetrical value).

④ The transfer current thus determined shall not be larger than the rated transfer current I_4 stated by the manufacturer.

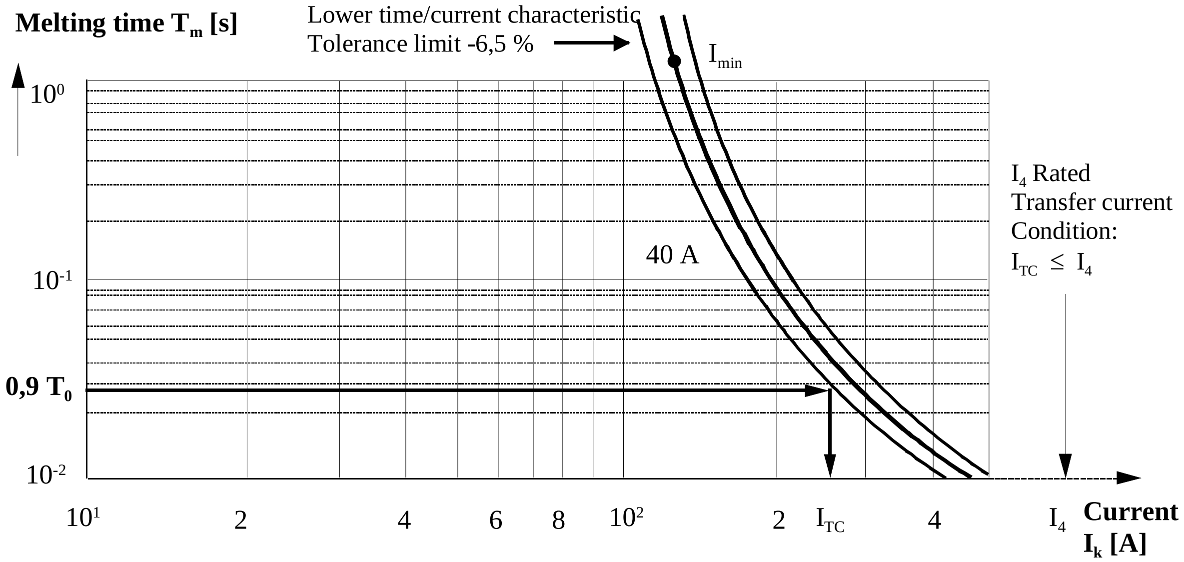

Figure C-22: Determination of the transfer current from a fuse characteristic

Example with a 40 A HRC fuse and an RMU unit type 8DJ10

- HRC fuse, type 3GA: I_{rHH} = 40 A
- Switch opening time: T_0 = 30 ms

=> Transfer current for this combination: I_{TC} = 250 A

The following paragraph describes the mathematical background for the striker pin initiated opening. Figure C-23 shows a section of a current/time characteristic, in the region of the transfer current. Over this small range the characteristic can be represented as straight lines.

In a three-phase circuit, the first fuse melts after time T_{ml} under conditions of symmetrical fault current I_{3pol}.

The second fuse melts after T_{m2} , under the residual fault current $0.87 \cdot I_{3pol}$. Time T_{m2} is smaller than the melt time for $0.87 \cdot I_{3pol}$ in accordance with the upper characteristic (P_x), because this fuse has already carried the larger current I_{3pol} for time T_{m1}.

The time-current characteristic is a measure for the melt-energy, from which the times T_{m1} and T_{m2} can be calculated. The mathematical procedure is described in appendix B of the standard.

Under the conditions assumed in IEC 62271-200, there is a fixed relationship between T_{m1} und T_{m2}

$$\Delta T = T_{m2} - T_{m1} = 1.1 \cdot T_{m1}$$

At the transfer point: $T_0 = \Delta T = 1.1 \cdot T_{m1}$. T_0 is the opening time of the switch.

From the melt time of the first fuse $T_{m1} = 0.9 \times T$ follows the associated transfer current in accordance with the time/current characteristic of the fuse (see also Figure C-22).

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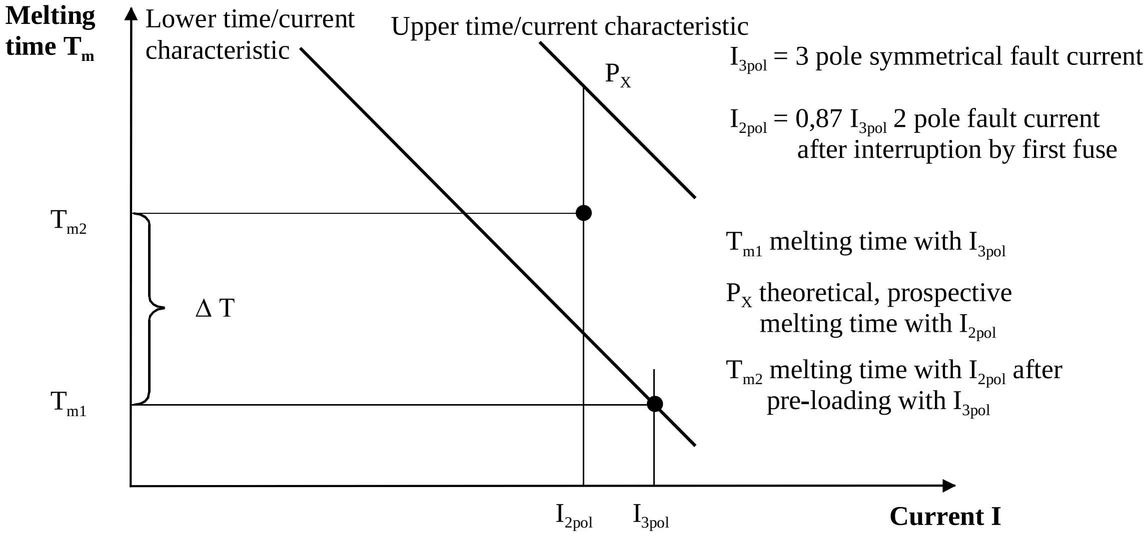

Figure C-23: Melting time of fuse in the region of the transfer current

C 7 Transformer protection in unit substations

This mainly concerns the unit substations of the utility companies. In industrial plants, the operating conditions are different; e.g. climatic stress, accessibility, substation building. Moreover, different switchgear types, devices and auxiliary equipment are used there. The large number of unit substations used by the utility companies requires economically acceptable equipment. This requirement is especially taken into consideration here; however, the technical aspects apply basically for all switchgear types.

In Germany, several 100,000 unit substations are in operation in the power distribution system. Short-circuit protection of the transformers in these substations has been cared for by HRC fuses for decades. In recent years, alternatives are increasingly being discussed in connection with SF_6-insulated ring-main units. There, the HRC fuse is the only device that is not integrated into the hermetically sealed housing. However, the location of the fuse must conform with the concept in order not to detract from the advantages of the gas-insulated technology; and this is a hard task. The alternatives for the short-circuit protection of distribution transformers are:

- HRC fuses
- IK-interrupters
- circuit-breakers

All three possibilities have their pros and cons. Technical and economical aspects must be evaluated; safety and reliability can stand against the demand for freedom from maintenance. The decision has to be taken by the user, as there is not only one correct solution. The comparison explains the features of the three protection concepts; possible transformer faults are described in advance.

C 7.1 Internal transformer faults

Most transformer faults begin as turn, winding or layer faults. They can develop over a long period of time. The fault currents can often lie in the range of the rated transformer current. Depending on the duration, the fault current

- can be self-extinguishing due to the arc-quenching effect of the oil
- develop to a three-phase short-circuit current (evolving fault).

Tests were carried out with 10 and 20 kV distribution transformers in order to examine fault development. The transformers had different built-in faults. Figure C-24 shows the fault currents and their duration as well as the tripping characteristics of the protection relay and the HRC fuse. Low-current faults are either not recognized at all (1) or only detected by the protection relay after some time (2), (3) and (4). Higher fault currents are cleared by the fuse and the protection relay (5), (7) before they evolve to a short-circuit. Case (6) is critical because the low-current fault is not cleared before it evolves to a short-circuit.

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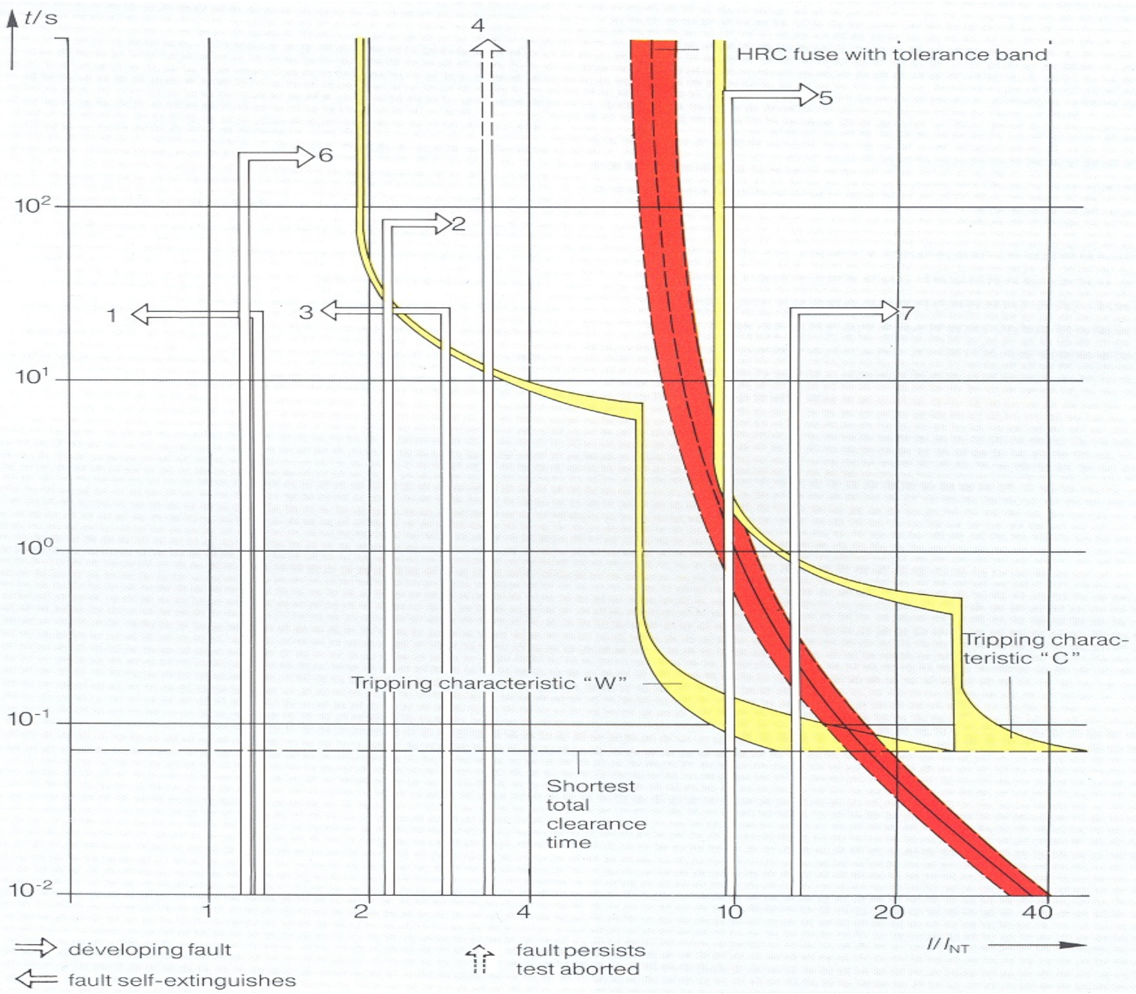

Figure C-24: Fault currents and tripping characteristics of the protection devices

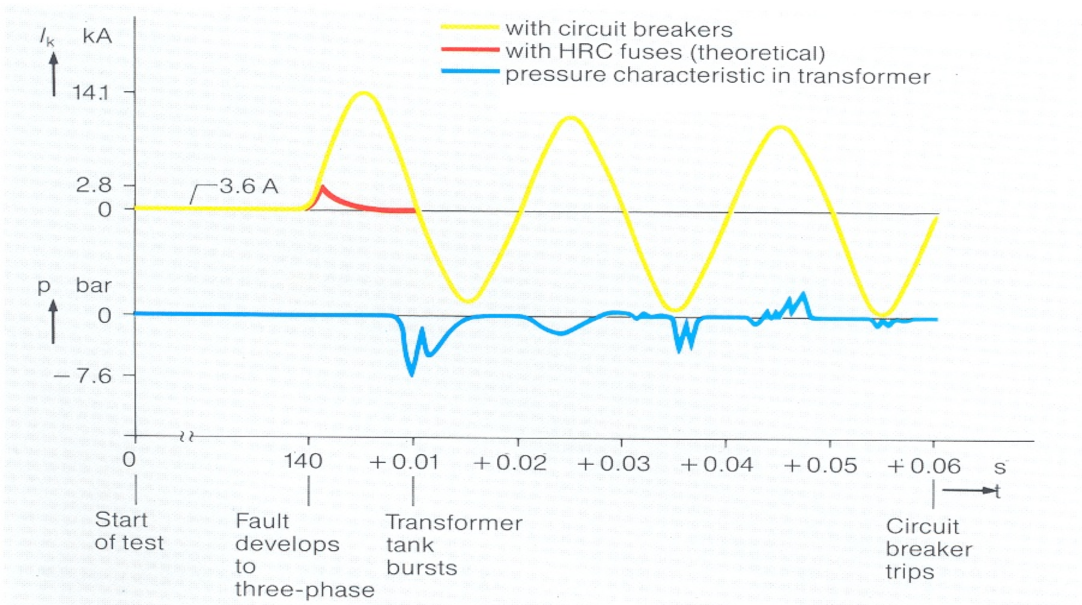

Figure C-25: Fault development in a distribution transformer

Figure C-25 shows the development of the short-circuit and the pressure in the transformer for this case. The 10 kA short-circuit (r.m.s. value) makes the tank burst after 10 ms. The circuit-breaker does not open until 60 ms after, due to the operating time of the protection relay and that of the breaker. Therefore it would not have been able to prevent the bursting of the tank. In contrast to this, a HRC fuse would have operated after 10 ms, and thus prevented the explosion of the transformer. The result shows that the options of transformer protection with a circuit-breaker or a HRC fuse must be carefully considered.

C 7.2 Protection by HRC fuses

For short-circuit protection, the HRC fuse offers

- a limitation of the peak short-circuit current
- an arc-quenching time of a half-wave, 10 ms

The very short pre-arcing time and the current-limiting features of the fuse reduce the mechanical and thermal stresses for the transformer considerably. These are the electrodynamic forces of the peak short-circuit current, as well as the pressure and temperature rise due to the arc. In the case of evolving faults, the fuse can therefore prevent the bursting of the transformer tank.

The limitation of the peak short-circuit current also reduces the stress for other connected equipment, such as the incoming cables.

Small fault currents ranging between the rated fuse current and the minimum breaking current are not cleared by the fuse; it is a back-up type fuse (see chapter C 5). It is only operated by a higher fault current.

When selecting HRC fuses, the switching capacity of the switch has to be observed. In the case of single-pole operation of the fuse, the switch-disconnector must break the fault current in two poles. Hereby the current must not exceed the breaking capacity of the switch. To avoid this, the selection criteria according to the IEC Publication 62271-105 for fuse-switch combinations must be observed.

Regarding its application in unit substations, the fuse requires

- no auxiliary equipment
- no maintenance

In contrast to protection relays, the HRC fuse itself does not need a power supply, which is normally not provided in unit substations anyway. The fuse itself is maintenance-free, but it needs care in its installation. It must be installed so that it is independent of the climate, in order to

- keep its insulating capacity intact
- prevent the flow of surface creepage currents.

Moreover, the location of the fuse must not lead to an undue temperature rise, as the consequence would be failure due to pre-ageing.

These are stringent requirements, but they are met by modern switchgear. Single-pole insulated fuse chambers which are sealed to all sides guarantee a climate-proof installation. In most of the cases, the fuse chamber is still included in the switchgear interlocks; it can only be replaced when the feeder is de-energized, and this excludes faults due to maloperation.

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C 7.3 Protection by IK-interrupter

The IK-interrupter is a special fuse installed in the transformer tank. It is also hermetically sealed and oil-insulated – and thus, climate-proof. Its function corresponds to that of a HRC fuse. The IK-interrupter is only available for transformers up to 630 kVA.

Its disadvantages are the inaccessibility of the elements and the installation in oil, as the need for replacement cannot be excluded, even without a transformer fault; e.g. after a short-circuit on the low-voltage side.

C 7.4 Protection by circuit-breaker

Circuit-breakers with a CT-operated protection relay open in the event of fault, according to the inverse-time or definite time characteristic of the protection relay. In comparison with the switch-fuse combination, this method has the following features

- the circuit-breaker controls all fault currents
- the protection relay can also detect smaller fault currents

The circuit-breaker is able to break all currents appearing at its location - in contrast to the switch, which can only perform this in combination with a fuse. The replacement of components (fuses) is also not required. CT-operated protection relays enable transformer protection without an additional auxiliary voltage. The critical range, in which fault current is not detected, is smaller than that of a fuse (tripping characteristic 1).

Only a range of very small fault currents is not detected by this combination.

Disadvantages when compared with HRC fuses:

- no current-limiting effect
- long breaking time

The grading time for evolving faults is critical. Based on the operating time of the protection relay and the operating time of the circuit-breaker, the switching operation is delayed 60 milliseconds at least, which has negative effects on the extent of the damage. The missing current-limiting effect increases the stresses for the equipment.

Additional expenses are required for

- the additional isolating distance for the circuit-breaker
- the maintenance of the breaker and the CT-operated relay
- climate-protected installation of the protective equipment

A circuit-breaker or a suitable switch always requires an additional disconnector or a mechanism to establish the isolating distance (e.g. three-position switch). Circuit-breakers and instrument transformers are not maintenance-free. Also regarding the resistance to extreme climates, they must meet the same requirements as the fuse-switch combinations.

The aforesaid applies to small transformers, usually in utility network unit substations. At higher transformer ratings – in industrial plant – (as from about 2 MVA, depending on the voltage level), adequate transformer protection is generally possible only with a circuit-breaker.

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C 8 Surge arresters

Surge arresters protect devices and switchgear units. They limit overvoltages by diverting them. Overvoltages appear either due to lightning strikes in overhead lines (external overvoltages), or as internal overvoltages in the form of switching overvoltages or earth faults. The usual types of surge arresters today are shown in the following figures.

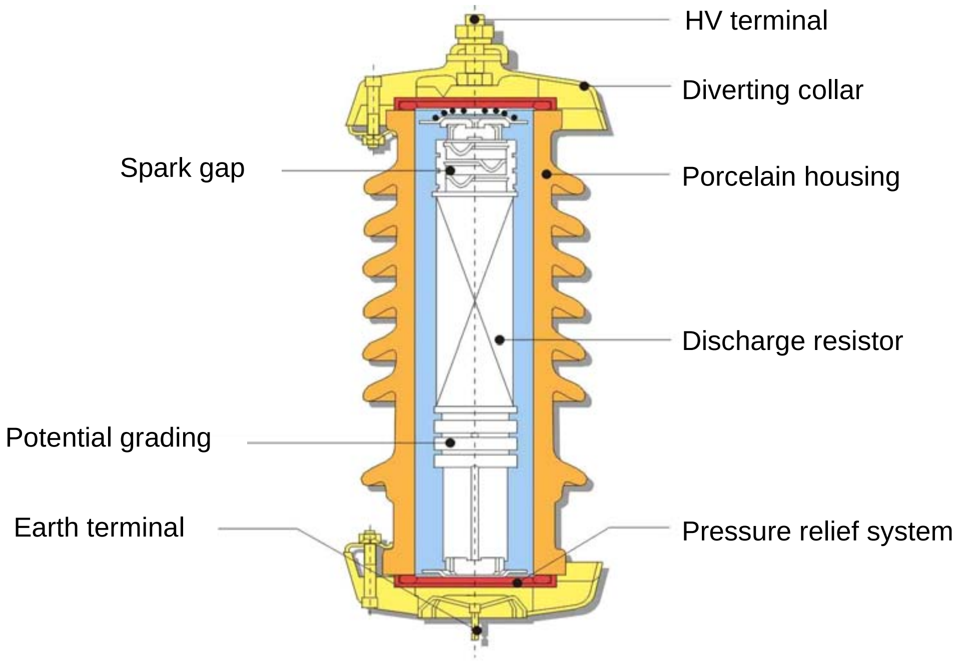

Figure C-26: Surge arrester (example Siemens 3EG type)

C 8.1 Spark-gap arresters

They consist of a non-linear, voltage-dependent resistor (varistor) with a series-connected spark gap. In most cases, the varistor is made of silicon-carbide (SiC), abbreviated as SiC-arrester.

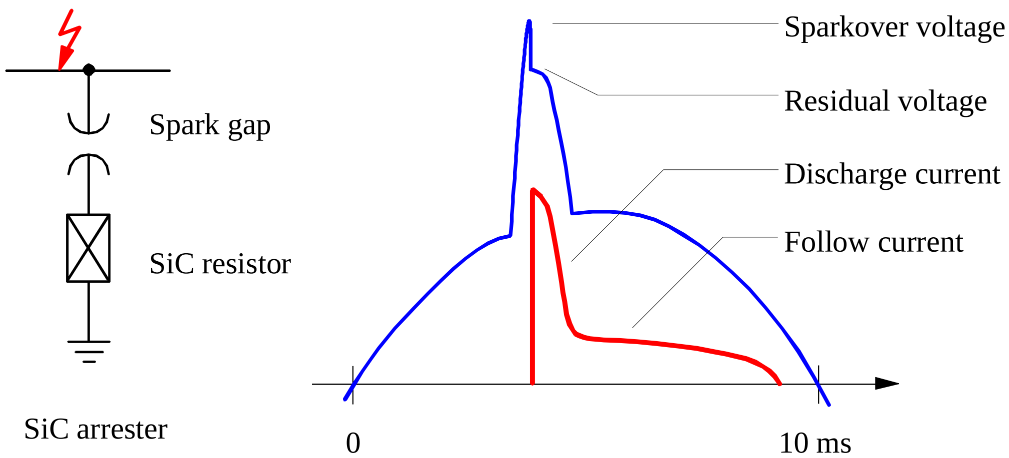

Figure C-27: Structure and mode of operation of SiC-arresters with spark gaps

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The spark gaps have two duties. First, they prevent the resistors from being continuously live during normal service. Second, they interrupt the discharge current in the next power- frequency current zero after operation of the arrester. When overvoltage waves with high currents rush in, the voltage-dependent resistors prevent the limiting voltage (residual voltage) from rising without limit (Figure C-27), and they limit the follow current.

C 8.2 Arresters without spark gaps

They consist of a stack of metal-oxide resistors with a strongly non-linear, voltage-dependent characteristic. The metal-oxide material (MO) is zinc-oxide (ZnO) in most cases. They are referred to as MO-arresters or ZnO-arresters.

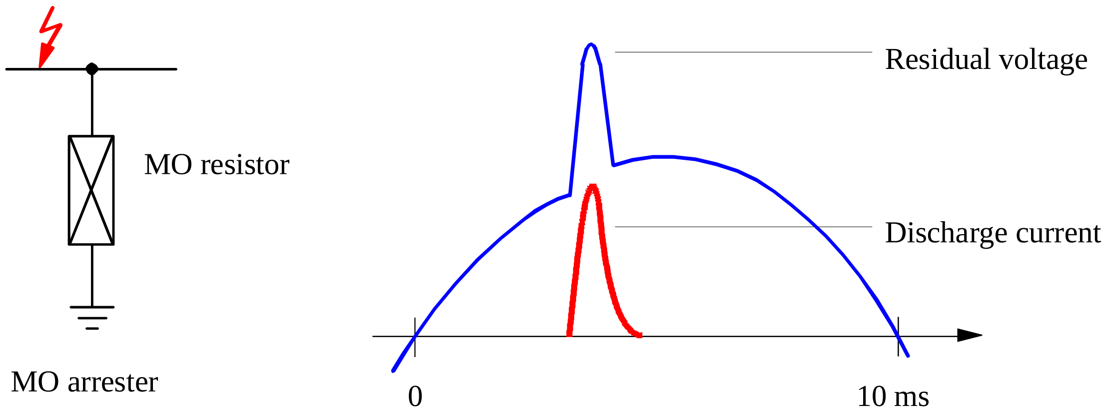

Figure C-28: Structure and mode of operation of MO-arresters

C 8.3 Surge limiters

Surge limiters have a zinc-oxide resistor in series with the spark gap. This type is used to protect against switching overvoltages, especially where low operating voltages are required, e.g for motor protection.

Figure C-29 compares the current-voltage characteristics of SiC and ZnO. The SiC-characteristic is flat, in contrast to the ZnO- characteristic. A current of approx. 100 A would flow through the SiC-resistance at normal voltage. That is why the arrester must be separated from the system by means of a spark gap. The characteristic is due to the spark gap, as shown in Figure C-27. After disruptive discharge of the gap, the voltage adjusts itself to the lower residual voltage.

ZnO has a steeper characteristic. At operating voltage, a residual current smaller than 1 mA flows through the ZnO-resistor. This current is permissible without time limitation. The resistor does not have to be separated from the system by means of a spark gap. The residual current heats up the resistor, and this is followed again by a current rise (negative temperature coefficient of the resistor material). Therefore, the characteristic must be exactly adjusted to the system conditions. Transient or short-time voltage increases and the neutral-point connection of the system have especially to be taken into account.

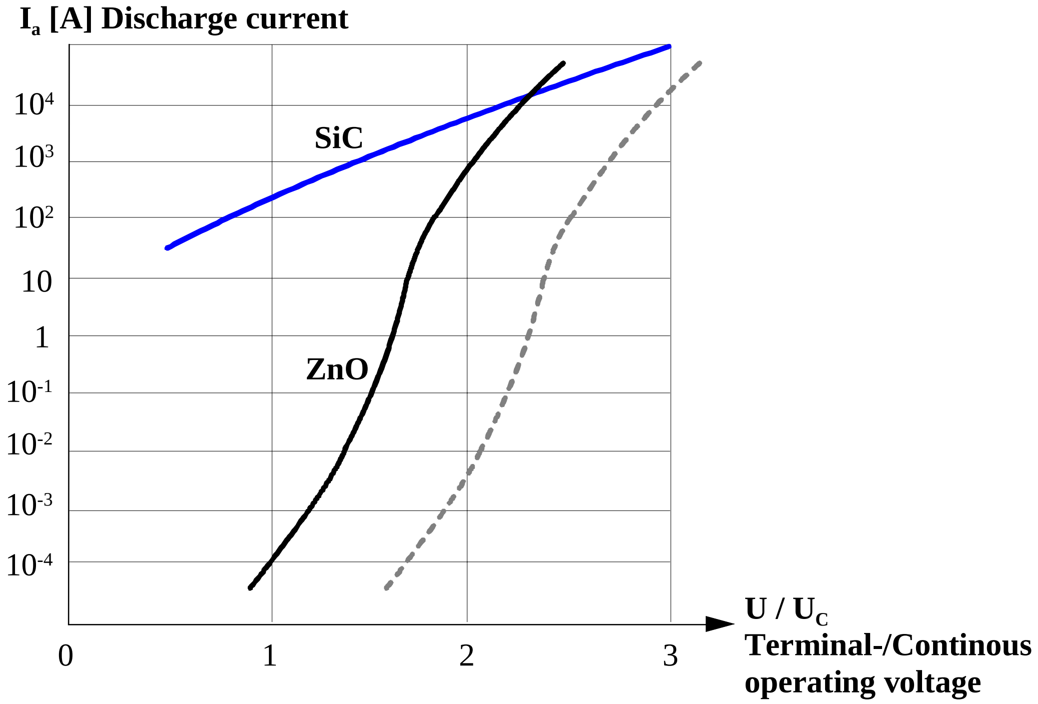

Figure C-29: Current voltage characteristics of SiC and ZnO

Effectively earthed systems

In effectively earthed systems, there is only a limited voltage increase in the healthy phases in the case of an earth fault; earth fault factor $\delta \leq 0.4$. Due to low earthing impedance the short-circuit current lies in the order of kA and is cleared within a few periods. Thus the surge arresters are not subjected to high voltage stress. In such systems, ZnO-arresters provide very low protection levels.

Systems with an isolated neutral or compensated systems

In compensated systems or in systems with an isolated neutral, there is a voltage increase in the healthy phases if an earth fault occurs. Then, the characteristic must be selected in such a way that negligible currents flow in the arresters of the healthy phases, even in the presence of that earth fault. The arrester is designed for the highest voltage stress which may occur under fault conditions; see dotted line in Figure C-29. The protection level is then, however, correspondingly higher.

Resistance-earthed systems

In resistance-earthed systems, the voltage increase in the healthy phases in case of an earth fault is time-limited, as the fault is detected and the corresponding circuit is switched off within seconds. Here, a ZnO-arrester with similar data as in the effectively earthed systems can be installed, if its energy absorption capacity is dimensioned for an operating voltage that may be increased for a short time.

Spark-gap arresters (SiC) can operate in any system, regardless of the method of neutral earthing. As a rule, their rated voltage is selected according to the maximum phase-to-phase system voltage. Thus, the earth fault condition in an unearthed network has already been considered.

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When especially low protection levels are required for special applications, e.g. for motor protection, surge limiters are used. Their ZnO-resistance gives a very low residual voltage. The spark gap separates the arrester from the system during normal service (there is no residual current flow), and "connects" it only in the event of overvoltages. Thus, the surge arrester enables low protection levels also in unearthed or compensated systems. This type of arrester is only available for switching overvoltages (low-energy overvoltages). It does not have the energy absorption capacity required for lightning protection duties. Small dimensions are more important here, as its typical applications also require installation in indoor switchgear.

Figure C-30: Examples of plug-in surge arresters

D PLANNING OF SWITCHGEAR INSTALLATIONS

D 1 Planning criteria

The planning of switchgear installations requires the creation of a harmony between objectives, duties, functions and influencing factors, and finding an economical solution from the many possibilities offered. There is no single, patent solution, because:

- the duties of switchboards can differ widely
- many influencing factors are interrelated or contradictory
- the same influencing factors and requirements can have different values for different users.

Before the question about switchgear construction can be considered, other questions must be clarified, for example its location and purpose in the network.

D 1.1 Main uses and requirements

Switchgear has to provide a high degree of safety, in order to ensure the protection of personnel and trouble-free system service. It must offer protection against electric shock and exclude the possibility of maloperation. If a fault occurs, its effects should be limited to the fault location and should never lead to personal injuries.
Medium voltage switchboards are components of a supply network, used in primary or secondary distribution systems. Characteristic of the primary distribution level are high load and short-circuit currents, along with substantial secondary equipment for the switchgear in terms of protection, measuring and (remote) control.

On the **primary distribution level** (Figure D-1) the following are found

- <u>transformer substations</u> (primary substations) where energy is fed in at a higher voltage and stepped down to medium voltage. The substations are almost all equipped with circuit-breakers. They switch large loads – usually in industrial plant, or cable ring feeders, which themselves provide the infeed to switchgear on the secondary distribution level.

On the **scondary distribution level** substations are equipped with load interrupter switches or with a mixture of load interrupter switches and circuit-breakers, the proportion of load interrupter switches being significantly higher. The currents are lower; short-circuit protection is often provided by the assigned circuit-breaker on the primary distribution level. Generally, less is demanded of the secondary equipment. Typical forms are the

- <u>consumer substation</u>, where the energy is distributed with the infed network voltage (medium voltage). A tie breaker (coupler) in the substation can mark the boundary between the utility´s property and that of the consumer, who is free to expand the substation. Measuring and metering equipment are comprised for billing the electrical energy provided.

- <u>unit or rural secondary substations</u>, where the energy is stepped down from medium voltage to low voltage and distributed at this level. In industrial plants, unit substations are often installed in the production centres and, at the same time, in the consumption centres. Then they are called load-centre substations. For compact non-manned walk-in unit substations, the terms prefabricated substations, packaged substations or kiosk substations have become conventional.

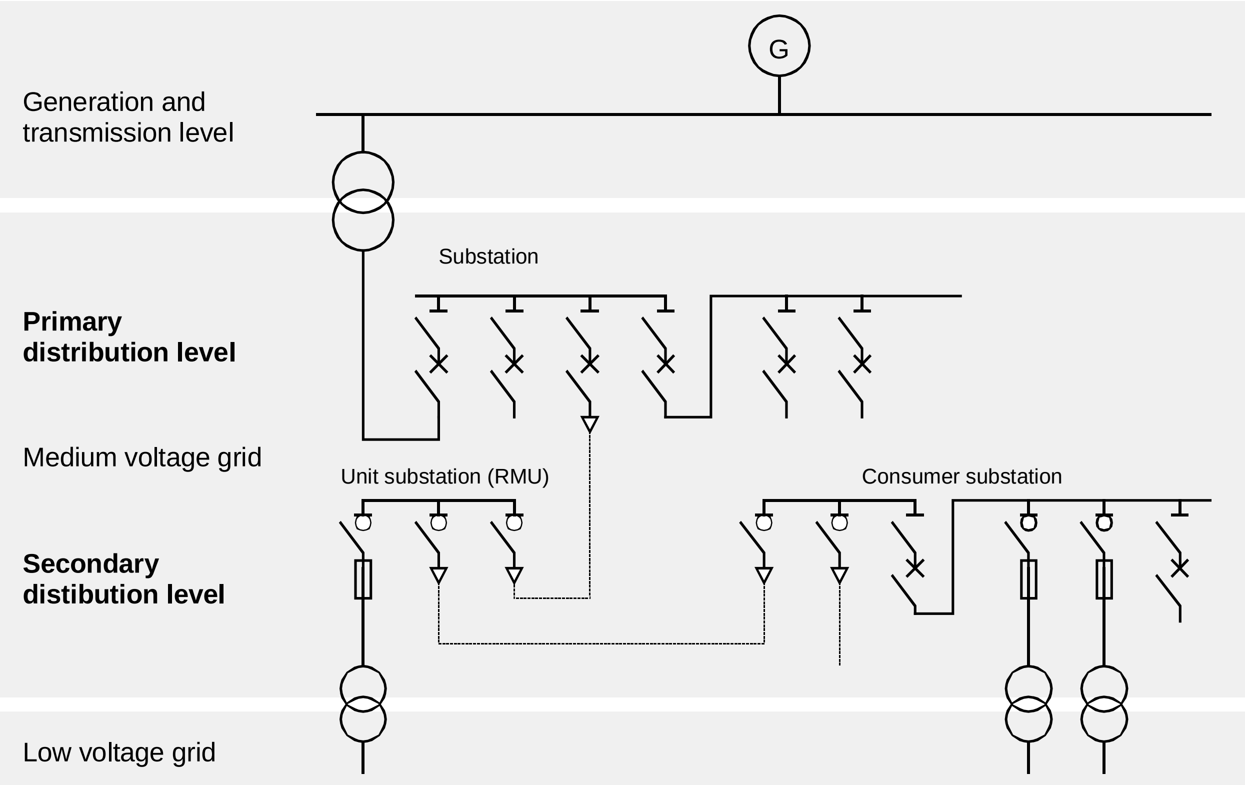

Figure D-1: Main uses for substations in the distribution network

The selection of the equipment most suited to these locations may be predetermined by the network planners and finally defined by the amount of energy to be distributed at each location.

D 1.2 Selection criteria

Selection criteria may be determined by the existing system, others are conditionally selectable, and some others are free, i.e. they can be chosen according to the best functional compliance and the needs of the user.

Pre-determined factors are for example the

- nominal system voltage
- system frequency
- peak short-circuit current
- system type (cable, overhead line)
- neutral point connection
- environmental conditions
- standards and legislation

Conditionally selectable criteria are the

- insulation level, depending on the system type, neutral point connection, over- voltage protection, site altitude

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- short-circuit duration, depending on the system structure and the protection concept
- classification of the location, depending on the type of personnel that will be allowed access
- type of construction of the switchgear, depending on the selected classification of the location

Many criteria still remain **freely selectable**:

- main switching device: circuit-breaker, switch-disconnector, contactor, fuse
- disconnecting device: withdrawable or truck-type systems or fixed-mounted disconnectors
- switchgear type and insulation: air-insulated or hermetically sealed, gas-insulated (SF_6)
- hand or power operated mechanism
- local or remote control or station control system
- circuit arrangement: single busbar or multiple busbars
- enclosure
- partitioning
- accessibility of compartments
- category of service continuity (when accessing a compartment)
- type of shock protection when working (metal or insulating partitions)
- method to verify the safe isolation from supply
- method of earthing and short-circuiting
- resistance against internal arc faults (IAC classification)

Depending on the combination required and the degree of compliance with individual criteria, these multiple considerations lead to an almost unlimited number of different switchgear types.

The following chapters describe first the main influencing factors mentioned above.

D 2 Rules for design and construction

D 2.1 Standards and application guides

The construction, production, testing, erection and operation of switchgear is regulated by numerous standards.

- **Electrotechnical standards** specify safety features in e.g.
  - Design
  - Manufacture and testing
  - Erection and operation

  => **The most important standards for switchgear are listed in section H**

- **Design standards** govern e.g. protection against electric shock (from touching), protection against the ingress of foreign bodies and water, temperature rise in busbars, or the dimensions of connections and joints.

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- **Rules laid down by the German statutory industrial accident insurance institutions, known as “Berufsgenossenschaften” or “BGs”,** (accident prevention regulations) deal particularly with sector-specific hazards. These institutions devise rules that companies must comply with. They define safety requirements applicable to equipment, processes, organizational procedures and occupational safety. Typical accident prevention regulations and references to other occupational safety regulations and standards are listed in the **BG rules** and **BG information** for health and safety.
- There are also guidelines (recommendations) issued by associations, such as the VDN / VDEW[6] publications on the requirements applying to the planning, construction and operation of switchgear used by utilities.
- Finally, internal factory or user standards, which may possibly add to the national standards, may exist.

D 2.2 Types of manufacture and installation according to the standards

The standards distinguish between two main switchgear groups

- factory-assembled, type-tested switchgear subdivided in those with
  - metal enclosure acc. to IEC 62271-200 / VDE 0671-200 (former IEC 60298 / VDE 0670-6),
  - insulation enclosure acc. to IEC 62271-201 (former IEC 60466)
- switchgear assembled at site or workshop-assembled according to IEC 61936 / VDE 0101 (which nowadays is only very rarely built new, but many examples of which are still in service)

D 2.2 a Switchgear according to IEC 61936 / VDE 0101

In terms of development, these are the oldest designs. The switchgear is dimensioned according to tables or standardized calculation procedures. The clearances between live parts and against earth are stipulated by minimum dimensions (Table D-1). When the clearances are smaller than the minimum, the dielectric strength must be proved by tests. This can occur, for example, when installing components. For this case, the standard provides a "tested terminal zone". The dielectric strength of smaller clearances is proved by means of an impulse voltage test and a power-frequency test (also on a model with 1:1 scale). The final installation conditions must then be included in the installation or operating instructions.

Almost without exception, this type of switchgear is now standardized. Standard switching devices and instrument transformers are fixed-mounted in the supporting structure and interconnected by means of bars. Such constructions are more flexible than type-tested switchgear. In most of the cases, any necessary repairs can be carried out with local resources, without stocks and without waiting for special parts. Planning with standard switchgear is simple. It is only necessary to select and combine the suitable panel types for each case.

The rules according to IEC 61936 / VDE 0101, such as minimum clearances, apply also to individual built-on units or to modifications to type-tested switchgear (e.g. surge arresters, cable termination cubicles).

[6] VDN, VDEW see Appendix AI 1

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Nominal system voltage (U_n r.m.s) kV	Highest equipment voltage (U_m r.m.s) kV	Rated short-duration power-frequency withstand voltage (r.m.s) kV	Rated lightning impulse withstand voltage 1.2/50 µs (peak value) kV	Minimum clearances phase-to-earth and phase-to-phase *Indoor installation* mm
3	3.6	10	20 40	60 60
6	7.2	20	40 60	60 90
10	12	28	60 75	90 120
20	24	50	95 125	160 220
30	36	70	145 170	270 320

Table D-1: Minimum clearance in air according to IEC 61936 / VDE 0101

D 2.2 b Switchgear according to IEC 62271-200 / VDE 0671-200

This type of switchgear is smaller and more compact in terms of its dimensions, as the dielectric strength is not determined by minimum clearances. Tests replace the minimum clearances.

All technical data are proven by type tests. The quality of manufacture is controlled by routine tests. Extensive machining guarantees dimensional constancy (which is important for interchangeability). The high investment for tests and production are only acceptable for a large number of units, and that is why standardization is essential. However, this can restrict the degree of freedom when planning.

The testing program prescribed comprises.

Type tests

- insulation level
- temperature-rise and resistance tests of the main circuits
- rated peak withstand current and rated short-time current
- making and breaking capacity of the switching devices
- mechanical function of the switching devices and of the removable switchgear parts
- touch protection against live parts and moving parts
- protection of personnel against dangerous electrical effects (leackage currents)
- Optional: protection agiantst interal arcing

Routine tests

- power-frequency test of the main circuits
- voltage test of auxiliary circuits and control circuits
- resistance test of the main circuits

- mechanical function test
- test of the auxiliary equipment
- verification of the wiring

D 2.2 c Insulation enclosed switchgear according to IEC 62271-201

On this design, the outer enclosure is made of solid insulation material. In other respects the same applies (concerning testing) as does to metal-enclosed switchgear. Switchgear enclosed in nothing other than insulant is however seldom produced any more today.

D 2.2 d Erection and connection of switchgear

IEC 61936 / VDE 0101 includes additional chapters on general erection specifications and governs the setup, connection and earthing of switchgear at its place of operation. This standard applies to all types of switchgear, both type-tested and built up in stages; see also D 8.2.

Operation of all types is governed by EN 50110 / VDE 0105.

D 3 Insulation level

The insulation level is selected according to the voltage stress expected and other factors that may have an influence on the insulation:

- alternating voltage under normal service conditions
- temporary voltage increases
- lightning overvoltages
- pollution of the insulator surfaces
- site altitude above 1000 m

According to the standards for the insulation level of medium voltage switchgear, switching overvoltages do not have to be generally taken into account. If switching overvoltages can arise due to specific system conditions (e.g. cable oscillations) or specific consumers (e.g. switching of pure inductive currents), protective measures have to be taken directly in the feeder concerned.

Insulation levels are standardized. The values shown in table C3 are valid for site altitudes up to 1000 m above sea level. At higher altitudes, the insulation level must be adjusted; see chapter D 4.3. If it is not adequate for the place of installation, further measures must be taken, e.g. surge arresters to limit possible internal or external overvoltages, or selection of the next higher rated voltage, with overall higher dielectric strength levels.

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Rated voltage U_r / kV (r.m.s.)	Rated lightning impulse withstand voltage U_p / kV (peak value)		Rated short-duration power-frequency withstand voltage U_d / kV (r.m.s.)	
	Phase-to earth, between the phases and across the open switching device	Across the isolating distance	Phase-to earth, between the phases and across the open switching device	Across the isolating distance
3.6	20 40	23 46	10	12
7.2	40 60	46 70	20	23
12	60 75	70 85	28	32
17.5	75 95	85 110	38	45
24	95 125	110 145	50	60
36	145 170	170 195	70	80

Table D-2: Insulation levels according to IEC 60694 / VDE 0670-1000

D 4 Environmental influences

IEC 60694 / VDE 0670-1000 defines "normal", i.e. permissible environmental conditions for indoor switching devices. Normal indoor conditions can be achieved either by appropriate design of the buildings or by provisions at the enclosure or at the devices themselves. The decision depends on the type and size of the substation. In extensive transformer substations, it may be better to invest in the building, whereas in unit substations, provisions at the enclosure and at the devices may be more economical.

If there are no “normal ambient conditions” at the place of installation, manufacturer and operator must reach special agreement and take particular measures.

D 4.1 Temperature

Maximum value	40° C
Average over a period of 24 hours	35° C
Minimum value class minus 5	- 5° C
Minimum value class minus 25	-25° C

If it is expected that the maximum values will be exceeded at site, the devices must be operated at a value lower than their rated current, or devices of a higher class must be installed. If it is expected that the temperature will drop below the minimum values, room or panel heating must be installed.

The limit values mentioned apply during operation. In general they may be exceeded during transport or storage. The manufacturers supply the relative information.

D 4.2 Atmospheric humidity

For indoor switchgear it is assumed that the humidity within the enclosure can reach high values, but that there is normally no condensation on the equipment installed. This assumption in IEC 62271-200 / VDE 0671-200 is valid as a modification of IEC 60694 / VDE 0670-1000.

A heater in the panel or at the switching device avoids condensation problems. Temperature-dependent or humidity-dependent heating is widely used but constant heating is better and safer. Room heating is also useful. In larger substations it is in any case necessary because other equipment, such as protection, control and telecontrol systems also require a dry indoor atmosphere. Even battery rooms require heating, as the capacity of a battery depends on the temperature of the acid. At temperatures below 20°C, the capacity decreases by approx. 1% of the rated value per degree Centigrade.

D 4.3 Site altitude

The standardised insulation levels are related to standard atmospheric conditions, i.e. 1013 hPa atmospheric pressure, 20°C temperature and 11 g/m³ water content. Air density decreases with increasing altitude, and so does its insulation capability. According to the standards, the quality of the insulation required at sea level is considered adequate for site altitudes of up to 1000 m, i.e. the reduction of approx. 9% for this altitude is ignored. The standards do not provide guidelines for site altitudes above 1000 m.

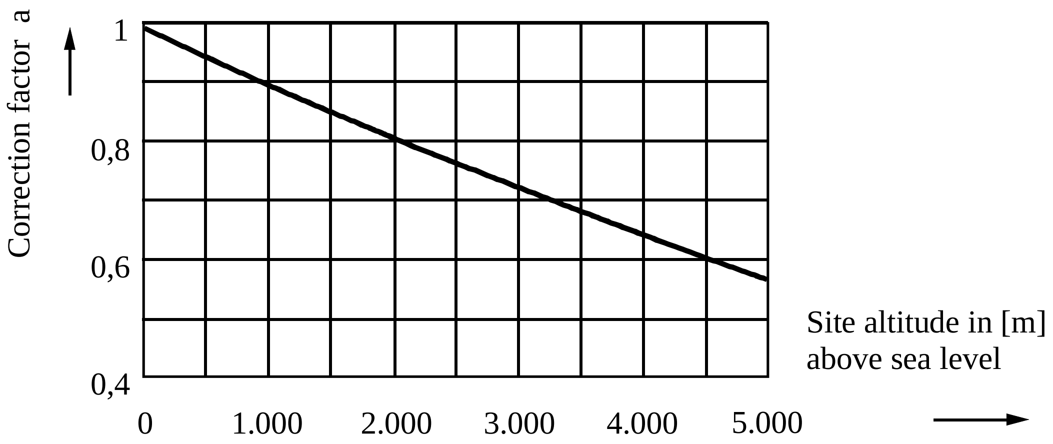

Figure D-2: Correction factor for the insulating capacity

As the insulation quality required by the standards has proved to be satisfactory for altitudes up to 1000 m, the concept is considered valid for higher altitudes. Therefore the correction factor a for the altitude is based on the insulation capability at 1000 m, which is already 9% lower than at sea level (corresponding to 0.91 or 1/1.1).

The following formula results:

$$\textit{Rated insulation level to be selected} \geq \frac{\textit{required insulation level}}{1.1 \cdot a}$$

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Example:	Site altitude	3000 m above sea level
	Required rated lightning impulse withstand voltage for a 15 kV switchgear (acc. to ANSI/IEEE)	95 kV
	Correction factor a	0.73
	Rated lightning impulse withstand voltage to be selected	95 kV/(1.1 · 0.73) = 118 kV

Switchgear with a rated voltage of 24 kV, List 2 (rated lightning impulse withstand voltage 125 kV) meets this requirement. However, to determine the actual insulating capability at site, for testing purposes, the reduction of the insulation withstand capability must be calculated from its value at sea level:

Withstand voltage = a · Rated withstand voltage of the selected device

Example:	Site altitude	3000 m above sea level
	Rated lightning impulse withstand voltage (specified value at sea level) for a 15 kV switchgear according to ANSI	95 kV
	Correction factor a	0.73
	Actual insulating capacity at 3000 m	69 kV

Definition: Rated insulation level = <u>Rated</u> short-duration power-frequency withstand voltage U_d
<u>rated</u> lightning impulse withstand voltage U_p

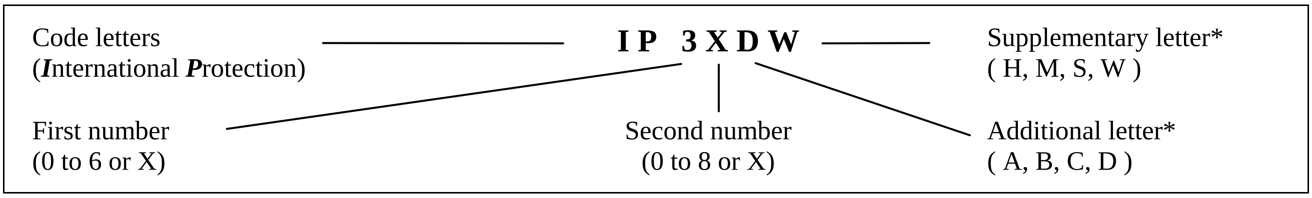
Insulation level = short-duration power-frequency withstand voltage and lightning impulse withstand voltage

D 4.4 Environmental atmosphere

IEC 60694 / VDE 0670-1000 defines: The environmental atmosphere is not substantially polluted by dust, smoke, corrosive or inflammatory gases, vapours or salt.

D 4.5 IP Degrees of Protection

This refers to the protection against ingress of water and solid foreign objects, but above all the protection of personnel against electric shock and against touching of moving parts. The degree of protection is classified by IEC 60529 / VDE 0470-1 in the form of an IP-code.



* The use of an additional or supplementary letter is optional.

The first number describes the quality of protection against ingress of solid foreign objects, against electric shock and touching of moving parts; the second one the protection against ingress of water. For medium-voltage switchgear, the following degrees of protection are preferred:

First number	2,3 or 4
Second number	1 or 4

For indoor switchgear, the designation of the protection against ingress of water is considered to be superfluous in most cases. Thus an X is used instead of the second figure, e.g. IP3X.

Especially for indoor switchgear - generally speaking for installations in clean rooms - the additional letter for protection against contact is of interest. The coupling of personnel protection with foreign body protection, indicated by a common number, can cause considerable difficulty in design. If, for example, large ventilation holes are necessary, a higher degree of protection against foreign body ingress is difficult to achieve - although not exactly necessary in clean rooms. In contrast, a high degree of personnel protection can be achieved by relatively simple means, even with low foreign body protection, by adequate shrouding, labyrinths or distance to live parts within the housing.

Therefore an additional letter can specify the degree of protection against the access to hazardous parts, if

- the actual personnel protection is of higher quality than that given by the first number, or
- only the personnel protection is indicated, without stating a degree of foreign body protection; first number = X.

The additional letter is, however, allowed only when the housing fulfils all lower degrees of protection.

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First number	Degree of protection (description / definition) against access to hazardous parts [7]	against ingress of solid foreign objects
0	Not protected	Not protected
1	Protected against access to hazardous parts with the back of a hand The access probe, sphere 50 mm ∅, shall have adequate clearance from hazardous parts	Protected against solid foreign objects of 50 mm ∅ and greater The object probe, sphere of 50 mm ∅, shall not fully penetrate[8]
2	Protected against access to hazardous parts with a finger The jointed test finger, 12 mm ∅, 80 mm length, shall have adequate clearance from hazardous parts	Protected against solid foreign objects of 12.5 mm ∅ and greater The object probe, sphere of 12.5 mm ∅, shall not fully penetrate [8]
3	Protected against access to hazardous parts with a tool The access probe of 2.5 mm ∅ shall not penetrate	Protected against solid foreign objects of 2.5 mm ∅ and greater The object probe, sphere of 2.5 mm ∅, shall not penetrate at all [8]
4	Protected against access to hazardous parts with a wire The access probe of 2.5 mm ∅ shall not penetrate	Protected against solid foreign objects of 1.0 mm ∅ and greater The object probe, sphere of 1.0 mm ∅, shall not penetrate at all [8]
5	Protected against access to hazardous parts with a wire The access probe of 2.5 mm ∅ shall not penetrate	Dust protected Ingress of dust is not totally prevented, but dust shall not penetrate in a quantity to interfer with satisfactory operation of the apparatus or to impair safety
6	Protected against access to hazardous parts with a wire The access probe of 2.5 mm ∅ shall not penetrate	Dust tight No ingress of dust

Table D-3: Degrees of protection against access to harzadous parts and ingress of solid foreign objects

[7] In the case of the first characteristic numerals 3, 4, 5 and 6 protection against access to hazardous parts is satisfied if adequate clearance is kept.
[8] The full diameter of the object probe shall not pass through an opening in the enclosure.

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Second number	Degree of protection against ingress of water
0	Not protected
1	Protected against vertically falling water drops Vertically falling drops shall have no harmfull effects
2	Protected against vertically falling water drops when enclosure tilted up to 15° Vertically falling drops shall have no harmfull effects when enclosure is tilted at any angle up to 15° on either side of the vertical
3	Protected against spraying water Water sprayed at an angle up to 60° on either side of the vertical shall have no harmful effects
4	Protected against splashing water Water splashed against the enclosure from any direction shall have no harmful effects
5	Protected against water jets Water projected in jets against the enclosure from any direction shall have no harmful effects
6	Protected against powerful water jets Water projected in powerful jets against the enclosure from any direction shall have no harmful effects
7	Protected against the effects of temporary immersion in water Ingress of water in quantities causing harmful effects shall not be possible when the enclosure is temporarily immersed in water under standardized conditions of pressure and time
8	Protected against the effects of continuous immersion in water Ingress of water in quantities causing harmful effects shall not be possible when the enclosure is continuously immersed in water under conditions which shall be agreed between manufacturer and user but which are more severe than for numeral 7

Table D-4: Degrees of protection agianst ingress of water

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Additional letter	Degree of protection against access to hazardous parts
A	Protected against access with the back of a hand The access probe, sphere 50 mm ∅, shall have adequate clearance from hazardous parts
B	Protected against access with a finger The jointed test finger, 12 mm ∅, 80 mm length, shall have adequate clearance from hazardous parts
C	Protected against access with a tool The access probe of 2.5 mm ∅, 100 mm length, shall have adequate clearance from hazardous parts
D	Protected against access with a wire The access probe of 1.0 mm ∅, 100 mm length, shall have adequate clearance from hazardous parts

Table D-5: Degrees of protection against access to hazardous parts indicated by the additional letter

To prove the degree of protection IEC 60529 / VDE 0470-1 specifies test devices and methods. The following tables clarify the meanings of the code numbers and letters

A supplementary letter can, furthermore, be added behind the second code number or after the first extension letter, if the associated product standard permits.

Supplementary letter	Significance
H	High voltage apparatus
M	Water protection, when moving parts of the apparatus are in operation, e.g. rotating parts of a machine
S	Water protection, when moving parts of the apparatus are stationary
W	Suitable for use under specified weather conditions and provided with additional protective features or processes

Table D-6: Supplementary letter of the IP code

Enclosed switchgear that is suitable for specific weather conditions (outdoor installation) can be designated by adding the letter W, e.g. IP44W. The standard does not provide a definition of this weather protection, the provisions required must be agreed upon.

D 5 Switchgear availability

High availability means: no breakdown or very rare breakdowns of the power supply and, if a fault should still occur, then only with a short interruption of power flow. When considering the desired degree of availability it should not be forgotten that an appropriate system layout (multiway supply) is also important for this aim. Very high requirements justify provisions not only within the system, but also in the switchgear.

Switchgear achieves a high availability if

- the need of maintenance is low
- the extent of required maintenance is small
- the possibility of maintenance is good
- the probability of faults is low
- the fault effects are limited
- the components to be repaired are accessible easily and without danger.

While an interruption of the power for the purpose of maintenance can be planned, in the case of faults it happens suddenly and very often at the worst time. Economical and operational reasons decide which of the a.m. features are the priorities for a particular switchboard.

The different constructional principles of switchboard types offer different possibilities.

D 5.1 Influence of the type of switchgear construction

D 5.1 a Gas-insulated, metal-enclosed switchgear

All external disturbances (pollution layers, corrosion, humidity) are completely and totally excluded from the components of the main circuit. Maloperation is prevented by interlocks. The probability of faults due to external influences is extremely low. Moreover, if the construction is single-pole encapsulation, fault effects are very limited (only earth faults are even conceivable, that is, phase to phase faults are impossible).

The use of practically maintenance-free components (vacuum interrupters, current and voltage transformers without high- voltage windings, metal-enclosed cable sealing ends) minimizes the need for maintenance. Under these circumstances, the need for accessibility becomes less and less important.

D 5.1 b Air-insulated metal-enclosed switchgear

External disturbances are precluded to a large extent, and mal-operation is prevented by interlocks. Therefore, the probability of faults is low.

The importance of freedom from maintenance for the components is not so important, because they are easily accessible.

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D 5.1 c Compartmented switchgear

Those switchgear is internally subdivided into functional compartments, e.g. for the busbar, the circuit-breaker and the cable terminals. In contrast to metal enclosed switchgear without partitions, it has the following advantages:

- automatic protection against electric shock during work on specific components, while adjacent components remain in operation,
- limitation of the effects of faults is archivable.

In gas-insulated switchgear, compartmentalization is inherent for constructional reasons. Air-insulated switchgear is available with or without partitions, or with a partial compartmentalization where several functions are in one compartment.

The arrangement and design of the compartments has a major influence on the availability of switchgear; see chapters D 5.2 and D 5.3 below.

D 5.1 d Cubicle type switchgear

If adjacent panels are live, working in one part of the panel (e.g. at the cable termination) is only safe after insertion of protective barriers (insulating plates, in most cases). If that is not possible, the system must be shut down (at least the busbar section concerned). In non-compartmented or partially compartmented switchgear the limitation of fault effects is lower than in compartmented switchgear.

D 5.1 e Switchgear with withdrawable components

In most cases, only the main switching device is withdrawable. Gives ease of accessibility not only to the part withdrawn, but also to the components remaining in the stationary part, as there is more space left for access after the main device has been withdrawn. Furthermore, in this switchgear type, disconnectors have been replaced by isolating contacts. Fewer devices imply less maintenance and fewer sources of fault. The compact arrangement enables robust mechanical interlocks.

D 5.1 f Switchgear with fixed-mounted components

Offers the greatest freedom regarding the selection of components. Faults due to maloperation can also be prevented here by mechanical and electrical operation. The degree of accessibility for maintenance or repair purposes depends on the particular design, the better it is, the larger is the panel. Working is only possible after insertion of protective barriers. Replacement of components (e.g. breakers) is complicated, as the fixing and connecting bolts must be detached and heavy devices must be lifted. That applies less to gas-insulated fixed-mounted switchgear, as the GIS and its built-in components are largely maintenance-free, dispensing with the need for access.

D 5.1 g Open switchgear

It offers no protection against external influences and hardly any limitation of fault effects. It is installed only where a clean, dry, heated or even air-conditioned room is available; where the breakers are operated from a remote location or at least from outside the switchgear room, and where, if necessary, a longer reconditioning time is acceptable. Open type switchgear is practically never built nowadays, but it is still permissible.

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D 5.2 Accessibility of compartments

The overall availability of switchgear is likewise significantly influenced by how quickly (and with what method) a compartment can be opened. With reference to these aspects, the standard distinguishes between four types of compartment. Three of them differ in terms of access control:

- With an **interlock-controlled accessible compartment,** an interlock in the switchpanel allows access after the live parts have been isolated and earthed. It is envisaged that this type should be opened in the context of normal operation or maintenance, e.g. for changing HRC fuses (all forms of repair or installation work are not counted as operation or maintenance).
- With a **procedure-based accessible compartment,** access is controlled by a lock in combination with instructions. It is likewise intended that this type should be opened for normal operation or maintenance.
- A **tool-based accessible compartment** – for example a cable termination compartment – can only be opened by means of a special tool in accordance with particular instructions. This type of compartment can only be opened in certain eventualities, i.e. <u>not</u> in the course of normal operation or maintenance.

The fourth type is found in gas-insulated switchgear where access to built-in components is not required:

- A **non-accessible compartment** must not be opened. Opening the compartment can destroy it and impair the function of the overall system.

D 5.3 Operational availability during maintenance/modification work

It is the subdividing of the switchgear and the design of the compartments that determine the availability of the overall system while work is being done, i.e. which parts of the system must be taken out of operation when a compartment is opened. The more appropriately the functions are divided up between a number of compartments (busbar, disconnector, main and earthing switch, cable termination), the lesser the extent of stoppages if a compartment has to be isolated and earthed.

The standard has created a category of “loss of availability”. This category indicates which parts of the switchgear have to be taken out of operation when an accessible compartment is opened; accessibility usually concerns mainly the switching device.

Category **LSC 2B** indicates the highest level of availability and means that - apart from the panel with the opened compartment – all other adjacent panels remain energized and in operation; the system remains available.

Category **LSC 2A** applies to switchgear in which the panel with opened compartment goes completely out of operation; all other panels can however remain in operation.

Category **LSC 1** refers to switchgear that does not comply with LSC 2A or 2B. The “1“ stands for the lowest level of availability and means that – apart from the opened panel – at least one other has to be shut down, or even the entire busbar section.

The LSC categories designate accessible compartments and are intended for installations in which the switching device is accessible. Since with gas-insulated systems it is neither necessary nor consequently possible to open the compartments, no LSC category is generally stated for gas-insulated switchgear.

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D 5.4 Redundancy, reserve and back-up

In every case, the achievment of higher reliability requires provision of reserves: in the cable sizes, the power of the transformers, the components and the material as well as in emergency generators. Depending on the admissible duration of the breakdown of the power supply, we distinguish between instantaneous, minutes and hours reserves.

D 5.4 a Instantaneous reserve

This reserve generally avoids a de-energized pause, or the de-energized pause is so short (< 350 ms), that most consumers do not notice it.

Some simple examples:

- Two transmission paths are operated in parallel. If one of them breaks down, the total demand is supplied from the other one. Precondition: both of them must be dimensioned for the full power.
- The current is supplied through one of two possible transmission paths only. If this path breaks down, automatic transfer to the reserve path takes place. There may be a common reserve for several paths or feeders.

D 5.4 b Minutes reserve

This reserve limits the de-energized pause to minutes. Within this period of time, alternative sources in the transmission system can be selected by means of switching operations which take load flows and priorities into account.

D 5.4 c Hours reserve

Here, the de-energized pause lasts until either the damage is repaired, or a power supply is provided again through a provisional arrangement or through emergency equipment.

It is evident that the power supply in industrial and commercial areas as well as in densely populated residential and business areas must provide for instantaneous reserve. Secondary possibilities for minutes or hours reserve can be required additionally, or may at least be useful.

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D 6 Busbar systems

The decision on single or multiple busbar systems depends on the operational requirements. The following points play an important part:

- Number of outgoing and incoming feeders
- Shall any parts of the switchgear be operated separately?
- Shall any consumers be transferable to different supplies?
- Is uninterrupted transfer required?
- Which switchgear sections shall remain in operation during maintenance?

D 6.1 Single busbar

For switchgear with a low power throughput or for switchgear with only a few feeders (up to approx. 5 feeders), an undivided single busbar is sufficient in most cases, even if there are two incoming feeders (typical example: ring main unit; see chapter D 6.4). If there are more feeders, which automatically implies a higher power throughput, it is advisable to subdivide the single busbar one or more times. The most important principle to be observed is: one section for each incoming feeder. Disconnectors, switch-disconnectors or circuit-breakers may be used to achieve this busbar sectionalization.

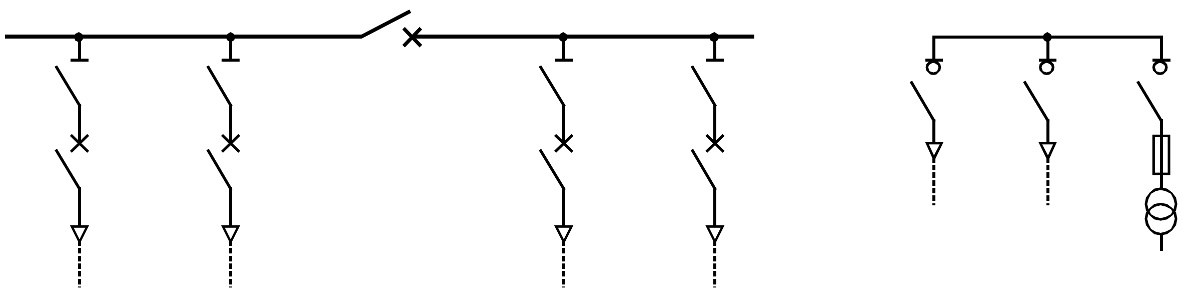

Figure D-3: Single busbar with sectionalizer (left) and in a unit substation (right)

D 6.1 a Bus sectionalization using disconnectors

A disconnector can be used, when the busbar sections are normally operated either constantly separated or constantly interconnected, and if they are only switched over in special cases, e.g. to enable maintenance or only to allow ”minutes reserve”. In the case of disconnectors or switch-disconnectors, which are firmly connected to both sides of the busbar, it must be taken into account that they can only be maintained when both sections are de-energised. In contrast, disconnect and isolating contacts of switchgear trucks (withdrawable switchgear) are such simple elements, that they hardly need any maintenance.

D 6.1 b Bus sectionalisation using circuit-breakers

A circuit-breaker is used when the busbar sections are alternately operated in separate or interconnected mode, or when changes of the actual switching state shall be carried out automatically and instantaneously, e.g. to provide instantaneous reserve or for selective system division in the case of fault.

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D 6.1 c Open or closed bus section?

Both possibilities are correct under appropriate circumstances. The mode of operation has no direct influence on the selection and the equipment of the switchgear, but the following has to be observed:

In open operation, subsystems are formed, so that only part of the consumers are directly involved in the event of breakdowns. As only few system impedances (e.g. transformers, cables) are in parallel, the short-circuit currents remain low, and this possibly allows lighter breakers, smaller cables, i.e. cheaper components. In the case of a breakdown of supply, instantaneous reserve can still be guaranteed by means of a bus section with circuit-breaker and an automatic transfer system. The short-circuit current does not increase, as one incoming path has been disconnected. Reserves must be planned and installed; but then, they are available without restrictions in the event of fault.

In the closed bus section mode, load differences can be balanced automatically, but faults can also have effects on the whole system. A faulted incoming feeder can cause an overload in a second one, which is then also disconnected. This has the consequence that the load is supplied through fewer and fewer paths, because they break down one after the other (Cascade disconnection). Moreover, the short-circuit current can reach very high values; all components must be dimensioned for it, even when selective isolation from the system is provided by means of a bus section with circuit-breaker and an automatic system for instantaneous fault clearance. Common reserve paths can be installed instead of dedicated paths; but they are also only available depending on the actual switching and load conditions.

Most switchgear assemblies are equipped with single busbars, which demonstrates their adequacy for almost all supply duties. Not only small substations use this principle, but also others with more than 40 feeders and several bus sections. Among these, there are switchgear assemblies where four sections are connected in a busbar ring, so that each section has a neighbour to the left and to the right as a possible reserve source. Another frequent type is main substations, where all incoming feeders are arranged on one side and all outgoing feeders on the other side of the bus section, which is additionally equipped with measuring and metering equipment. The purpose is to obtain clear differentiation between a consumer network and the general system of a regional utility.

D 6.2 Double busbar

Some operational requirements are influenced by contractual or technical conditions in such a way, that they cannot be satisfactorily met by a single busbar switchgear. Reasons for that could be, for example:

a) A factory receives its power supply from the regional utility company, but it also uses its own production steam for power generation. Its own generator is not allowed to be connected to the utility system, but optimum use of its capacity must be made.

b) In a system there are some consumers which cause heavy load impulses, some which are sensitive to system fluctuations, and some which are insensitive to them. These latter shall be transferrable to the steady or to the affected busbar depending on the load conditions.

c) In a system there are consumers with different priorities, which may therefore be connected to a secure or a less secure busbar.

d) A system must be divided into two subsystems due to limited fault withstand capability of the existing equipment, or increase of demand necessitates transfers for load equalization e.g. in case of an unforeseen power requirement.

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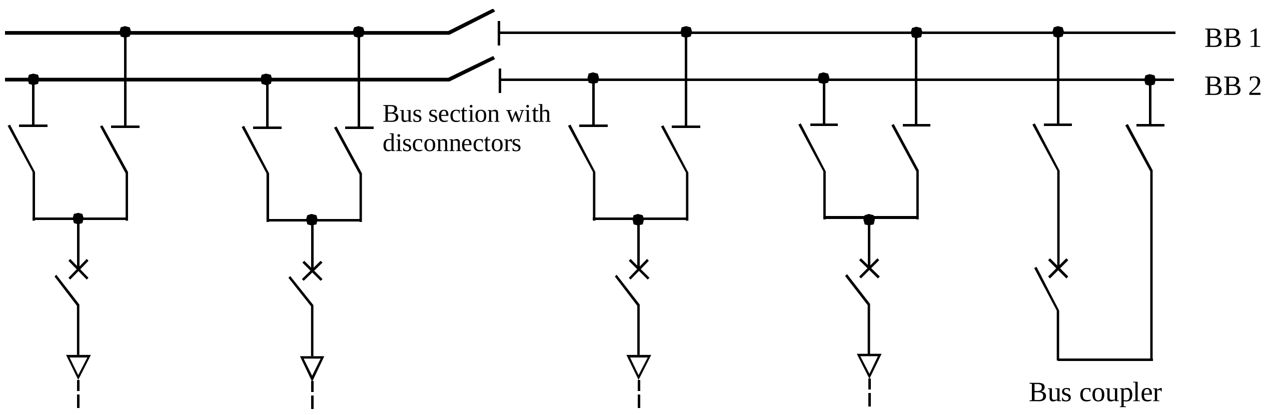

Figure D-4: Double busbar with a bus section with disconnectors and a bus coupler

Example a) leads to a double busbar without bus coupler. For every busbar transfer, the current flow to the consumer must be momentarily interrupted. Interlocks are only required, within each panel, between the circuit-breaker and the disconnectors, then between both busbar disconnectors under an either/or condition.

The classical double busbar, suitable for the examples b) - d), has a transverse bus coupler which enables a busbar transfer without interruption of current flow. However, besides the individual panel interlocks, this arrangement also requires interlocks with the bus coupler.

As a general rule, double busbars are operated separately and, if a coupling has been provided, they are only interconnected for a short time for circuit transfer. For this short coupling phase, and under specified safety conditions, The standards (IEC 61936 / VDE 0101) even permit the short-circuit current to exceed the rated values of the switchgear.

D 6.3 Transfer busbar

For extreme requirements, such as uninterrupted operation "at all events", and where even a double busbar is not sufficient, a transfer busbar can be added. It is available as a double busbar plus single busbar assembly. Theoretically, it could also be arranged as a combination of the bypass disconnector with a double busbar, but this leads to complicated types of construction. The cost depends decisively on the switchgear type; see chapter D 7.

When operating the transfer busbar, the effect of its use upon the protection system must be considered:

a) If the current transformers are mounted directly at the cable termination, the tripping command of the protection must be switched over from the bypassed circuit-breaker to the bus coupler circuit-breaker.

b) If the current transformers are mounted at the circuit- breaker, only the bus coupler protection can be effective, as the existing transformers are also bypassed. In this case, the ratios of the instrument transformers in both feeders must be approximately the same, and the tripping threshold relay setting has to be adjusted to suit the feeder concerned.

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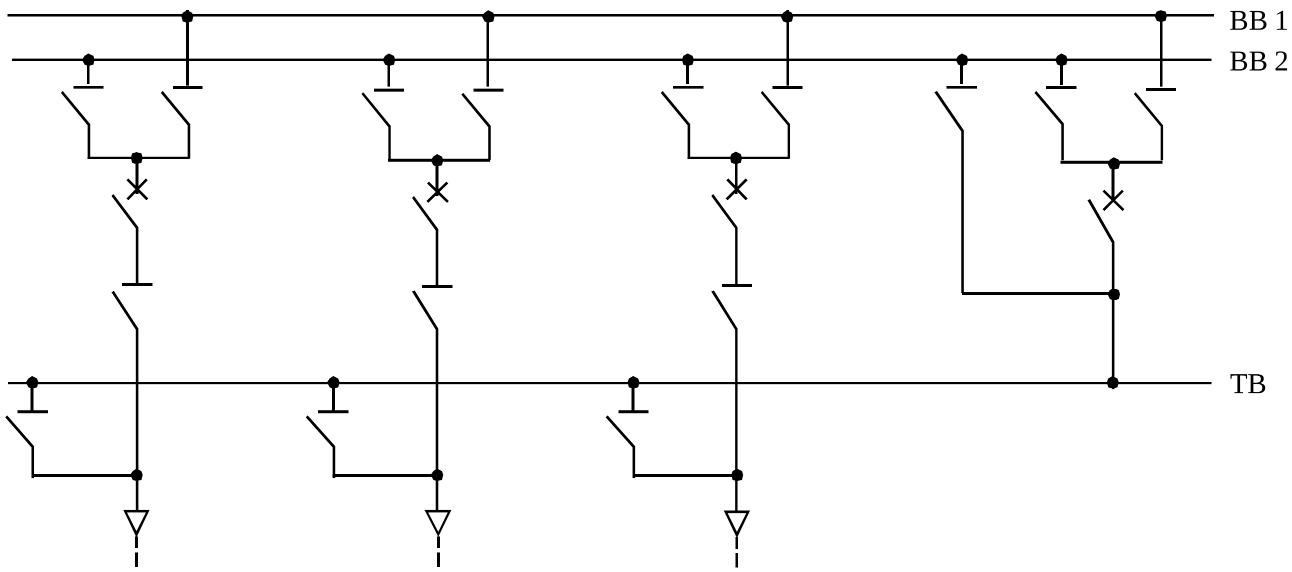

Figure D-5: Transfer busbar

D 6.4 Unit and consumer substations

Unit substations contain a single busbar with a transformer feeder for supply of the low voltage system (LV). In most of the cases they are looped into a ring cable which runs between two main switching substations. Switch-disconnectors operate the supply cables. In the case of a fault, the ring can be opened at any unit substation. A fused switch-disconnector combination enables a separate disconnection of the transformer in the case of a fault and limits the short-circuit current to the transformer at the same time. As shown in Figure D-6 there are extended unit substations as well, called “consumer substations“, in which the switchgear (of any configuration) of a customer is connected to the the ring cable. At the supply point – with load interrupter switch or circuit-breaker – the energy is measured and metered for billing.

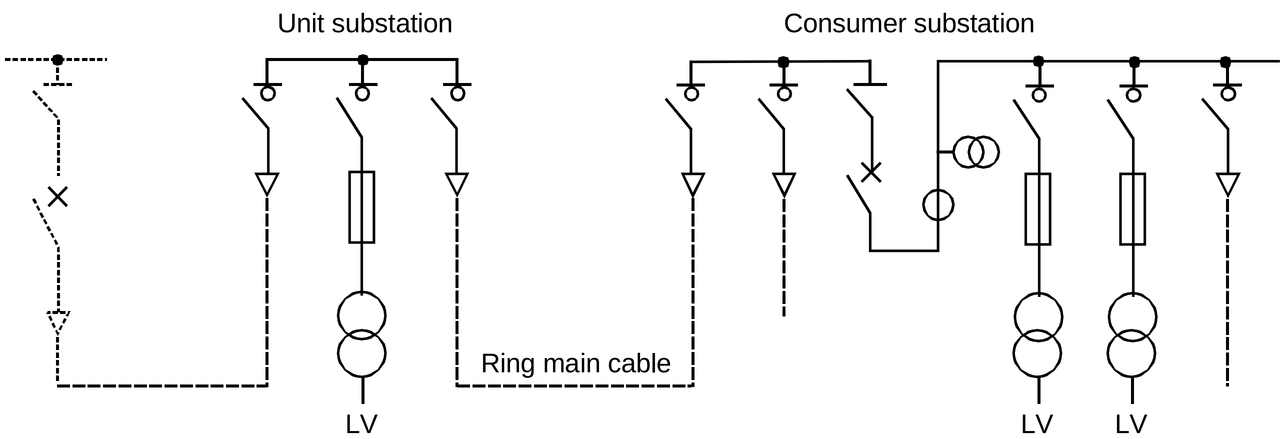

Figure D-6: Unit and consumer substations in a cable ring

D 7 Double-busbar switchgear

Double-busbar switchgear is available in different designs:

1) with one disconnector per busbar, fixed-mounted in the supporting structure. The circuit-breaker can also be fixed- mounted (Figure D-7a) or be arranged on a truck or on a with-drawable unit (Figure D-7b).

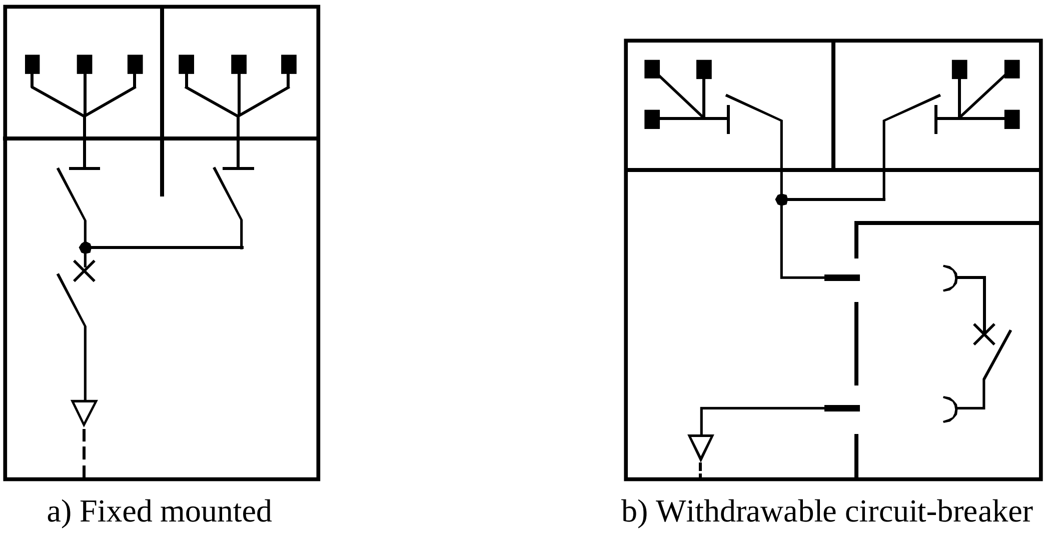

Figure D-7: Double busbar switchgear, fixed mounted disconnectors

(2) as a so called two-breaker switchgear in truck-type or withdrawable-unit design, where each feeder consists of 2 stationary parts with common instrument transformers and cable terminations; as a rule, the circuit-breaker is only provided once per feeder. Each of the two panel rows comprises one of the busbar systems. Depending on preference, two arrangements are possible:

(2a) Back-to-back arrangement, where circuit-breaker connections are linked through the rear walls (Figure D-8).

(2b) Face-to-face arrangement (also called wall-to-wall arrangement), where the two panel rows are placed with their fronts facing the common operating aisle.

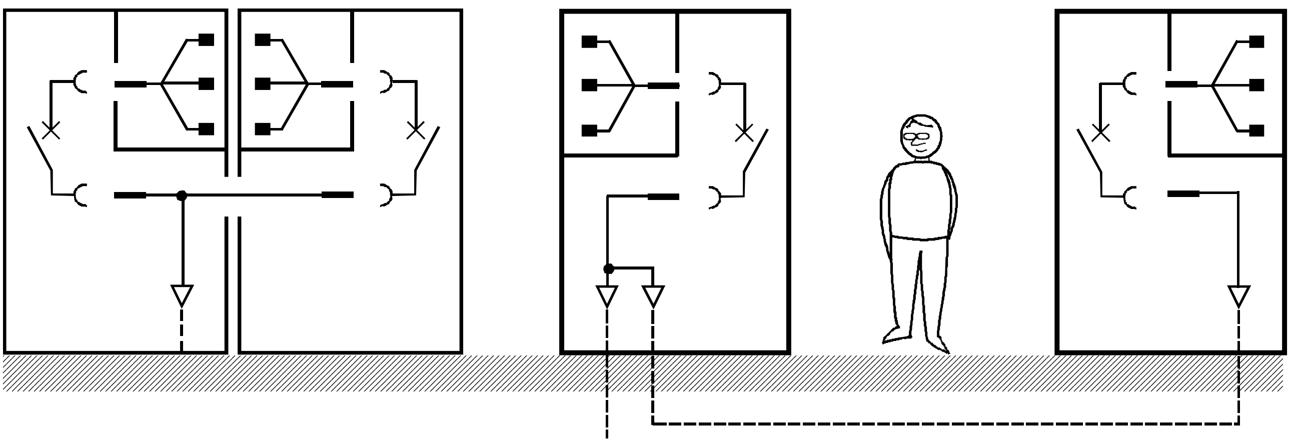

Figure D-8: Back-to-back and face-to-face arrangement

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Each of the three designs has its advantages and disadvantages, which are, briefly.

D 7.1 Fixed-mounted disconnectors

This switchgear design is very suitable for hand-operated switchgear where a busbar transfer is carried out very often, because it is much easier to switch a disconnector than to move switchgear trucks around. It is especially suitable for remote control, as the additional expense for power-operated mechanisms at the disconnectors is quite low. However, depending on the switchgear size, a sophisticated and costly interlocking system (switchgear interlocking system) may become necessary, see also chapter D 9.1.

The floor area required is less than for truck-type switchgear, but the rooms must be higher.

D 7.2 Two-breaker arrangement

This is very suitable for hand-operated switchgear where a busbar transfer is not carried out very often, because the distances for a busbar transfer can be quite long, e.g. in the case of back-to-back, right around the complete switchboard. A remote-controlled busbar transfer is possible when all feeders concerned are equipped with two circuit-breakers and both of them are equipped with a motor-operated drive mechanism. In modern designs (switchgear with withdrawable units) the additional expense remains within reasonable limits.

A bus coupler is not required when the expected balancing current between the two busbars during the coupling operation does not exceed the rated (normal) current of the feeders. In this case, the coupling operation is performed by means of a second circuit-breaker, which is inserted in the feeder concerned. This procedure requires at least one reserve breaker on a truck, or withdrawable unit. After the transfer and decoupling operations have been finalized, the formerly active breaker becomes the reserve breaker. The overcurrent protection of a feeder does not detect the coupling current. No more interlocks than the obligatory ones between the main switching device and the drive mechanism are necessary.

If a bus coupler is required due to the magnitude of the coupling current, only one of the stationary parts of the bus coupler panel has to be equipped with a circuit-breaker. In the other one, a rigid bar connection from the lower connection to the busbar is sufficient. However, in most cases this stationary part is also equipped with isolating contacts, but only an isolating truck or disconnector link is inserted. In addition, interlocks must be provided between the bus coupler circuit-breaker and the feeders.

D 7.2 a Back-to-back arrangement

The main advantage in contrast to 2b is the short link between the two stationary parts of a feeder. This link remains within the enclosure and it can therefore be dimensioned without problems for higher currents by means of bars. Furthermore, the combined cable compartments of the two stationary parts offer a lot of space for parallel cable terminations, instrument transformers, surge arresters if required, and an earthing switch. The interlocking of the earthing switch against the two switchgear trucks or withdrawable units can easily and safely be achieved with simple mechanical means.

A disadvantage regarding 2b is the more complicated busbar transfer, due to the long way around the complete switchgear row and the subsequent risk of confusion of panels.This disadvantage dis-

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appears when each feeder is equipped with two circuit-breakers, as e.g. in case of switchgear with full remote control.

The floor area required is the largest of all three designs, as it requires two operating aisles of the width required to withdraw the breaker and at least one free access at both front sides. A room height of 2.5 to 3 m is enough, the same as for single busbar switchgear.

D 7.2 b Face-to-face arrangement

The main advantage in contrast to 2a is the clear spatial segregation of the two busbar systems and, at the same time, the clear identification of the two panels corresponding to the same feeder. Their interconnection, however, is more complicated, because it has to run underneath the common operating aisle, thus reaching a length of 5 to 8 m outside the enclosure. For smaller currents, cables are installed, which are frequently preassembled single-core plastic-insulated cables. This can increase the number of sealing ends per feeder three times; moreover, the connecting cables are not covered by the overcurrent protection of the feeder but by the busbar protection. So, if there is a fault on one interconnecting cable, the incoming feeder protection operates, causing shutdown of a complete busbar section.

The interconnections can also be designed as bar ducts. In the case of higher currents, bars are always required. The expense is quite high, especially when the bars have to be transposed in order to get the same phase sequence from the left to the right.

The interlocking of the earthing switch against the opposite stationary part is also more complicated. In most of the cases, a solenoid interlock is provided, or an earthing truck instead of earthing switches.

The floor area required is smaller than in 2a, as it only requires one operating aisle. The room height is the same as in 2a. The interested reader is also referred to the vertical isolation method of providing double busbar selection.

D 7.3 Aspects of selection

When deciding on a single or a double busbar, the following should be generally taken into consideration: In single-busbar switchgear the switching state is always clear to see. Therefore it is always easy to assess its status during a hectic situation resulting from system faults, thus reducing the possibility of maloperation. For any transfer required after a fault, only circuit-breakers have to be operated. If a wrong breaker should be opened or closed, this has no extensive consequences, except that a part of the system (consumer) could possibly be separated from its supply without need. However, this can be corrected immediately, as the circuit-breakers are suitable for making and breaking of load currents, short-circuit currents and earth fault currents several times consecutively.

On the other hand, in double-busbar switchgear with fixed-mounted disconnectors, the bus coupler circuit-breaker and several disconnectors must be operated in an exactly prescribed sequence for busbar transfer. Disconnectors are not adequate for breaking currents of a considerable magnitude. If a disconnector is operated under load by mistake, an internal fault occurs (arc fault), causing damage to the equipment relative to its current value and the duration of the arc. The repair work can last hours or days. To avoid that, a sophisticated and expensive interlocking system must be installed. In spite of this system, multiple-busbar switchgear is still not very easy to survey, i.e. an operator may possibly not realize immediately why a particular disconnector will not open or close although the interlocking has authorized it.

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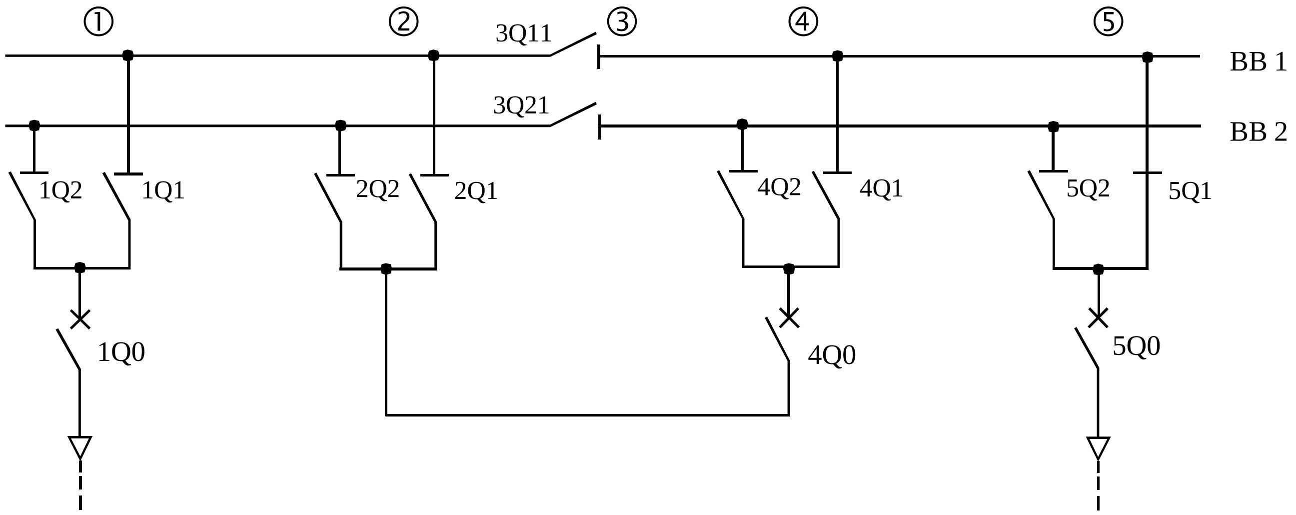

Step	Switching device	Status
1	2Q1	ON
2	4Q1	ON
3	4Q0	ON
4	3Q11	ON
5	4Q0	OFF
6	4Q1	OFF

Step	Switching device	Status
7	4Q2	ON
8	4Q0	ON
9	5Q2	ON
10	5Q1	OFF
11	4Q0	OFF
12	4Q2	OFF

Step	Switching device	Status
13	4Q1	ON
14	4Q0	ON
15	3Q11	OFF
16	4Q0	OFF
17	4Q1	OFF
18	2Q1	OFF

Figure D-9: Example for a busbar transfer

Double-busbar switchgear is only really viable, when several supply systems must be operated side by side and the consumers must be transferred frequently from one system to another.

One should never try to ensure reliable power supply by providing as many possibilities of transfer as possible, e.g. by combined bus sections, bus couplers and diagonal bus couplers. The more complicated the switchgear, the more sources of fault; not to mention the investment required, because finally it will be found necessary to "interconnect" busbars at 1000, 2000 or even 3000 A, and not only control cables, although the draft of the circuit diagram may look like that at first.

The following example with a combined coupler (Figure D-9) shows that no less than 18 single switching operations must be carried out in a prescribed sequence in order to transfer feeder (5) without interruption from busbar system BB 1 (as shown) to busbar BB 2.

A reliable power supply cannot be achieved effectively and economically in one switchboard only, but only in combination with the system, e.g. by means of several supplies through different routes.

D 7.4 Switch disconnectors in double busbar switchboards

There are networks, in which operational requirements necessitate frequent changes of busbar. Because of the low number of operations for which switch disconnectors are suitable, compared with primary switching devices, not all types of switchboard are adequate for this duty. Switches and switch-disconnectors have, in practice, a mechanical life of 1000 (IEC minimum) to 5000 operations. Thereafter, at the very least, maintenance work is necessary. In gas insulated assemblies particulary, where access requires a lot of work - if access is possible at all – the necessity for frequent busbar changeover must be taken into account when selecting the type of switchboard.

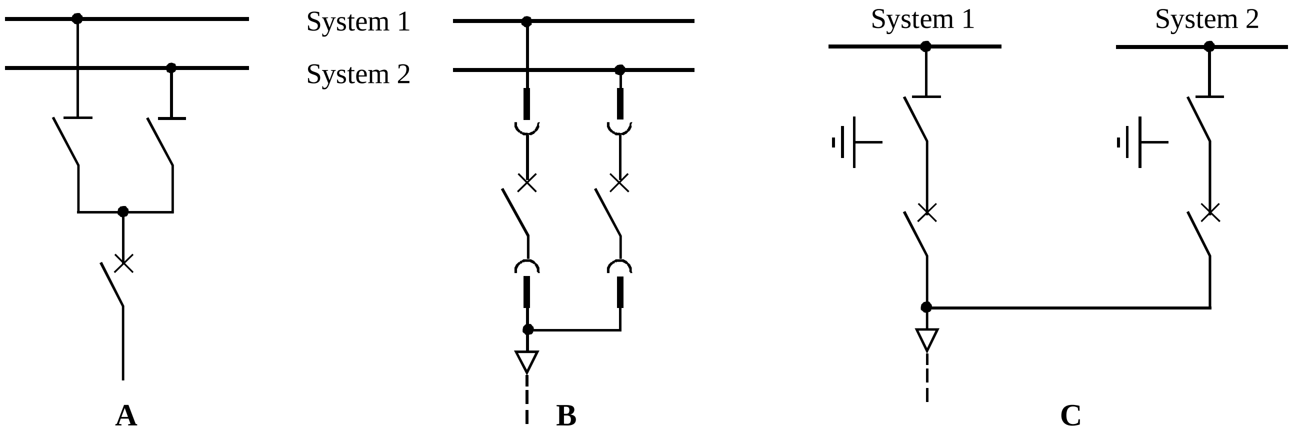

Figure D-10: Disconnector arrangements in double busbar switchgear

DB switchboards are available in the "classic" arrangement (A), as two-breaker systems (B) or using two single busbar boards as in (C). For frequent busbar changeover only (B) and (C) are suitable. In these systems, only the circuit-breakers need to be operated, the switch-diconnectors are opened only for work on the system. The classic arrangement (A) is not suitable since the switches must be opened and closed for each system changeover. Their design life is then soon exhausted, maintenance intervals rapidly shortened and the effectiveness of the systems reduced.

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D 8 Electrical operating areas

D 8.1 Type of operating area

In closed electrical operating rooms, i.e. in rooms that are provided for exclusive operation of electrical installations and that are kept under lock and key, not only enclosed switchgear, but also open switchgear may be installed. Electrical staff and electrotechnically qualified personnel have free access, but others must be accompanied by authorized personnel (EN 50110 / VDE 0105).

The doors and exits of closed electrical operating rooms must open outwards; they must be provided with warning labels; their door-locks must prevent the access of unauthorized people but enable personnel inside to leave the room without a key (panic lock).

In ordinary workrooms, i.e. in rooms that are provided for any kind of operational work and that can be accessed regularly by uninstructed personnel, e.g. workshops or factory rooms, only enclosed switchgear, which provides full protection against direct contact, may be installed,. If it is expected that personnel will permanently stay near an enclosed switchgear, additional measures must be taken to restrict the danger to the personnel in the case of fault (IEC 61936 / VDE 0101).

Furthermore, when installing switchgear in public buildings (e.g. office buildings, department stores, meeting rooms, residential buildings), governmental regulations must be observed.

D 8.2 Installation of switchgear

D 8.2 a Indoor switchgear

The installation of switchgear in an operating room is regulated by IEC 61936 / VDE 0101. Considering the safety aspect, this standard defines:

- Aisles must have a width of at least 800 mm. The aisle width must not be reduced by any objects projecting into it, e.g. fixed-mounted operating mechanisms, switchgear trucks in disconnected position.
- Switchgear doors must close in the escape direction, or it must be possible to open them only so wide, that the remaining aisle width is at least 500 mm.
- For installation aisles behind enclosed switchgear, a width of 500 mm is sufficient.
- For extensions, the aisle widths of the existing switchgear are admissible.
- Exits are to be arranged in such a way, that the escape route within the room does not exceed 20m.
- If an operating aisle does not exceed 10 m, one exit is enough. An exit or emergency possibilities shall be provided at both ends of the escape route if its length exceeds 10 m.

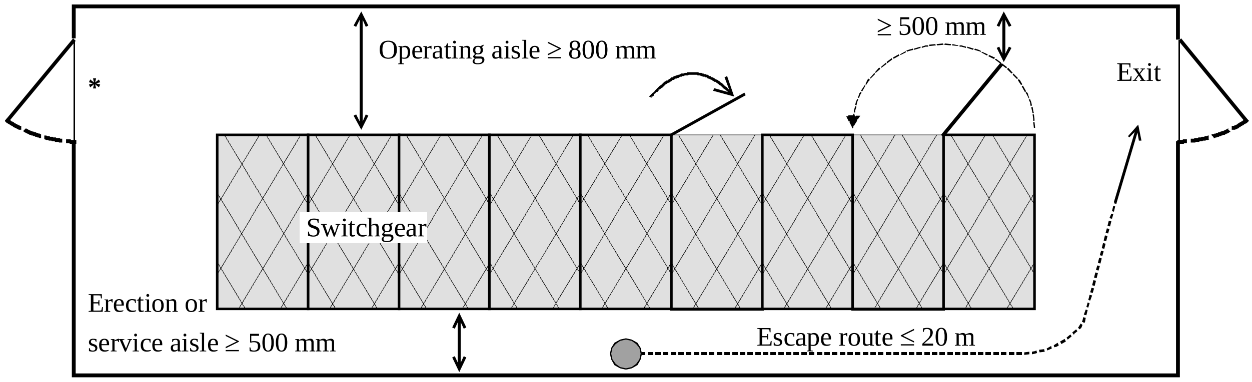

Figure D-11: Installation of switchgear (example)

The following applies for the height of the aisles:

- The minimum aisle height beneath covers or enclosures is 2000 mm.
- The aisle heights beneath active parts must have a minimum height specified in tables; however not less than 2500 mm.
- The transport of switchgear parts must be considered when selecting the aisle heights.

D 8.2 b Switchgear accessible to the public

A typical example for such installations are unit substations. The following items are also valid for all other "Installations in enclosed construction outside closed electrical operating rooms" (IEC 61936 / VDE 0101).

These substations must be designed in such a way that they do not endanger people standing close to them - even in case of fault. On the other hand, external influences must also not disturb the switchgear.

If a permanent presence of people close to the switchgear is expected, additional measures must be taken, such as:

- increased insulation
- minimum-oil or no-oil circuit-breakers
- rapidly operating protective equipment
- pressure relief equipment

D 8.2 c Gas-insulated switchgear

This applies especially to SF_6-insulated switchgear. IEC 61936 / VDE 0101 generally requests the following:

- Pressure relief devices (bursting devices) must not endanger operating personnel.
- Pipes and valves for gas supply must be protected; i.e. they may not project into aisles.
- SF_6 pipes must be marked, if they could be confused with other pipes.
- For gas-insulated switchgear with several pressure chambers, clearly assigned drawings must be provided, showing the switchgear structure and the location of the barriers.

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Moreover, the ventilation of SF_6 switchgear rooms is prescribed:

- Switchgear above the ground requires only natural transverse ventilation; half of the ventilation section shall be close to the floor (SF_6 is heavier than air). Non-manned switchgear rooms are exempted. In case of fault, forced ventilation must be possible.
- Underground rooms require facilities for forced ventilation in case gas should accumulate in dangerous quantities.
- Rooms, wells, pits and ducts that are in connection with the switchgear room must also be ventilated.
- In the case of forced ventilation, any gas-air mixture close to the floor must also be drawn off.
- Forced ventilation is not required when the gas volume of the largest gas chamber at atmospheric pressure is at most 10% of the room volume. This also includes the gas storage tanks.

Other requirements regarding the design of the operational room result from the protection against the effects of arc faults; see chapter D 10.2 c.

D 9 Personnel protection

For every switchgear construction, protective measures are prescribed against direct contact or hazardous approach to active parts. In the most simple case, this can be a barrier or a railing at the appropriate distance; the best protection against electric shock is the total metal enclosure.

The definition of the degree of personnel protection required and the type of operating room are decisive for the type of enclosure of the switchgear. The operational action for which the protection is provided also has to be be observed, as well as the qualification of the personnel operating and working at the switchgear.

Which degree of protection shall the switchgear provide

- during operation and control
- when performing planned work
- during reconditioning after faults?

D 9.1 Protection during operation

According to EN 50110 / VDE 0105 the operation of switchgear comprises observation and setting (switching).

Since numerous old-design, open switchgear installations are still in use (and will remain so for many years), accident prevention regulations specify minimum personal safety requirementsfor such equipment. For example in Germany the BGV A3 regulation[9] states that people must be protected to a substantial extent from arcs, to which end the following (or equivalent) measures can be taken:

a) Switch-disconnectors instead of disconnectors with interlocks

b) Protection against maloperation for disconnectors and earthing switches, e.g. interlocking, make-proof earthing switches, non-interchangeable key interlocks.

c) Protection against maloperation for disconnectors and earthing switches, e.g. interlocking, make-proof earthing switches, non-interchangeable key interlocks.

d) Provision of suitable protective devices, e.g. arc guide plates, arc windows, full-wall doors, separation walls.

Open switchgear with its barriers, railings or screens can only provide a low degree of protection (only against accidental contact according to IEC 61936 / VDE 0101). In enclosed switchgear or in switchgear with at least enclosed operating fronts, the circuit-breakers are generally operated e.g. by means of an outside pushbutton, i.e. with the front door closed. Disconnectors, switch-disconnectors and earthing switches are also operated from outside by means of linkages. Today, constructions implying the opening of the door for this purpose should not be taken into consideration anymore. It is absurd to reduce the quality of protection considerably just when carrying out a switching operation, which is a change of state that is undoubtedly more dangerous than static operation, and which always implies a person standing close to the switchgear.

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[9] BGV A3 (formerly VBG 4) is an accident prevention regulation issued by the statutory industrial accident insurance institution (“Berufsgenossenschaft”). It requires that old switchgear be retrofitted. Details are specified in VDE 0101, issue o5.1989. See also BG-Information 559, which provides instructions for modifying high voltage switchgear (01-2002) and describes examples.

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The alternatives mentioned in a) and b) require critical consideration.

Switch-disconnectors or disconnectors with switchgear interlock?

Item a) ”Switch-disconnectors instead of disconnectors with switchgear interlock”, continues: "The switch- disconnectors must be able to break the maximum normal current arising at their location, and they must be suitable for making onto a short-circuit." At first sight, the following arguments speak for the simplification:

- simple technology with fewer components, because then
- no feeder interlocking is required, and
- no inter-cubicle switchgear interlocks are required.

However, it must be considered that incorrect switching operations are possible, which can result in breakdown of supply.

Cable disconnectors - if provided - must be switch- disconnectors, as disconnectors cannot switch off under load.

Feeder earthing is possible, even if voltage is still applied. Consequently, the switchgear must be equipped with make-proof earthing switches. This is safe for the operating personnel, but it does not avoid a fault and possible supply failure.

In this case earthing is already possible when only the circuit-breaker is open, but the isolating distance to the busbar has not been established. For this reason, (in switchgear with disconnectors and a switchgear interlocking system) the earthing switch is only interlocked against the disconnector and not against the circuit-breaker!

Double busbars can be interconnected via the two switch- disconnectors of a feeder, without the bus coupling circuit-breaker. In this case, not only the rated normal current, but also the short-circuit current of this link can be exceeded, which means a serious danger if this under-rated coupling is not removed after busbar transfer of the feeder. On the other hand, an inter-cubicle switchgear interlock would force the opening of the coupling.

Another argument against the solution with switch-disconnectors - independent of the above mentioned reasons - is the breaking capacity of the devices. Further to the maximum normal current, additional marginal conditions affect the breaking capacity required:

- the power factor cos φ
- a possible system earth fault
- a possible earth fault in the feeder to be disconnected
- the possibility of an evolving fault, i.e. the normal current turns into a short-circuit current during switching off.

In the case of strong inductive currents e.g. with motors, shunt reactors and other special consumers, most of the conventional (not SF_6 or vacuum) switches have only a limited breaking capacity.

In the case of a system earth fault, i.e. on the busbar side, the switch is stressed in the healthy phases with a higher transient recovery voltage.

In the case of an earth fault in the feeder to be disconnected, the switch must not only break the normal current, but also the superimposed earth fault current of the system.

In the case of a short-circuit (evolving fault) the switch-disconnector has no short-circuit breaking capacity.

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The probability of these critical cases can by no means be neglected. Thus, the solution with switch-disconnectors does not provide the protection required for all service conditions.

In contrast to this, a disconnector with switchgear interlock completely provides the personnel protection required. A circuit-breaker has the breaking capacity required; the disconnector always opens in the de-energized condition.

Today, withdrawable circuit-breakers are replacing the disconnectors to a large extent. Moving between connected and disconnected position should only be possible with the front door closed, except when a second protective wall with covers is located behind the front door, providing (almost) the same protection as the front door. Compartmented switchgear is often designed in this way today. Constructions with the front plate moving out totally or partially are also safe, if protection against electric shock is ensured by other means.

Protective devices and remote control

The items c and d can only be considered as supplementary measures. Remote control as the only measure would only ensure personnel safety, but it would not prevent operational or supply breakdowns if no provisions have been made against remote maloperation. The same applies for protective devices. Only the combination of active and passive measures (interlocks, switchgear interlocking system and resistance to internal faults) enables a trouble-free service and the safety of the personnel.

D 9.2 Protection during work

D 9.2 a General

According to EN 50110 / VDE 0105, working on switchgear covers maintenance, e.g. cleaning, modifying, commissioning and clearing of faults. The ideal case that the whole switchgear is switched off before beginning with the work is very rare during practical service. So, as part of the switchgear remains in operation, it is nesessary to work near live parts. According to EN 50110, the following "5 Safety Rules" for the place of work must be carried out

- Isolation
- Securing against reclosing
- Verifying safe isolation from voltage (dead state)
- Earthing and short-circuiting
- Covering or fencing adjacent live parts

In principle, these are requirements concerning the future user, but the possibility to comply with them must already be taken into account during planning, and the procurement of the required devices must also be considered. Designs of switchgear which require to be opened the front door in order to carry out the check for dead state, earthing and short-circuiting and covering live parts should not be considered for new installations. It does not make any sense to lower the protection against hazardous parts during work which needs even more protective measures and where personnel is always present in contrast to normal operation.

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D 9.2 b During planned work

In open and in enclosed but non-compartmented or semi-compartmented switchgear, enough portable devices for protection against adjacent live parts must be provided besides the fixed- mounted panel partitions. When the work has been previously planned, suitable protective devices e.g. insulating plates or covers can be provided in time. According to EN 50110, these need only offer partial protection against reaching into dangerous zones, i.e. protection against accidental contact. The working personnel themselves must always take care that they do not reach into dangerous zones with the body nor with objects (EN 50110). This means, that a certain direct responsibility is expected of qualified personnel in charge of the work. Today, there is partially compartmented switchgear on the market offering total protection against touching at least for important parts of the components installed, e.g. the cable connection, by means of portable protective devices. In this way, this switchgear type already exceeds the requirements of EN 50110.

In enclosed and compartmented switchgear, the partitions are an always effective, fixed-mounted part of every panel besides the separation walls. They provide permanent total protection against contact and they do not need to be brought along when required.

D 9.2 c After faults

For this type of work, basically the same applies as in the previous section. However, additionally it happens that in the hectic state of such actions even highly qualified personnel may forget some safety rule or ignore it consciously in order to save time. This risk is almost non-existent in switchgear with permanent total protection against electric shock by means of automatic shutters or interlocked access barriers.

D 9.3 Degree of protection of the enclosure

For the enclosures, the degree of protection against electric shock is specified with regard to the size of openings, according to IEC 60529 / VDE 0470-1. Hereby it is determined if test objects of different sizes (fingers, tools, wire) can enter the enclosure, unduly approaching live parts. The classification is parallel to that of the protection against solid foreign bodies; see also chapter D 4.5.

D 10 Internal arc faults

Disruptive discharges between the poles or to earthed parts leading to an arc burning freely within the switchgear are called internal faults or arc faults. Although the probability of such an event is low, it cannot be neglected completely. In the old German Federal States, the frequency of such a fault is estimated to be 1 internal fault per 10,000 (10^{-5} p.a.) panels and per year with air-insulated switchgear and to be even only 1 fault per 100,000 (10^{-6} p.a.) panels with gas-insulated switchgear. Such an event can imply risk of injuries to the personnel present, but this probability is even lower. When making efforts regarding the maximum personnel safety possible, the main aim should be to avoid internal faults or to limit their duration and their effects.

D 10.1 Causes and effects

Causes for internal faults can be:

- Defects of material or functional faults of devices
- Overstressing, pollution, humidity
- Negligence during operation and maintenance

The first group appears rarely, but if it does, it appears in conjunction with causes of the second group in most cases. The user can exclude these sources of fault to a large extent by correct use and appropriate maintenance in time. The third group can be reduced by instructing the personnel, but especially by installing switchgear types offering a high degree of protection against electric shock, which implies a high protection against ingress of solid foreign bodies e.g. when working, as well as a complete interlocking system.

IEC 62271-200 / VDE 0671-200 list the most frequent causes of fault in Appendix A, as quoted below. The standard also gives examples of methods by which the probability of fault and the results can be reduced.

Fault location	**Possible causes**
Cable compartments	- Inadequate design - Faulty installation - Failure of solid or liquid insulation (defective or missing)
Disconnectors, switches and earthing switches	Maloperation
Bolted connections and contacts	- Corrosion - Faulty assembly
Instrument transformers	Ferro-resonance; short-circuit on secondary (LV) side of VT, open terminals of CT
Circuit-breakers	Insufficient maintenance
Allgemein	- Error by personnel - Ageing under electric stresses - Pollution, moisture ingress of dust, vermin, etc. - Overvoltages

Table D-7: Internal fault arcs – locations and causes

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The short-circuit current (I_K) flowing through the arc and the arc voltage (U_{arc}), which depends on the distances between phases (arc length), determine the power converted; $W_{Lb} \approx U_{Lb} \cdot I_K \cdot t$. An arc burning freely in air has a voltage of approx. U_{LB} = 15 - 20 V/cm. In Figure D-12 the listed effects of such an arc are taken from a fault arc test.

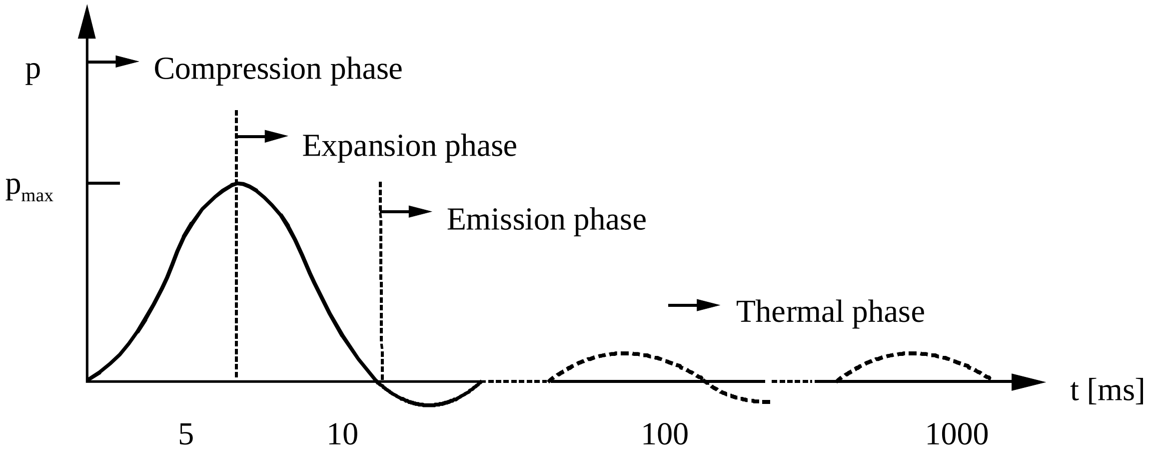

Figure D-12: Basic pressure characteristic of a fault arc

Examples from a fault arc test 12 kV / 50 kA / 0.1 sec (Type 8BK)

Temperature	≈ 10.000° C
Energy	7.8 MWs = 2.2 kWh
Power	200 MW after 9 ms
Peak pressure	1.1 bar after 8.8 ms
Surface load	≈ 10 t/m^2

The enormously high power of the arc effects, above all, a sudden temperature rise of the air within the cubicle which, in turn, (within 10 ms) causes a steep fronted pressure wave. The pressure peak can be limited by the provision of pressure relief vents but the pressure wave will severely stress the cubicle and the building. Flying debris can present serious hazards for personnel. If pressure relief is inadequate, even the building may collapse.

After approximately 100 ms, the thermal phase begins: material melts, vapourises and decomposes; fire may result. Hot gases and decomposition products, perhaps toxic, can seriously endanger personnel.

Whilst the pressure rise is unavoidable, the effects of the thermal phase can be prevented by fast acting protective devices; by detection of the arc by sensors, which react to optical or pressure signals and rapidly open the feeder breakers.

In the case of arcs in SF_6, the pressure rise is slower. The arc voltage of the SF_6 arc is smaller than that of air. Thus, the arc energy is lower. The enclosure subjected to pressure may remain closed, i.e. the pressure relief does not operate.

However, if gas does stream out, (toxic) SF_6 decomposition products must be expected. Gaseous and dusty decomposition products containing fluorine and sulphur are aggressive and react with the air humidity. Therefore, measures must be taken after an arc fault, such as room ventilation (compare with chapter C D 8.2 c) and putting on breathing protection and protective clothing when entering the room; Health and Safety authorities have issued instructions on this subject.

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D 10.2 Protection against arc faults

Accident prevention regulations demand that systems be set up such that persons are largely protected against the effects of internal faults. This applies not only to new equipment but to existing installations too (In Germany, BGV A3 states that these must be upgraded by means of measures specified in VDE 0101, issue o5.1989, item 4.4; see also chapter D 9.1, items a – d).

An effective protection against arc faults can be achieved by:

- the switchgear
- the system layout
- the switchgear building

D 10.2 a Measures during system layout

The system configuration and the magnitude of the short-circuit current are decisive for the effects of a possible fault. Some measures could be:

- Division of the switchgear installation into several sections each with its own incoming feeder
- The use of feeder transformers with high short-circuit impedance (u_z) i.e. a smaller short-circuit current
- Special consumers, such as motors, require a higher system fault level in order to avoid strong voltage dips during starting. Such consumers can also be separated from "normal" ones and be fed by a separate transformer.

The division of the switchgear into several sections has the following advantages:

- smaller short-circuit currents are possible; this implies a smaller arc energy,
- a simple system structure enables system protection with short tripping times,
- only small parts of the system break down if a fault occurs.

D 10.2 b Measures in the switchgear

First of all, the construction of the switchgear itself should prevent arc faults. This comprises e.g. feeder-related and switchgear-related interlocks and interlock systems, protection against electric shock, automatically closing shutters as well as type and extent of the insulating material used. For air-insulated switchgear, this may become quite expensive depending on the degree of realization, whereas gas-insulated switchgear automatically comprises a great part of the provisions mentioned due to its construction.

Second, protective systems with a short tripping time can reduce the fault duration. Suitable systems are busbar differential protection or sensors reacting to light, pressure or temperature. When switchgear is remote controlled, there is no need for personnel to stay next to it.

Third, there are arc killers for limiting the duration of the arcing fault. They stop the flow of energy to the arc by short-circuiting the incoming feeders, e.g. by means of a make-proof earthing switch (earthing switch with short-circuit making capacity). An arc killer can be activated electrically via sensor electronics, or mechanically, as is the case for example with hermetically sealed gas-insulated secondary distribution switchgear, in which – in the event of an arc – the deformation of the vessel (caused by pressure) triggers a make-proof earthing switch.

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Fourth, a switchgear enclosure which is resistant against internal faults reduces the danger so much, that the required personnel safety is guaranteed. The criteria an enclosure must comply with in order to prove its resistance against internal faults are described in chapter D 10.3 c.

Fifth (in special eventualities), additional precautions in the design of the pressure relief can effectively reduce the stress on the switchgear compartment and the surrounding area. Figure D-13 shows an example with the so-called pressure absorber: Expanded metal sections in a pressure relief duct on the panel rear cool the outgoing arc gases and consequently effectively reduce the excess pressure.

Such measures are however costly and therefore only appropriate in certain circumstances, e.g. in order to protect the structure of old buildings. Since arcs only very seldom occur in modern switchgear, pressure absorbers are generally not required.

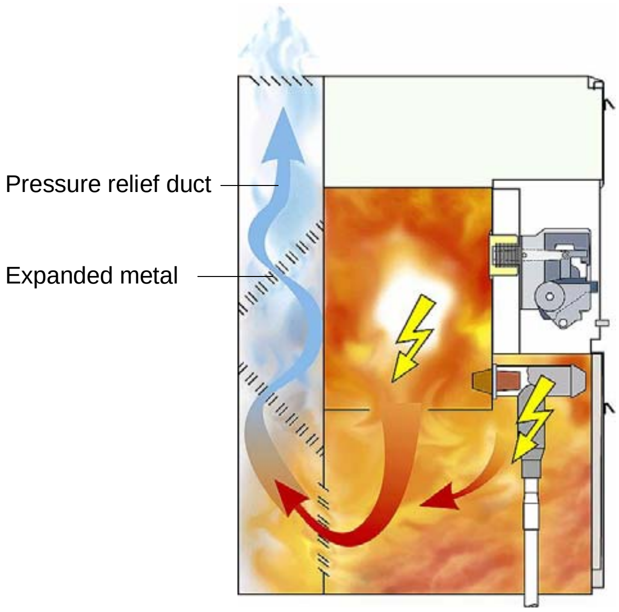

Figure D-13: Absorbers damp the overpressure in the building

D 10.2 c Measures in the switchgear building

In the event of fault, the conditions in the building must also be considered, even when installing switchgear that is resistant to internal faults.

Hot gas streaming out through the pressure relief flaps of the switchgear can be reflected at walls and low ceilings and hurt somebody.

Relief is accomplished by a correct opening direction of the pressure relief flaps and air guides leading the gas flow to the ceiling. If the room is low, the air guides should reach up to the ceiling; the pressure is relieved to the outside or to another room (cable basement).

The pressure wave stresses the ceilings, walls, doors and windows of the building. An overpressure of approx. 1 kPa (this corresponds to a force of 100 kg/m²) can destroy a brick wall; a concrete wall withstands about 5 kPa.

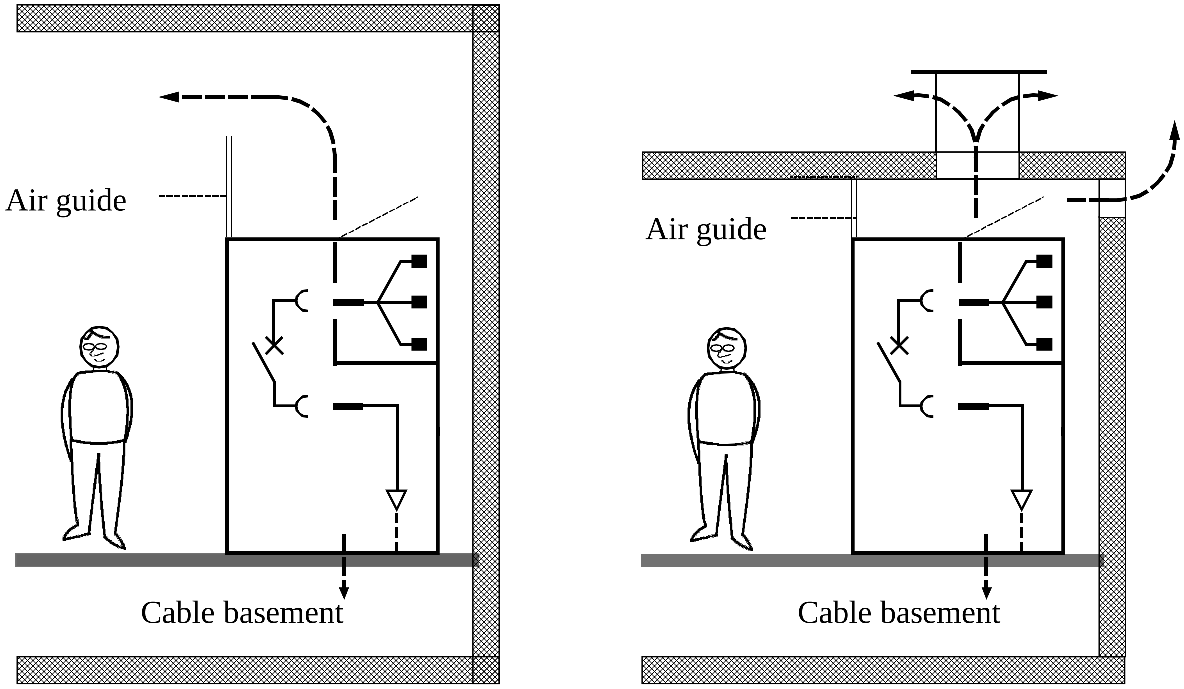

Figure D-14: Pressure relief (example) for high and low buildings

So it is necessary to provide constructional measures for pressure relief in the building. These are e.g. wall and ceiling openings or ventilation ducts.

- They must be closed during normal service in order to prevent ingress of climatic influences and vermin.
- When the pressure relief opens, no parts may fly around and endanger people.
- The pressure relief must be designed to prevent danger to people by gas streaming out. This is especially important in unit substations at public places.

Computer programs are available for the pressure stress in the event of arc faults. The manufacturer and the user of the switchgear must agree upon the measures to be taken for pressure relief of the building during the planning stage. In most of the cases no expensive additional measures must be taken, as the openings (ventilation) provided for other purposes can be used for pressure relief.

D 10.3 Internal arc test

The behaviour of metal-enclosed switchgear in case of internal arc faults – regarding the level of protection to persons – can be determined by a test. IEC 62271-200 / VDE 0671-200 Appendix A defines the test sequence, the marginal conditions and the evaluation of the results. It is mainly a matter of proving that no doors open, no parts fly off, no holes burn into the accessible outer walls, and that personnel standing in front of the switchgear is not hurt by dangerous hot gas streaming out of slots or being reflected from the ceiling.

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D 10.3 a Test arrangement

The test arrangement takes the actual conditions in a service room into account. When placing the indicators, the question of access to the switchgear is decisive. It is divided into two types: type A is only installed in closed electrical operating rooms, type B is generally accessible for the public (unit substation). The main requirements regarding the test arrangement are:

- The installation conditions have to correspond to the normal service conditions as much as possible. At least the ceiling, the floor and two perpendicularly arranged walls should be reproduced.
- The test object has to consist of two switchgear panels (in the case of a panel-type switchgear).
- The switchgear panel has to be equipped with internals; but mock-ups of the same material and volume are permissible.
- The power supply and the point of ignition are to be selected to produce the maximum stress. The direction of power flow must be arranged so that the test represents an outgoing feeder panel (the most likely case).
- Each switchgear compartment has to be tested.
- The thermal effect of the hot gases is registered by indicators of black cotton cloth that have to be arranged as shown in Figure D-15 and Figure D-16. For degree of accessibility A (qualified staff) more resilient materials are used (working clothes) than for degree of accessibility B (public).

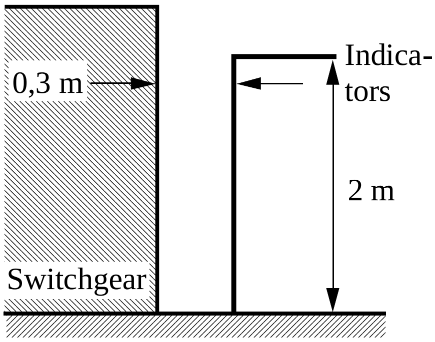
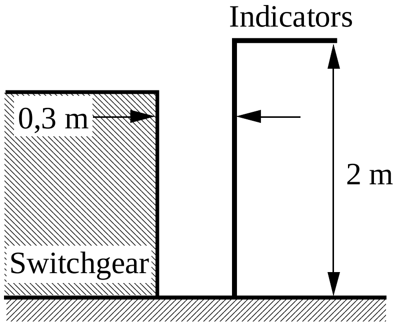
Horizontal and vertical material indicators arranged in a chessboard pattern show whether – during the arc- dangerous hot gases escape from the enclosure.

The room simulation consists of ceiling, floor and two right-angled arranged walls.

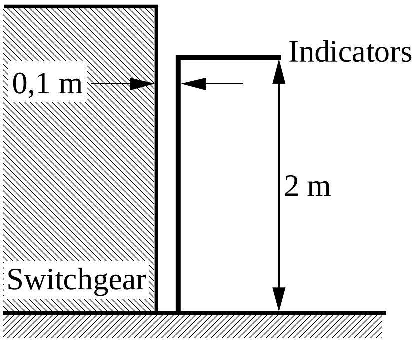
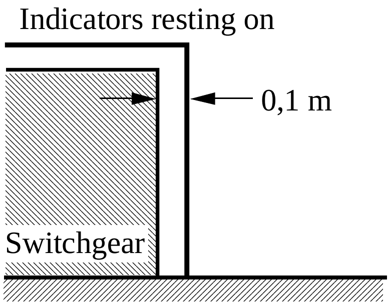
Figure D-15: Test set-up in the room simulation

<table>
<tr><th rowspan="2">Degree of accessibility</th><th colspan="2">Height of switchgear</th></tr>
<tr><th>above 2 m</th><th>less than 2 m</th></tr>
<tr><td>A

Only for experts and authoriesed personnel

Closed electrical operating rooms</td><td>
</td><td>
</td></tr>
<tr><td>B

Always accessible

On public places</td><td>
</td><td>
</td></tr>
<tr><td>C

Pole mounted

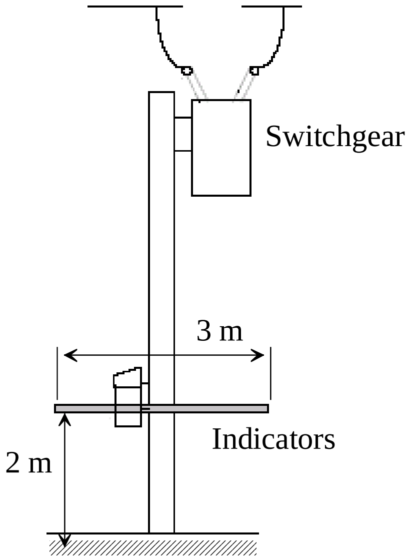
Publicly accessible</td><td>
</td><td></td></tr>
</table>

Figure D-16: Arrangement of the indicators

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D 10.3 b Test duration

It has to be equal to the actually expected arc duration, in accordance with the protective equipment; preferred values are 0.1 / 0.5 and 1.0 s. In practice, most switchgear installations must undergo a test lasting 1 s.

D 10.3 c Evaluation and acceptance

Five criteria take the effects of an internal arc fault into consideration. For switchgear to be designated as qualified in terms of arc faults, they must all be met.

Criterion No. 1
Correctly secured doors and covers do not open. Deformations are accepted, provided that no part comes as far as the position of the indicators or the walls (whichever is the closest) in every side. The switchgear and controlgear do not need to comply with its IP code after the test.

If the switchgear will be mounted closer to the wall than tested, two additional conditions shall be met: the permanent deformation must be less than the intended distance to the wall, and no exhausting gases are directed to the wall.

Criterion No. 2
No fragmentation of the enclosure occurs within the time specified for the test. Projections of small parts, up to an individual mass of 60 g, are accepted (This means small plastic parts such as for example pushbuttons).

Criterion No. 3
Arcing does not cause holes in the accessible sides up to a height of 2 m.

Criterion No. 4
Indicators do not ignite due to the effect of hot gases.

Should they start to burn during the test, the assessment criterion is met, if it can be proved that the ignition was caused by glowing particles rather than hot gases. Pictures taken by e.g. high-speed cameras or video can establish evidence.

Indicators ignited as a result of paint or stickers burning are also excluded.

Criterion No. 5
The earthing conections of the enclosure must remain effective.

In the test report, the evaluation is written down together with other prescribed information, comprising:

- Rated values and description of the switchgear panel tested, together with a drawing. The drawing shall describe details that are important for the mechanical strength. In addition, the following must be included: the location of the pressure relief flaps, the replica of the room and the switchgear fixing.
- Location of the supply and the point of ignition
- Arrangement and type of material of the indicators

- Test current:
  - the r.m.s. value of the AC component during the first three half-waves
  - the highest peak current
  - the mean value of the AC component over the actual test duration
  - the test duration
- Oscillograms of currents and voltages
- Arrangements of the test specimen deviating from the normal service condition.
- The evaluation of the test results

Tests of the behaviour in the case of internal faults are very expensive, and they are therefore only viable for standard types manufactured in large quantities. Even these types comprise many variants of rated values and component combinations. Therefore it is permissible to deduce the behaviour of a comparable design from that of tested arrangements.

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E DESIGNS AND APPLICATION OF SWITCHGEAR

E 1 Classification of the designs

Starting with the standard according to which they are built, medium-voltage switchgear designs can be classified by way of their features, as shown in Figure E-1. The systematic classification scheme starts with the type of enclosure and the standard in line with which the switchgear is built.

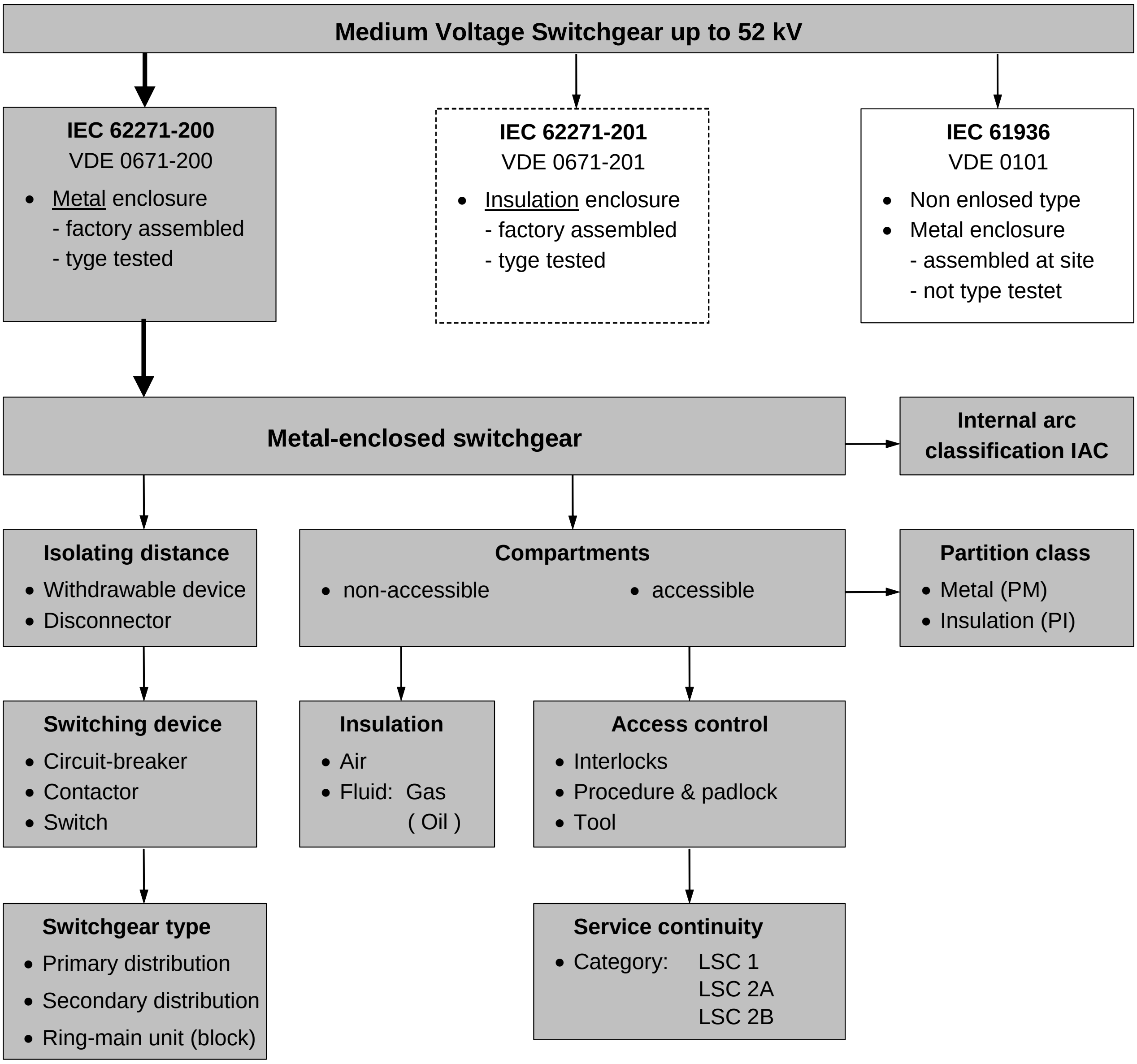

Figure E-1: Classifications of the switchgear designs

Further subcategorization and classificationof the switchgear reflect the main design features and the operational requirements.

- Isolating distance: Must switching devices be replaceable (withdrawable or fixed-mounted)?
- Switching device and panel type are determined by the switching duty and the contextual conditions of the network.

- Compartments: Which ones must be accessible and with what manner of control, which parts of the system can be shut down (availability)?
- Insulation: By means of gas (hermetically sealed) or air, depending on ambient conditions, required degree of safety, space requirement etc.
- Classification in terms of arc faults: This means evidence of particular behavior relevant to personal safety in the event of an internal short-circuit with arc.

A classification in terms of age starts with non-type-tested switchgear to IEC 61936 / VDE 0101. This type of switchgear is assembled with type-tested equipment (circuit-breakers, disconnectors, instrument transformers etc.), but it is not type-tested itself. The security of the type-test is replaced by the security of the ratings. The "minimum clearances in air" as fundamentals for the insulation rating are based on decades of experience. This also applies for the design of the current carrying bars regarding the loading capacity, and according to IEC 60865 regarding the fault withstand capability. This type of design without obligatory tests offers a certain freedom of assembly. The air insulation conforming with minimum clearances leads to larger dimensions in most cases, but it reduces the amount of insulating material, and thus, the problems caused by deterioration of the dielectric strength and by fire.

Switchgear to IEC 61936 / VDE 0101 is usually not factory assembled, but put together in workshops or on site. Many years ago, most switchgear was built this way, hence numerous such assemblies still being in use. Such switchgear is usually open, i.e. not enclosed (or only partially). For special cases, switchgear may still be built in accordance with this standard, but with metal enclosure.

E 2 Enclosure

For the purpose of power distribution, it would be simplest to screw the busbar and the devices to the wall side by side. Such "installations" did and do really exist. However, the whole installation must be switched off for any work to be carried out. For safe working and, in the event of fault, the complete installation is always affected. Historically, subdivisions were soon provided by means of separation walls between the feeders, then separation from the aisles, first by means of barriers or ropes, later on by screen doors and finally by sheet steel.

The highest level of protection is given by completely enclosed switchgear. If it is designed according to the standards, it has a full enclosure, and interlocks that prevent maloperation of the switching devices.

The metal enclosure has a double function. It protects

- the switchgear against disturbing influences, thus ensuring reliability
- the personnel against contact with live parts or against dangerous approach from outside. The degree of this protection is designated with IP (see chapter D 4.5).

According to IEC 61936 / VDE 0101 IP2X is sufficient for closed electrical operating areas which are only accessible to qualified staff. In rooms without access of the public, at least IP3X must be achieved, and in rooms that are accessible to everybody, even IP4X is not enough.

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E 2.1 Metal enclosure

The all-round earthed metal enlclosure provides a very high degree of safety, both for persons and in terms of operating reliability. For switchgear according to IEC 62271-200 / VDE 0671-200, all data are proven by type tests of a defined extent. The quality of manufacture is controlled by routine tests. Machining and (often) automatic production, especially that of the supporting structures, guarantees narrow and constant tolerances. However, the expense of type tests, the production planning and the manufacture are only viable for large production quantities. The specifications of all countries of the European Community and many other countries, are harmonised. That is why these switchgear types are the basis of the world-wide export trade of the switchgear manufacturers.

Nowadays these designs dominate the market, and are available for up to very heavy duties – 63 kA rated short-circuit breaking current and 5000 A rated normal current of the busbar / 4500 A rated normal current of the feeders. The following sections describe further classifications and features.

E 2.2 Insulation enclosure

Switchgear to IEC 62271-201 / VDE 0671-201 is likewise factory-assembled and type-tested, but has no metal outer enclosure; this is made of insulating material, usually cast resin. This type of enclosure involves considerable effort in terms of manufacture and testing. Solid insulation must be free of partial discharges, since these can cause serious deterioration in the insulation over the long term. Insulation enclosures are used only for special purposes; there are very few such systems on the market. This switchgear type is consequently not dealt with in the following.

E 3 Isolating distance

The question of the isolating distance – fixed-mounted or withdrawable switching devices – arises almost exclusively for air-insulated switchgear, since (owing to the sealed enclosure) gas-insulated switchgear comprises only fixed-mounted equipment, with certain very rare exceptions.

The isolating distance required between the busbar and the circuit-breaker can be established by means of disconnectors. But then, an interlock between the disconnector and the circuit- breaker is always required. There are not many good solutions available for this purpose – especially in the case of double-busbar switchgear and manually operated drives. That is why some switchgear designs refrain from interlocks and use switch-disconnectors instead of disconnectors. This is permissible according to the standards, but many technical questions regarding safety and reliability remain open.

Therefore, in air-insulated switchgear the isolating distance is often established by moving the main switching device (circuit-breaker), which is connected via moving contacts, within the panel from the connected to a "disconnected" position and vice versa. Of course, this must only be possible when the breaker is open. The interlocking required is feeder-related and easy to implement. When assigning the attribute ”disconnectorless” to this type of switchgear, the responsibility for all the problems encountered in non-withdrawable switchgear types has been put on the disconnector. This is not an objective view however, as the switching errors are not caused by the disconnector, but by missing or bad interlocking.

The "withdrawable" part of the switchgear, a circuit-breaker in most cases, was a so-called switchgear truck for a long time. In that design, every breaker has its own truck, on which it rests even when it is outside the panel, e.g. for maintenance. This truck is heavy and expensive and makes

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high demands on the floor of the switchgear room. The maintenance requirements of modern circuit-breakers are so low, that it is not worth providing one truck for every circuit-breaker. That is why it has now become the common practice to move the breaker to its positions within the panel as a carriage on a rail. If a breaker must be totally removed from the panel as an exception, a central service truck provided for the whole switchgear is enough. This truck can be very convenient. Regarding all other aspects – e.g. interlocking – switchgear trucks or withdrawable units are treated in the same way and provide the same facilities.

E 4 Methods of compartmentalization

So that work can be done while the switchgear is in use and without having to shut down the entire system, the switchgear is divided up into individual compartments with a defined mutual IP degree of protection. This way, personnel safety and power supplies can be maintained at the same time. In most switchgear

- the busbars (for double busbars, each system),
- the main switching device and
- the cable connection

are located in separate compartments. If each of these functions has its own space, this is referred to as “compartmentalization“; otherwise “cubicles” are spoken of if a number of functions are combined in a shared space. The partitions and shutters must comprise a degree of protection of at least IP2X. The following lists some main variants of compartmentalization in air-insulated switchgear.

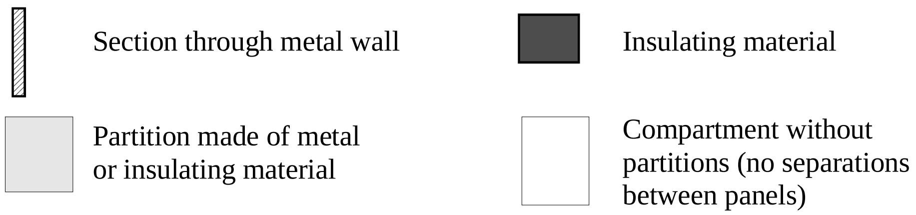

Figure E-2: Legend to the following grafics

E 4.1 Compartmentalization

Figure E-3 shows a typical example of switchgear with three compartments: for busbar, cable termination and switching device (on a truck or withdrawable unit). The circuit-breaker establishes or interrupts the connection between the busbar compartment and the cable compartment by means of its isolating contacts. In the disconnected position, it is therefore comparatively easy to isolate the circuit-breaker compartment from the other compartments. The other compartments can remain live while maintenance or other kind of work is carried out in the circuit-breaker compartment. The openings for the isolating contacts are automatically closed safe to touch in the disconnected position

Variant (a) has three compartments (separated by bushings in the connected position too) and a straight-through busbar compartment. In Variant (b), the compartments are not separated in the connected position. Variant (c) reflects (b) with additional busbar compartmentalization from panel to panel. The standard makes no detailed distinction between the variants, because it considers only the level of personal safety in the disconnected position.

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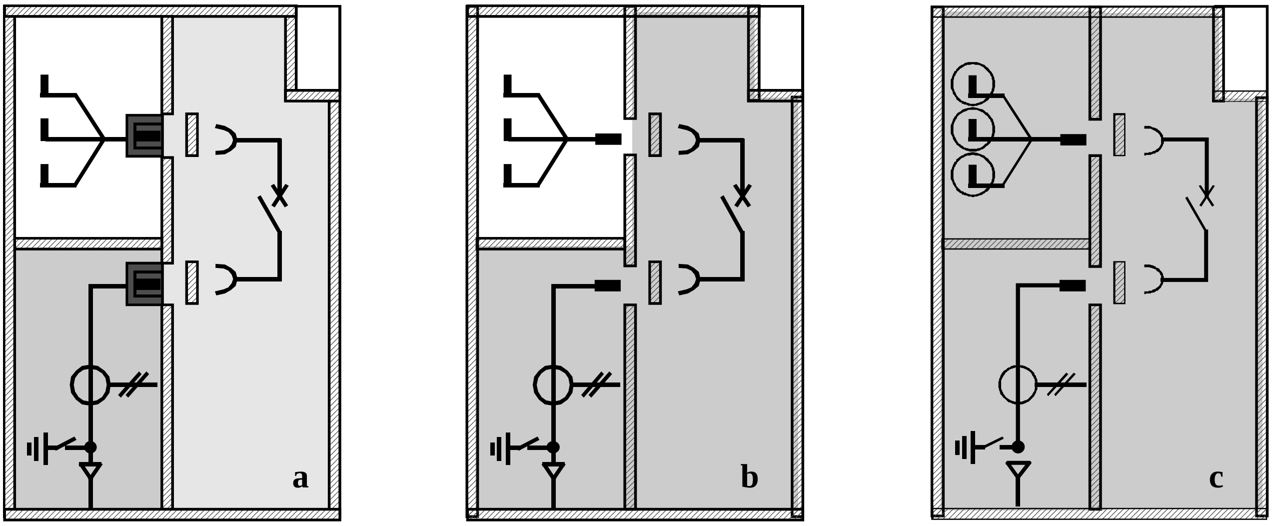

Figure E-3: Withdrawable or truck-type design with „compartmentalization“

Examples a to c feature most frequently the compartment classifications:

- Busbar – interlock-controlled accessible
- Switching device – interlock-controlled or procedure-based accessible (padlock)
- Cable – tool-based accessible
- Loss of service continuity category LSC 2B (see chapter E 4.6)

However, during service it can make a great difference whether all three compartments are separated from each other (a), whether all partitions are open (c) or whether the three compartments of a panel are separated from the adjacent panel. Version ‘a’ makes it possible to maintain the compartmentalization even in case of an internal fault and to limit the effects of the fault to its location; but this is not requested by any standard, and it is not common practice. Partitions are exclusively provided for protection against electric shock.

E 4.2 Cubicles

Switchgear is therefore available with cubicles. Figure E-4 shows a two-space variant (d) with fixed compartmentalization of the busbar and a shared space for switching device and cable termination. Arrangement (e) features temporary segregation (protective barrier) from the busbar; this plate can only be inserted in the disconnected position.

For the examples in Figure E-4 a distinction is made between the compartment classifications. For fixed-mounted compartmentalization (d) the following applies:

- Busbar: – tool-based accessible
- Switching device, cable – interlock-controlled or procedure-based (padlock) accessible
- Loss of service continuity category LSC 2A (see chapter E 4.6)

For temporary compartmentalization (e) with protective plate the following applies:

- Busbar – tool-based or procedure-based accessible
- Switching device, cable – interlock-controlled or procedure-based (padlock) accessible
- Loss of service continuity category LSC 2A (see chapter E 4.6)

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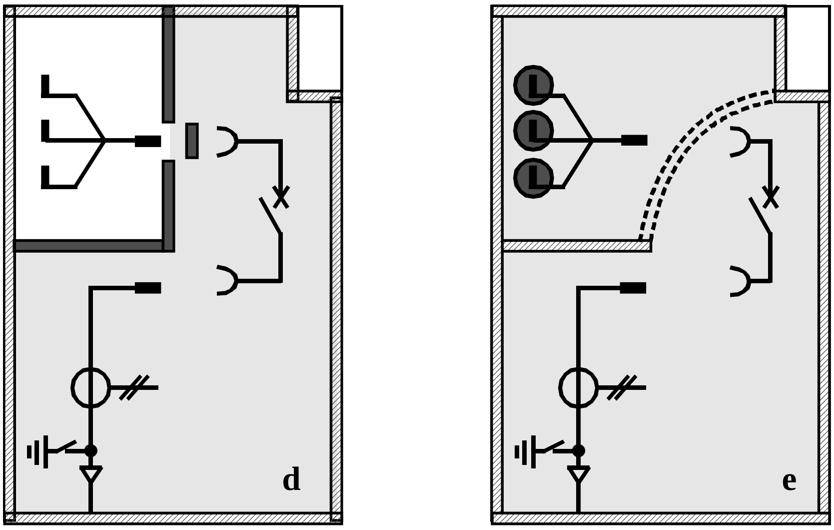

Figure E-4: Cubicle design with withdrawable or truck-type switching device

The degree of compartmentalization has a great influence on the panel dimensions. In the case of fixed mounted metal compartmentalization, the depth clearances required for insulation are more often needed than in the case of partial compartmentalization. That is why partially compartmented switchgear is much smaller in depth, by up to 800 mm. This is the reason why this type of switchgear is widespread.

Does the partially compartmented design have clear disadvantages in service when compared to the design with three compartments?

Service	Design	
	compartmented or metal-clad	cubicle type
Normal (undisturbed)	no difference	
Work in the cable compartment	withdrawable unit in disconnected position	
	automatic shock protection (shutter)	manual insertion of temporary barriers or temporary partitions
	remove partition to cable compartment	cable compartment freely accessible

Table E-1: Influence of compartmentalization on service

The table sets out the effects of the different types of partitioning on faults and work on the switchboard. The difference in the case of faults is not very significant – regarding the very reduced probability of fault in modern switchgear installations. Trained staff will also have no problems when working in partially compartmented switchgear, and there is no difference regarding safety. Assuming, that the insulating protective barrier has the full degree of protection, and that it is integrated into the feeder interlocking system when inserting and removing it. Partially compartmented switchgear can therefore often be found in the installations of utility companies. In contrast to this, in industrial plants, integral compartmentalization is often required in order to relieve the personnel of this responsibility.

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E 4.3 Partitioning of the busbars

Has additional partitioning – which is not required by the standards – of the busbar chamber, from cubicle to cubicle (busbar cross partitioing), in compartmented switchboards any purpose? Cross or transverse partitioning of the busbar compartment cannot improve protection against contact because work on the busbars always requires that the whole system be shut down.

If a fault occurs in a busbar chamber which does not have partitioning, the arc will run rapidly along the busbar, within 100 m/s, away from the source of energy - the incomer - and stand and burn at the end of the board until the power is cut off. Tests have shown that the busbar itself remains intact and shows only insignificant oxidation marks up to that point. The fault arc seriously damages only the end cubicle which is easily accessible for repair work. One could even extend the busbar beyond the end cubicle, into a sacrificial enclosure, but merit of this may be debatable because the direction in which the arc will travel is not always totally predictable. It is determined by the position of the incomer. If this is at the side (A in Figure E-5) the direction is clear but if it is in the middle (B), the arc could wander to both ends. In example (C) the direction is indefinite.

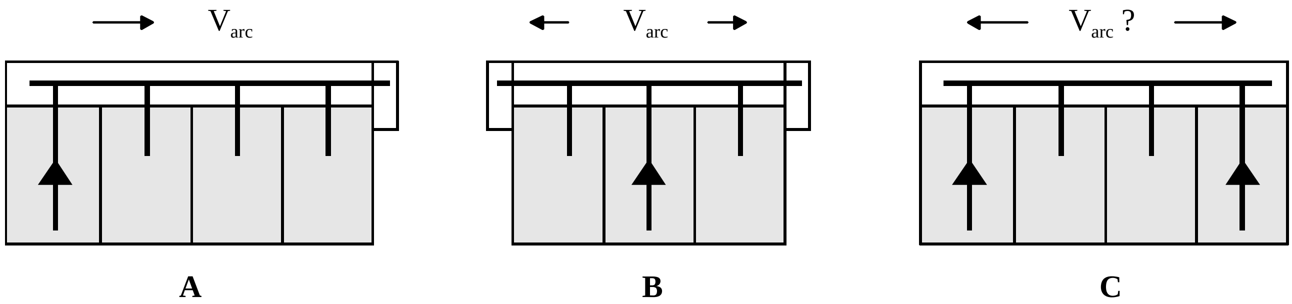

Figure E-5: Direction of fault arc travel for various locations of incomer

Transverse partitioning confines the arc. It burns at its source until it is cleared – if the partitioning is strong enough. Damage is largely confined to that cubicle but repair work in the centre of a switchboard will be more difficult than at an end cubicle.

Thus, whether transverse partitioning is advantageous or not must be examined case for case, but one should not over-emphasise such remotely likely arc faults. Transverse partitioning is an inherent feature in partly compartmented switchboards, because the busbars are almost always supported on bushings at the cubicle separation walls.

E 4.4 Accessibility of compartments

The operation of (and work done on) switchgear are significantly influenced by not only the internal subdivision, but also by how the compartments can be accessed and opened. The standard distinguishes between four types of compartment. Three of them differ in terms of access control:

- It is envisaged that an **interlock controlled accessible compartment** should be opened in the context of normal operation or maintenance, e.g. for changing HRC fuses (all forms of repair or installation work are not counted as operation or maintenance). An interlock in the switchpanel allows access after the live parts have been isolated and earthed.
- It is likewise intended that a **procedure-based accessible compartment** should be opened for normal operation or maintenance. Access is controlled by a lock in combination with instructions.

- A **tool-based accessible compartment** – for example a cable termination compartment – can only be opened in certain eventualities, i.e. not in the course of normal operation or maintenance. Such compartments can only be opened by means of a special tool and in accordance with particular instructions.

The fourth type concerns gas-insulated switchgear where access to built-in components is not required and consequently not possible.

- A **non-accessible compartment** must not be opened. Opening the compartment can destroy it and impair the function of the overall system.

E 4.5 Partition classes

While work is being done on the opened switchgear, partitions and shutters provide protection against high voltage from the next compartment or adjacent panel. The standard also defines the material of the partitioning.

- **Class PM** (partition metallic) indicates earthed, all-metal partitions and shutters between the main circuit and the opened compartment.
- **Class PI** (partition of insulating material) applies when at least one part of the partitioning is not metallic, i.e. one or more partitions or shutters are made of insulating material.

Which partition class is preferable? The instinctive reaction to this question is to tend towards the Class PM with its metal partitions, because it reliably earths all parts exposed to touching and provides shielding against electrical fields where work is being done. But both classes attain the same degree of safety-to-touch. The standard therefore allows partitions made of insulating material, which must however comply with very stringent test conditions:

- The insulation between conductor and touchable surface must withstand rated short-duration power frequency voltage and lightning impulse voltage.
- The insulating material of the partitions and shutters must itself withstand the same voltages.
- The insulation between conductor and inner surface of the partition (air) must withstand 150 % of the switchgear rated voltage
- Leakage currents must not be allowed to reach the touchable side of the partition or exceed 0.5 mA (threshold).

In objective terms, partitions made of insulating material tested in this way provide the same safety as metallic ones. In view of its other advantages, it should not be disregarded. Many thousands of panels with insulant partitions are giving successful, trouble-free service.

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E 4.6 Loss of service continuity category (LSC)

This category makes it possible to keep other compartments or panels energized while one compartment in the main circuit is open; accessibility usually concerns the switching device. LSC (Loss of Service Continuity) categories apply only to switchgear with accessible compartments. The definitions are best explained with reference to single-busbar systems.

Category		**If an accessible compartment in a panel is open, …**
LSC 1		• other panels must be shut down, i.e. at least one more
LSC 2	LSC 2A	• all other panels can remain energized.
	LSC 2B	• all other panels, and also the cable termination compartment of the opened panel, can remain energized.

Table E-2: Loss of service continuity categories

LSC 2B applies to switchgear featuring other accessible spaces apart from the busbar compartment (the busbar compartment is an exception, because opening it prevents switchgear operation). 2B means that apart from the panel with an opened compartment, all other adjacent panels (and even its own busbar compartment) remain energized and in operation; the system remains therefore available. Class 2B provides the highest degree of availability, and calls for partitions to the adjacent panels, in addition to at least 3 compartments and 2 isolating distances in the panel.

LSC 2A applies to switchgear of category LSC 2 that does not meet LSC 2B; the panel with opened compartment is taken fully out of operation. Class 2A requires partitions to the neighboring panels, in addition to at least 2 compartments and 1 isolating distance in the panel.

LSC 1 applies to switchgear that does not meet LSC 2. The 1 stands for the lowest level of availability and means that apart from the opened panel at least one more must be shut down. If the busbar is opened, all panels of this section must be isolated.

Gas-insulated switchgear: The LSC categories concern accessible compartments and are intended for installations in which the switching device is accessible. Since with GIS it is neither necessary nor consequently possible to open the compartments, no LSC category is generally stated for gas-insulated switchgear.

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E 5 Internal arc classification

The arc-related qualification IAC applies to switchgear that meets prescribed rating characteristics for the safety of personnel in the event of an internal arc fault. Evidence hereof is provided by specified tests.

=> For details of internal arc tests see chapter D 10.3.

After the test has been passed, the rating plate provides information on the scope of protection against arc faults, on the degree of accessibility, on the tested sides of the switchgear, on the current and on the test duration.

Classification:	IAC (Internal Arc Classified)
Accessibility:	A, B or C, indicating the side: F, L, R [10]
Test values:	Current [kA] and duration [s]

Example 1: Internal arc qualification IAC A FLR 31.5kA 1s
is granted to switchgear tested with 31.5 kA_{eff} for 1.0 s, accessible only to qualified staff, indicators at front, lateral and rear.

Mixed forms of accessibility are possible, e.g. certain sides are accessible to the public and others only to qualified staff or not at all. Switchgear according to example 2 could serve as a load center substation in a factory.

Example 2: Internal arc qualification IAC BF-AR 16kA 1s
goes to switchgear tested with 16 kA_{eff} for 1.0 s, with indicators at front and rear. Accessibility varies; the front is accessible to the public and the rear only to qualified staff, whereas the sides are inaccessible (e.g. surrounded by walls).

The internal arc qualification was introduced as evidence of defined criteria under specified test conditions, in order to make test results more comparable, thereby enabling a user to more easily assess the safety level.

[10] F = front, L = lateral, R = rear

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E 6 Gas insulation

Compartments can be filled with insulating media other than air. In the systematic representation (Figure E-1) they are classified as non-accessible, because the insualting medium has to be sealed inside. The standard uses the generic term “fluid“ for both gas and liquid, meaning in practice SF_6 and oil (oil-insulated switchgear is however now very rare).

Gas-insulated switchgear accounts in the meantime for a substantial share of the market. This is due to its notable advantages in terms of technology, efficiency and ecology, as described in the following section. Further information on the characteristics and handling of this gas is given in → chapter G 1.

E 6.1 Outstanding advantages of SF_6 switchgear

Most practical experience with SF_6 comes from the high-voltage level (voltages above 52 kV) where circuit-breakers with an arc quenching medium other than SF_6 are the exception. Most new indoor installations these days are gas-insulated and even outdoor ones employ SF_6 as the insulating and arc quenching medium. Medium-voltage circuit-breaker switchgear employ SF_6 as the insulating gas and almost exclusively vacuum interruption for handling high operating currents and short-circuit currents with high operating frequencies. Load-break switchgear on the other hand uses SF_6 for insulation and as the arc quenching medium (see chapter E 8.2). Both types of breaker – vacuum and SF_6 – have sealed enclosures and so can be classed as hermetically-sealed-for-life. In comparison with other available technologies SF_6 equipment offers a number of distinct advantages:

Maximum operational reliability

- It offers greater operational reliability than any other type of equipment currently available. Inside the enclosed gas compartments the primary conductors have complete protection against all external effects.
- Compartmentalization limits the effects of faults which are, in any case, extremely rare.
- The minimal use of plastics reduces the fire load, both in the extremely rare case of a fault in the equipment itself and in the event of fire due to external factors.
- The SF_6 insulation ensures complete freedom from oxidation for the contacts and screwed joints, which means that there is no gradual reduction in the current carrying capacity of the equipment as it ages.
- There is no reduction in insulation capacity due to external factors.

Optimum security of supply

Total enclosure also means that the equipment is almost completely **independent of the environment**. SF_6-insulated switchgear can also be used under difficult climatic conditions, for example,

- in humid areas where there is often condensation and frequent temperature changes, and even in places where there is a possibility of flooding.
- where the reliability of the insulation might otherwise be at risk from contamination, e.g. dust from industry or agriculture or from saline deposits in coastal areas. Enclosed switchgear completely eliminates this possibility throughout the whole service life of an installation.

- In contrast to air insulation, whose insulating capacity reduces with increasing altitude, SF_6-insulated switchgear retains its full insulating capacity regardless of height above sea level. So larger and more costly special designs, or equipment with higher insulation ratings - and therefore more costly - are avoided.
- SF_6 installations have the lowest failure rate of all; the MTBF is well in excess of 500 years.

Maximum operator safety

- The total enclosure of all live parts in earthed metal enclosures provides complete protection against electric shock and so ensures unrestricted operator safety.
- There is no possibility of an operator accidentally opening a gas vessel and thereby causing a dangerous situation.
- High-grade, maintenance-free switchgear remains hermetically sealed for its whole service life.
- SF_6-insulated switchgear makes a substantial contribution to reducing the accident risk.

Minimum space requirement

- Thanks to the high dielectric strength of the gas it is possible to build compact switchgear with a minimal space requirement.
- This often allows existing buildings to be used again by replacing old equipment with new.
- The excellent safety and low space requirement of SF_6 switchgear allows it to be sited directly in conurbations and at load centers, such as pedestrian zones, industrial manufacturing plants and caverns. The use of SF_6 secondary substations in the cabling projects for medium-voltage distribution networks that are currently in progress in Germany is also allowing many cables to be laid more conveniently in built-up areas.
- Therefore, this fulfils one of the basic essentials of power distribution, namely that substations should be placed as close as possible to load centers in order to keep transmission losses to a minimum, to conserve resources and to minimize costs.
- Major savings in building, land and transport costs can be achieved throughout the whole process chain.
- In several cases SF_6 switchgear is the only possible solution: for wind power plants (offshore), for large generator circuit-breakers and for extensions to existing installations.

Excellent economical and ecological features

- Distinct economic benefits come from:
  - the much longer service life
  - minimal maintenance expenditure thanks to maintenance-free gas compartments
  - reduced costs for land, buildings, transport and commissioning
  - maximum operational reliability as a prerequisite for the remote control and automation of power networks
- Ecological *and* economic benefits arise from:
  - Minimum transmission losses as a result of siting at load centers.
  - Thus making a valuable contribution to the reduction of primary energy consumption, and therefore emissions, and helping to optimize the overall economy of power supply systems.

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  - And the long service life of SF_6 switchgear also contributes to the conservation of resources.

- Aesthetic and ecological benefits for rural and city landscapes:
  - Because SF_6 installations are compact, need no maintenance, have extraordinarily high availability and are independent of climate they offer not only major ecological and economic advantages but can also be incorporated seamlessly into the existing landscape and architecture of our towns, cities and countryside.
  - Reclamation of areas previously barred to conventional secondary substations in cabled medium-voltage networks.

There is no longer any need to have anything to do with oil, previously the most popular insulating and arc quenching medium, and so the associated danger for the environment is much reduced. Since oil-filled switches needed more frequent maintenance, which also involved oil work - draining, sampling, cleaning, refilling, etc. – there was inevitably a likelihood of oil leaks.

Without using SF_6 as an insulating gas it would no longer be possible to meet the demand for safe, efficient switchgear. Assuming the same safety standards, the cost of building installations with solid insulation for operating voltages of 30 kV would be prohibitive. The same applies to the higher rated operating currents of up to, say, 2000 A.

Medium voltage switchgear with air-insulation for 20 kV are larger, for 30 kV even significantly larger than gas-insulated designs and require substantially more space.

In power stations, generator circuit-breakers for the higher ratings of more than several hundred MVA are only feasible thanks to the use of SF_6.

For high-voltage and extra-high-voltage switchgear for more than 145 kV the main benefit of SF_6 is the extraordinary amount of space it saves. In addition, when switching high-voltage operating currents and short-circuit currents with any arc quenching media other than SF_6 it is impossible to achieve anything like the same level of safety. Nonetheless, high operating pressures of between approximately 6 and 7 bar are still needed. Alternative arc quenching media are neither available at present nor forthcoming in the foreseeable future.

For voltage levels $\leq$ 36 kV in distribution systems, the saving in space and building volume achieves about 50% compared to switchgear using air or solid insulation – less than for high-voltage installations, since the insulation gas is filled at pressures in the order of only the atmospheric pressure. Nevertheless this argument is particularly important because of the very large numbers of switchgear installations and transformer substations that exist.

Looking at the ecological balance-sheet it is obvious that SF_6 installations are more economical than others and that they make a significant contribution to providing eco-friendly power supplies. In addition, the compact size of the equipment means that fewer materials are needed to manufacture it and, thanks to the small dimensions, the currents paths are also shorter and therefore the power losses lower.

➔ For further information about SF_6 see chapter G 1.

E 6.2 Characteristic features of gas-insulated switchgear

The particular character of this switchgear type has led to the appearance of many (almost) identical features:

- SF_6 as insulating medium
- Circuit-breakers employ vacuum as arc quenching medium
  Switches / switch-disconnectors employ SF_6 also for quenching
- three-position switch for isolation and earthing, or preparation for earthing
- earthing by means of circuit-breaker (in circuit-breaker switchgear)
- no cable disconnector
- shock-proof plug-in cable terminations
- very compact construction at all voltage levels
- all-round shockproofing (safe-to-touch) and protection against external influences
- largely maintenance-free.

The advantages of these features are evident and require no further explanation. The last item (maintenance-free) is a condition for this design, because switching devices inside the hermetically sealed enclosure are no longer accessible. But there are other advantages. All active parts are in insulating gas and are consequently protected against contamination, the ambient climate and small animals (vermin). In view of the high and constant quality of the insulation (which is unaffected by external influences), earth faults are practically ruled out. This means notably higher reliability.

An additional observation has to be made regarding the SF_6 insulation. There are also hermetically metal clad circuit-breaker switchgear assemblies that are not filled with SF_6 but with dry air, in order to spare the users the discussion about the gas and its decomposition products. The primary aims of hermetically sealed switchgear are also achieved by this switchgear type: the best shock protection as well as full protection against external influences. However, the other advantages of SF_6 are not provided. Many other switchgear installations are SF_6-insulated: switch-disconnector units, other types of circuit-breaker switchgear, high-voltage switchgear.

E 6.3 Encapsulation variants

The encapsulation can apply to the whole switchgear system or to parts thereof:

- single-pole encapsulation (Figure E-6)
- three-pole encapsulation (Figure E-7) oder auch in
- hybrid encapsulation (Figure E-8).

E 6.3 a Single-pole encapsulation

Switchgear with single-pole encapsulation can be manufactured economically when the number of different housings is minimized and an automated production is possible. Special attention must be given to the sheath currents. Normally, they are allowed to flow unhindered. This requires an encapsulation that is practically able to carry the rated busbar current. This represents no problems for the usual aluminium housings. In the case of short-circuit currents, the opposite current flows through the housings and the dynamic forces are eliminated to a large extent.

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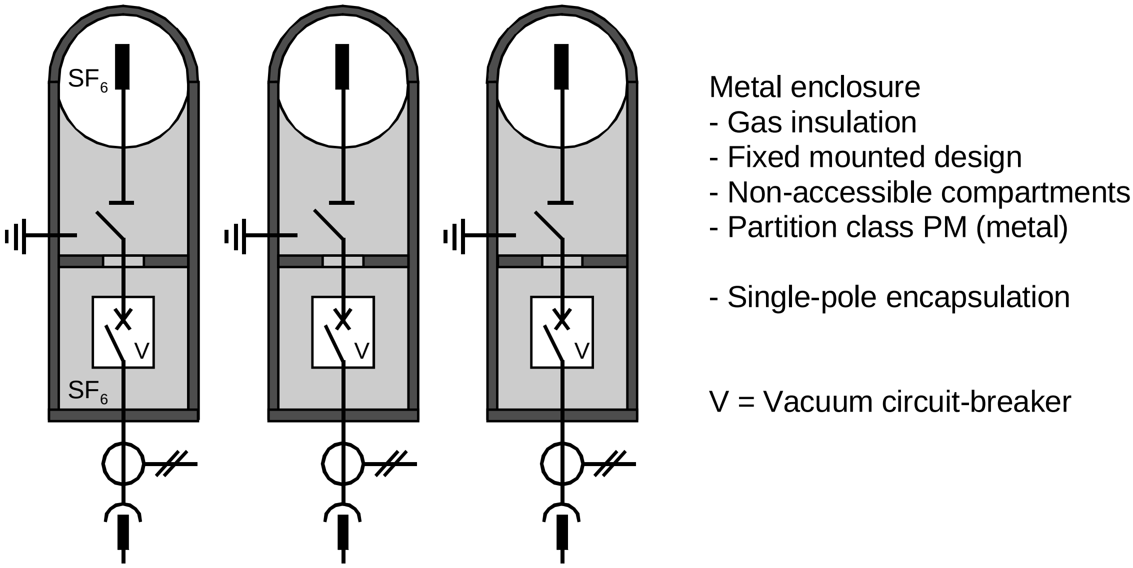


Figure E-6: GIS design with single-pole encapsulation

Seals have to be provided in a greater number, but they can be manufactured using the experienced O-ring system with a high quality and reliability. Switchgear faults are limited to one phase. Single-phase faults are often low in current and self-extinguishing in SF_6. Current transformers are mounted outside the housings at earth potential, as toroidal-core current transformers. The single-pole encapsulation is, so to speak, an extension of the feeder cable sheath, a "thick section in the cable run".

E 6.3 b Three-pole and hybrid encapsulation

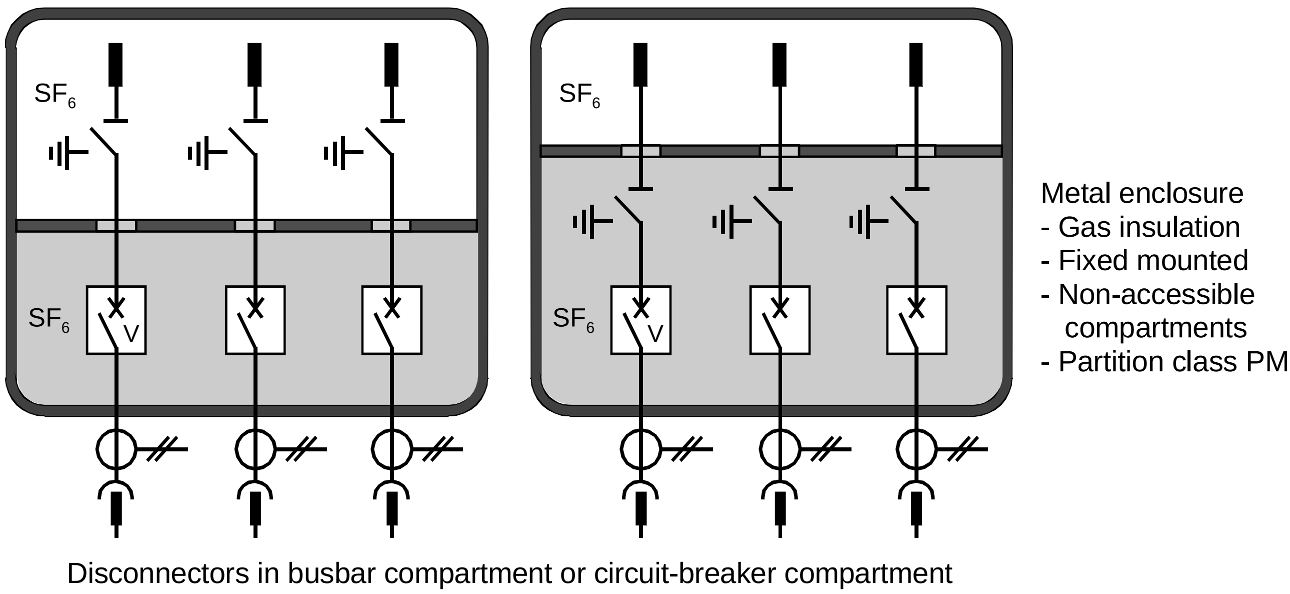
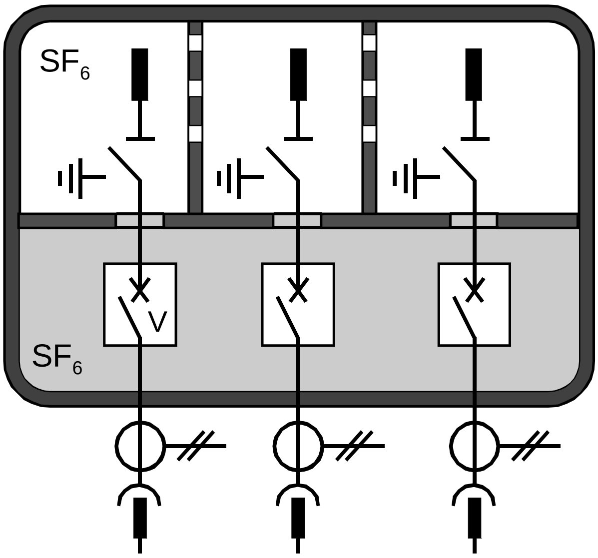


Figure E-7: GIS design with three-pole encapsulation

The three-pole encapsulation can be made of sheet steel due to small sheath currents; this can have economical advantages. The volume of a gas compartment is large in relation to the lengths of seals which may – depending on the method used – make the construction easier.

In the event of short-circuit currents, the dynamic stress for the components becomes very high, due to the small clearances in SF_6; and it is almost sure that every fault in the switchgear will be a three-phase fault. Nevertheless, the likelihood is extremely low, because of the high, almost unaffected by external influences, quality of the insulation.



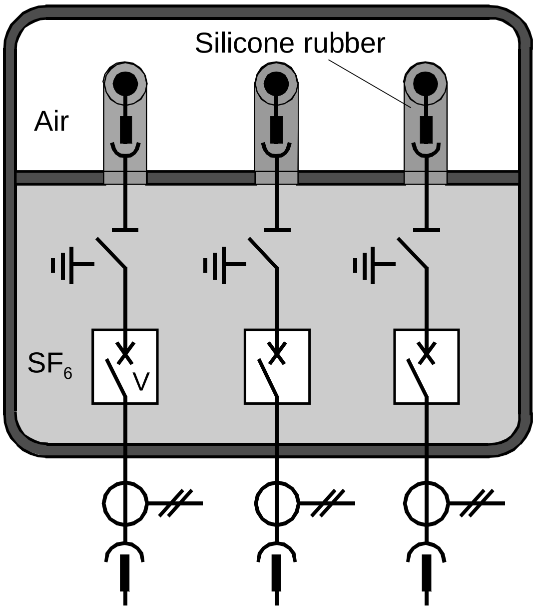
Metal enlosure
- Gas insulation
- Fixed mounted design
- Non-accessible compartments
- Partition class PM (metal)

- Hybrid encapsulation

V = Vacuum circuit-breaker

Figure E-8: GIS design with hybrid encapsulation

Switchgear with hybrid encapsulation (Figure E-8) features for example three-pole encapsulation in the feeder, whereas metal partitions separate the three phase conductors in the busbar compartment. Holes in the partitions ensure gas pressure equalization, with the result that the busbar compartment nonetheless forms just one gas compartment.



Metal enclosure
- Gas insulation
- Fixed mounted design
- Busbar compartment
  tool-based accessible
- CB compartment non-accessible
- Partition class PM (metal)

- Three-pole encapsulation

- Pluggable busbar
  with solid insulation

V = Vacuum circuit-breaker

Figure E-9: GIS design with solid-insulated pluggable busbar

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A further variant of three-pole encapsulation features SF_6-insulated individual panels, connected with an external, in-air busbar (Figure E-9). The pluggable bar is insulated and graded with silicone rubber, i.e. the insulation features a conductive, earthed coating that means it can be touched and makes it insensitive to climatic effects. Cross-pieces (Figure E-10) provide (via a conical plug-on system) the contact to the individual panels. The busbar with its pluggable connections can be quasi deemed a cable. Thanks to the metal cover on the busbar compartment the entire switchgear installation remains fully metal-enclosed. The advantage of this design is that neither at the installation stage, nor in any subsequent on-site expansion or modification, is any work on the gas system required.

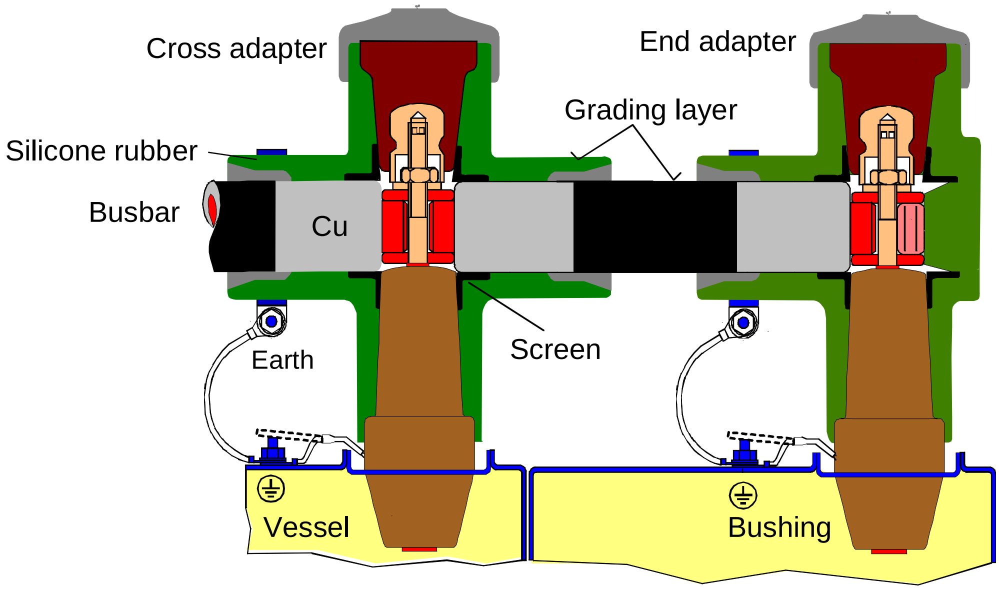

Figure E-10: Pluggable busbar with silicone rubber insulation

In all designs, current transformers must either be placed in the single-pole area (e.g. outside the encapsulation as cable-type versions, or in the area of the cable plug-on termination) or they must be of conventional design with their own high-voltage insulation. Most panels have current transformers with low-voltage insulation ouside the high-voltage compartment; only few manufacturers use "classic" SF_6-insulated transformers.

E 6.4 Pressure systems and gas filling

Medium voltage circuit-breaker switchgear is operated with gauge pressures of 50 kPa to 300 kPa. A series of factors determines the level of the gas pressure. Some of these are:

- the **insulating capability**;
  to achieve the required values, even with the very small clearances, only a small overpressure is necessary, due to the outstanding dielectric character of SF_6.
- the **rated current**;
  this determines the heat loss in the switchgear. Increased gas pressure improves the thermal conductivity of the gas. So for higher current ratings higher gas pressures are used. Due to its low viscosity and high density, SF_6 is a better heat conductor at the same pressure than air.
- the **vessels**;
  these must be designed to withstand the pressure, thus the lowest possible pressure is favoured. In any event, the enclosure must have a base strength - to carry its own weight and that of the components as well as to withstand the switching forces. Evacuation of the gas must also be considered.

For maintaining the pressure in gas-insulated switchgear, three different systems are recognized by the standards IEC 60694 / VDE 0670-1000:

- **Controlled pressure system** with automatic refilling,
  which is not used for medium voltage switchgear.

- **Closed pressure system** with manual refilling,
  which is the one most used at the moment. A leakage rate of ≤ 1 % per year, which means a control and refilling interval of 10 years should be achieved at least, otherwise the saved maintenance (cleaning) of the insulators will be replaced by the maintenance of the gas; in practice, the leakage rate is < 0.5 % per annum.

- **Sealed pressure system** without treatment of the gas filling during the expected service life, of minimum 35 years (in practice, a term of 40 to 50 years can be expected). All medium-voltage installations use this pressure system. The leakage rates are below 0.1 % per year; where welded enclosures are used the figure is even lower.

The gas pressure determines the construction and the dimensions of the switchgear housing to a large extent. For cost reasons, the gas pressure is selected as low as possible. If – as usual – SF_6 is used as insulating gas, atmospheric pressure is already sufficient to provide the insulating capacity required. However, an overpressure is applied, as pressure equal to atmospheric in a hermetically sealed housing has several disadvantages.

A hermetically sealed enclosure may suffer under-pressure when the external temperature falls to extremely low levels. This causes a reversal of the stress on all welded seams, joints and seals. This alternating stress is significantly more difficult to reliably withstand than a constant positive pressure.

A definite overpressure provides clear conditions for the mechanical stress. Figure E-11 shows a slightly positive over-pressure at even lowest temperatures, around -15°C. This also makes pressure monitoring more secure. In practice, the filling pressure varies depending on the manufacturer, between 20 kPa and 300 kPa (gauge, related to an atmospheric pressure of 101.3 kPa at 20°C).

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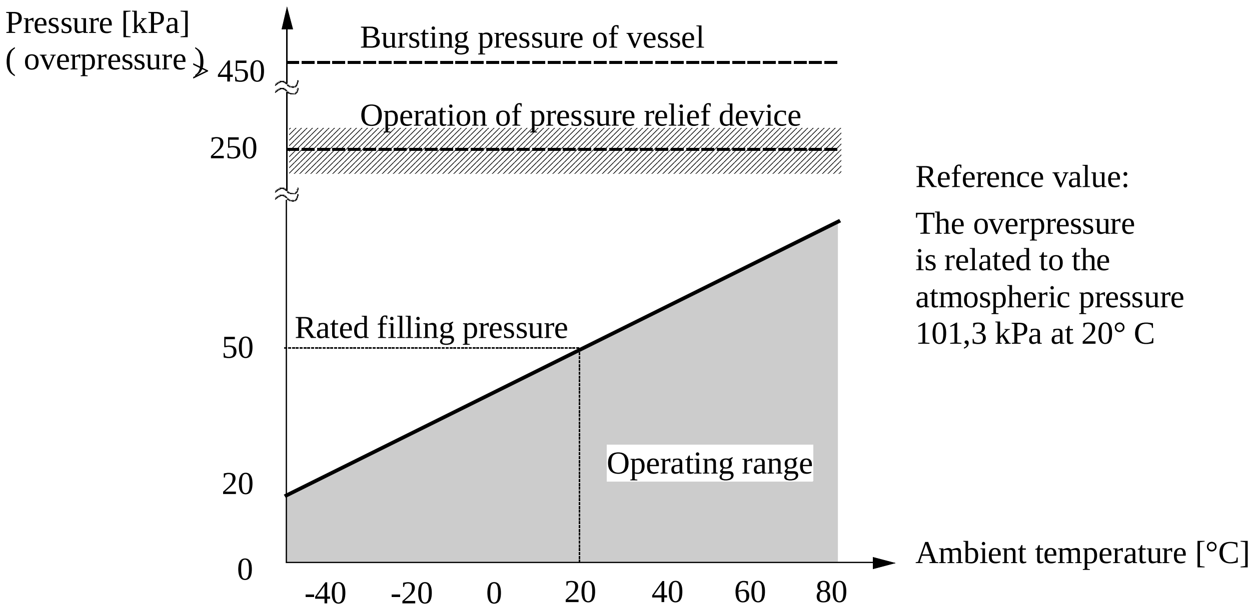

Figure E-11: Pressure range of a representative GIS (example)

For all three systems it is very important not only to maintain the gas density, but also its **dryness**. The dew-point temperature of the gas always has to be clearly below 0°C, in order to exclude the condensation of water inside.

Despite an overpressure of SF_6, there is a low pressure of water vapour in the enclosure compared to outside. Thus these partial pressure differences try to equalize in that water vapour diffuses constantly into the enclosure. The quantity of penetrating water depends on the quality of the seals. Only pure metallic seals (welded or soldered) or very long diffusion paths will ensure negligible ingress

The moisture content of the gas during operation is determined by the following parameters:

- **Moisture in the containers during filling**
  Water condenses out of the air on all surfaces. This can be removed only by careful drying and evacuation during the filling process. Not all enclosure designs allow evacuation; in those cases the air is driven off by the entry of SF_6 which, since it is heavier than air, is filled from the bottom, driving the air off through an opening in the top. This procedure allows a greater residue of moisture to remain on the internal surfaces.

- **Moisture content of the gas**
  New SF_6 at 100 kPa filling pressure has a dew point at approx. -40 °C. The moisture thus introduced is negligable.

- **Moisture ingress**
  This depends on the operating cycle, the external water vapour pressure (surrounding climate), length of seal perimeters and their water vapour diffusion characteristics.

- **Absorption capacity of drying agent**
  Usually, the absorption capability is approx. 20 %, related to weight, and can be exhausted after a few years.

Dryness is of essential importance over the whole operating temperature range, since the insulation strength of the gear is based on dry gas. Condensation can easily lead to flashover and failure.

Insulating gas can be filled by two methods:

First, the housing is evacuated, and then SF_6 is fed in. This method subjects the housing to strong mechanical stresses during evacuation, but has the advantage that moisture is mostly removed with the air.

This is not the case when using displacement filling. Here, the SF_6 is filled in slowly from below. As SF_6 is heavier than air, it displaces the air, which streams out of the housing at the top. This method causes far less mechanical stress and allows more economic design of the enclosure.

As a residual humidity can never be avoided, dehydrating substances are always put in the housing, regardless of the filling method, because the moisture content of the gas is a critical factor. A continous, satisfactory degree of dryness in the enclosure is ensured only when thorough drying, evacuation and diffusion-proof sealing (metallic, welded enclosure) is achieved during manufacture.

E 6.5 “Sealed-for-life“technology

How can an enclosure be built to remain gastight for year, even when various conductors and operating mechanisms pass through its walls?

Figure E-12 shows the hermetically welded enclosure of a sealed pressure system that meets these requirements. The welded enclosure brings a number of advantages. The entire enclosure can, when manufactured, be examined in an integral leak tester. The measured degree of tightness remains stable, for welding seams (unlike conventional seals or gaskets) are not subject to aging. Following evacuation and subsequent filling with insulating gas the enclosure attains factory-assembled status; there is no need for any work on the gas system when the switchgear is installed at its place of use. This greatly simplifies commissioning, since no gas-handling equipment nor specially trained staff are required.

The illustration shows a load switch block (RMU) for two ring cables and a transformer feeder with HRC fuse. The welded conductor bushings for fitting the fuse boxes can be seen at the top; below are the conical bushings of various sizes for the network cables (left and center) and the cable to the transformer. The middle of the vessel features the welded bellows for the moving mechanism parts.

Figure E-12: Example of a gas-tight, welded vessel

The electrical conductors and the mechanical parts for the switch operating mechanism must likewise be led out via sealed-for-life bushings (see Figure E-13). With static conductor bushings that is a relatively easy matter; the cast resin features a metal collar that is then welded to the vessel wall. Creating seals for moving parts is more complex. For gastight transmission of a mechanism move-

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ment metal bellows are used; they have been proving themselves for many years in conjunction with vacuum interrupters. Figure E-13 shows a typical switch disconnector operating mechanism.

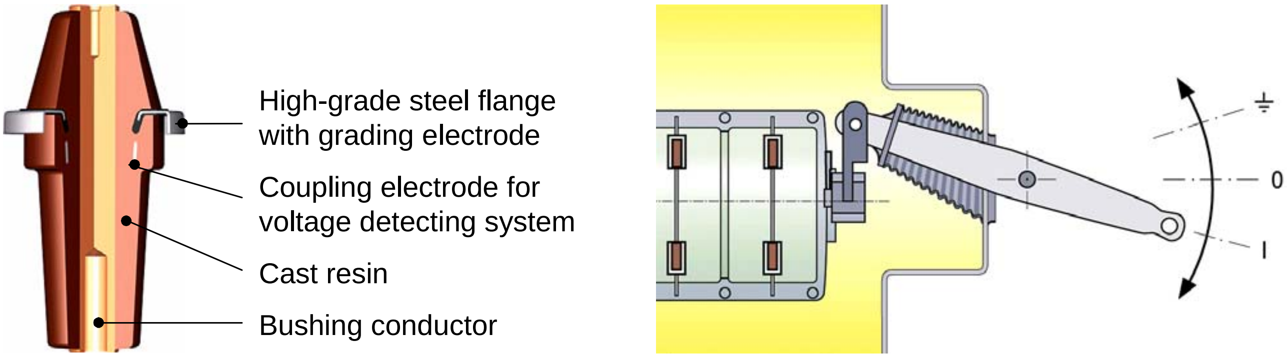


Figure E-13: Gas-tight bushing for conductor and gas-tight penetration for drive lever

Gas-filled compartments generally include a pressure relief device; this prevents – in the rare event of an internal fault involving excess pressure – bursting of the switchgear vessel. A rupture diaphragm is provided. The operating level (see Figure E-11) is coordinated such that the diaphragm breaks at a multiple of the normal pressure load, yet well below the pressure strength of the vessel, thus preventing an impermissible internal pressure buildup. This component is similarly welded into the vessel wall.

In the event of impermissible internal pressure, the concave membrane bends outwards and is cut open by the sharp metal points.

Figure E-14: Bursting disc for overpressure relief (example)

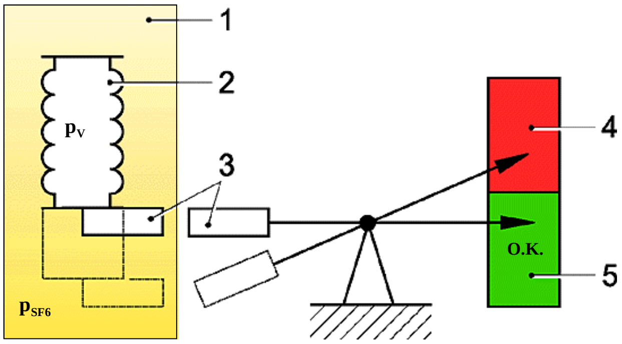
E 6.6 Gas monitoring

There are also different principles for this:

- direct pressure measuring
- differential pressure measuring
- indirect measuring; e.g. of the dielectric strength

Direct measuring by means of pressure gauges indicates the actual pressure; but this pressure is subject to fluctuations – independently of the sealing of the housing – due to the changes of temperature that are caused by the current load of the devices installed and by the environment. The connection of the measuring device to the housing is a possible weak point for leaks. Thus, direct measuring is not free from problems.

Differential pressure measuring is shown in Figure E-15. Actually, this is not a measuring, but a "ready for service" indication. The indication provides a qualitative statement whether the pressure lies within a permissible area or not, but it displays no absolute value. It shows a change of pressure between the housing pressure p_{SF6} and the reference pressure p_V. The reference housing consists of a gas-filled bellows; its length is changed by the force acting on its front surfaces as a consequence of the pressure difference.



1 Vessel
2 Pressure gauge box
3 Magnets

Indicator:
4 Not ready for operation
5 Ready for operation

Figure E-15: Gas pressure monitoring, example of a qualitative indication

This system is temperature-compensated and self-monitoring. Temperature fluctuations are almost equally transferred to both gas volumes. The housing pressure and the reference pressure change in the same way; the indication remains unchanged. If SF_6 streams out, the bellows expands - the indication moves to the red area. The same happens when the reference housing itself or both housings get leaky. The indication is transferred to the outside by means of two magnets. This makes this type of monitoring suitable for sealed pressure systems.

Indirect measuring is e.g. to check the dielectric strength of the gas. This method tests one characteristic – in fact, the decisive function – of the insulating gas. The principle is based on the measurement of the dielectric strength between two electrodes with a defined clearance.

E 6.7 Location of the disconnertors

Just as in other designs, the disconnector (three-position switch) can be installed in the circuit-breaker compartment or in the busbar compartment. However, as the disconnector has its insulating capacity only in SF_6, its most suitable location is different for single and double busbar arrangements.

E 6.7 a Single busbar

For single busbars: the disconnector is better not installed in the circuit-breaker compartment which would have to be evacuated for work on the interrupter (arrangement B in Figure E-16). If located in the busbar chamber however, (arrangementA) the internals below the separation plate can be removed, whilst the busbar and the disconnector remain fully pressurised and in operation.

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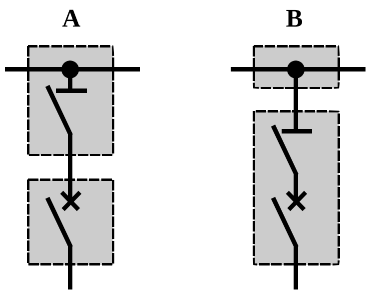


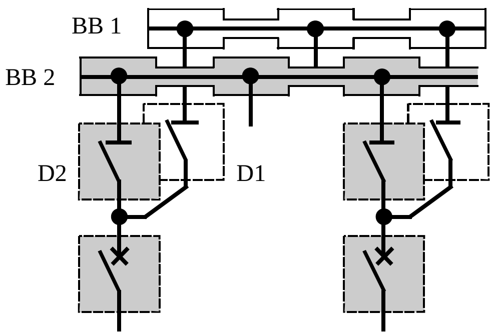
Place of work	Condition during work			
	Arrangement A		**Arrangement B**	
	BB	Feeder	BB	Feeder
Busbar	OFF	OFF	OFF	OFF
Disconnector	OFF	OFF	OFF	OFF
Circuit-breaker	**ON**	OFF	**OFF**	OFF

Figure E-16: Influence of location of disconnector on the service continuity of single busbar

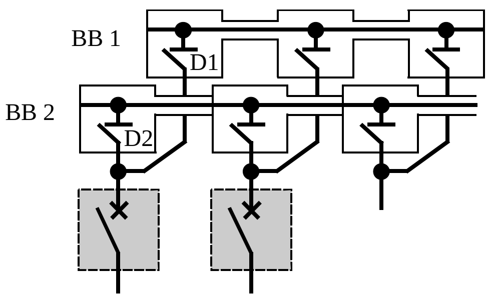
The same arrangement, additionally mounted on top, can also serve to extend a single-busbar switchboard without interruption of the service, or to implement a bus section with disconnector without need of a supplementary panel.

E 6.7 b Double busbar

In double-busbar arrangements the disconnectors should not be installed in the busbar compartment, but separately (arrangement C in Figure E-17), since each busbar is connected to the other one by the system interconnection in every active panel. If the disconnectors are in the same compartments as the busbars (arrangement D), no busbar could be evacuated as long as the other is in operation; but this is just the reason for having a double-busbar; to enable working on one while the other is in operation. If a busbar disconnector has to be accessible without isolation of both busbars, each bus-bar disconnector needs its own gas compartment (arrangement C).



Arrangement C	Condition during work	
Place of work	BB	Feeder
Busbar 1	BB 2 = ON	**ON**
Disconnector 1	BB 2 = ON	OFF
Circuit-breaker	BB 1 + 2 = ON	OFF



Arrangement D	Condition during work	
Place of work	BB	Feeder
Busbar 1	BB 2 = ON	**OFF** *
Disconnector 1	BB 2 = ON	**OFF** *
Circuit-breaker	BB 1 + 2 = ON	OFF

* All feeders which are connected to this compartment must be OFF.

Figure E-17: Influence of location of disconnector on the service continuity of double busbar

If the disconnectors are located in the circuit-breaker compartment for reasons of costs or better dimensions (arrangement D), or if they are not separated from the busbar in a double-busbar switchboard, the above mentioned ideals are lost or made much more difficult. When work is carried out at busbar 1, all the disconnectors of busbar 2 which are connected to this gas compartment of system 1 (and all these feeders as well) have to be switched off. That is not the purpose of a double busbar!

Remedy is then only possible by busbar compartmentalization (from panel to panel); incorporated in the left or right hand side panels at least it permits the extension of the installation without interruption of service.

E 6.8 Grouping of gas compartments

This applies to switchgear with pluggable busbar (Figure E-9), in which each individual panel forms its own gas compartment. The vessels generally feature metal seals (none made of organic material); all electrical and mechanical (for operating mechanisms) bushings are welded, resulting in a "hermetically sealed system". Work on the gas systems of such switchgear is no longer possible and not necessary. In the event of a fault the panel must be replaced; with the pluggable busbar this is however a quick and easy matter.

In switchgear with gas-insulated busbar, particularly in the case of single-pole encapsulation, subdivision of the gas compartments is significant for whether work can be done while operation continues (and for any resultant restrictions on such operation); in the event of any faults the way the gas compartments are grouped determines the extent of the effects thereof. The requirements for gas compartment grouping are relatively straightforward:

- Operation of a section of busbar is only possible when all its parts are in order. Therefore it it is entirely sufficient to operate and monitor the complete section of busbar as one gas compartment (Figure E-18), furthermore it is suitable to operate the three phases separately (Figure E-19).

- Operation of a section of busbar has to be possible even when a feeder is faulty. For this purpose it is necessary to operate and monitor the "feeder" gas compartment separately from the "busbar" gas compartment; in this case it is suitable to operate the three phases together.

- In double-busbar switchgear, operation still has to be possible when one of the busbars or a disconnector are faulty. This requires separate operation and monitoring of the gas compartments of the two disconnectors.

Any further subdivision of the gas compartments offers no operational advantages. Any further concentration produces operational restrictions and complicates fault locating. Of course, every gas compartment must have its own, defined pressure relief.

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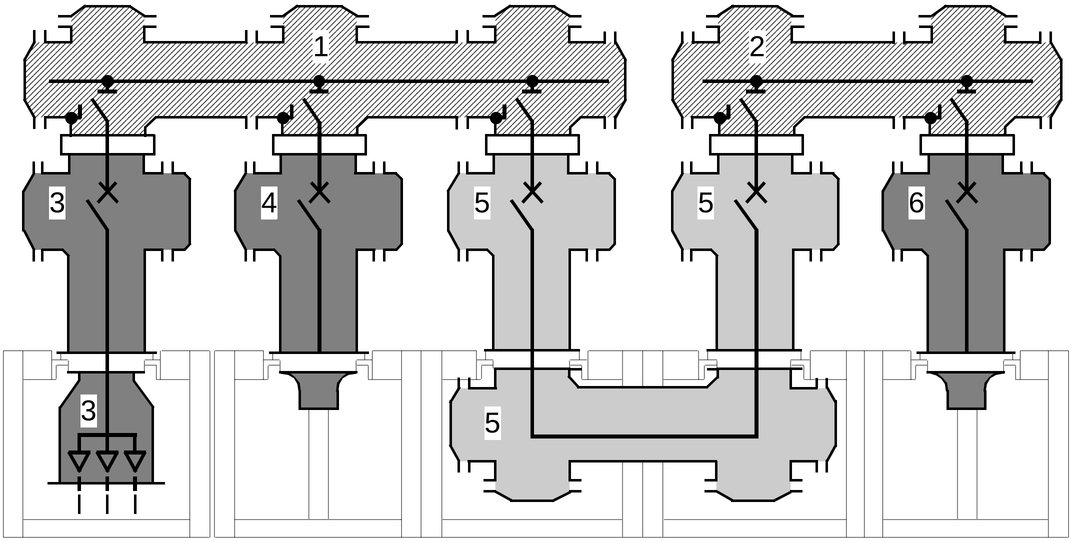

Figure E-18: Gas compartments of a single-pole encapsulated switchgear cross-section of double busbar (equal numerals = equal gas compartments)

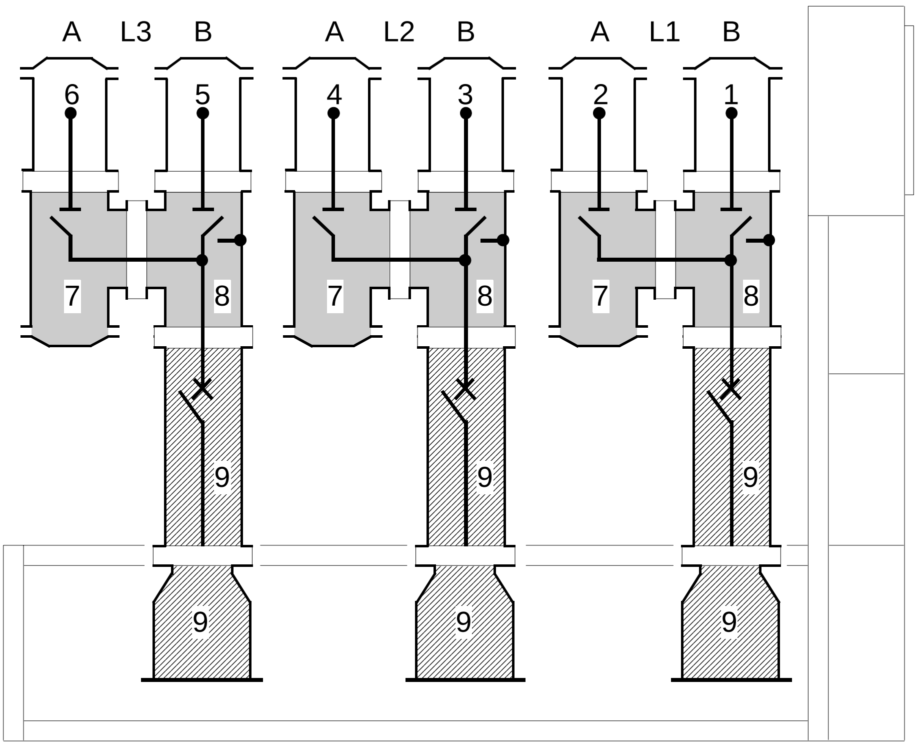

Figure E-19: Gas compartments of a single-pole encapsulated switchgear longitudinal section (equal numerals = equal gas compartments)

In three-pole encapsulated switchgear it is appropriate to operate the feeders and busbar as separate gas compartments. Long busbars make transverse barriers for the gas compartments a suitable option; the same applies to double busbar systems.

E 7 Switchgear type

The design of the panels – i.e. the modular components of the switchgear – depends (in addition to the requirements described so far) on other influential factors. Panels are frequently referred to according to the respective built-in device, e.g. circuit-breaker panel, load-interrupter switch panel or contactor panel. But such panels can look different, depending on whether they are built for primary distribution switchgear or secondary distribution switchgear, or for both types. These two variants can be described with reference to their significance and main uses in the network, as well as their technical features. The most important are:

- Rated normal current of busbar
- Short-circuit strength and switching capacity
- Switching device (circuit-breaker, load-interrupter switch, contactor)
- Frequency of switching operations
- Significance in network (primary or secondary distribution level)
- Network protection (with protective relay or HRC fuse)
- Secondary equipment (control, alarms, etc.)

This list sets out only the most important aspects. Grouping into primary and secondary distribution switchgear is arbitrary, and not the subject of e.g. standards. The systems are not always homogenous; there are many with a hybrid arrangement of the panels.

E 7.1 Primary distribution switchgear

As the name suggests, in primary distribution switchgear the figures for almost all the features listed are in the upper range, especially the currents. For example:

- The rated normal current of the busbar can be as high as 4000 A, and
- Short-circuit strength and switching capacity can reach 63 kA_{rms} / 160 kA_{peak}

In at least 80 % of panels the switching device is a circuit-breaker; there are only few load-interrupter switches and contactors. One of the main reasons for using circuit-breakers is to protect downstream equipment, for only this switching device is able to break all currents up to the full short-circuit current under all fault conditions.

Primary distribution switchgear always includes a (numerical) relay for network protection. It evaluates the signals from the current and voltage transformers and issues to the circuit-breaker a tripping command in accordance with specified criteria (protection algorithms). The simplest tripping criteria are just the current and the fault duration (time-overcurrent protection); for more complex protection duties the voltage is also evaluated and the direction of the fault location (directional overcurrent protection) or its distance (distance protection) deduced. With transformers and cables a differential protection relay compares the currents on both sides. This type of network protection is indeed intricate, but it can be precisely adapted to those operating requirements customary for switchgear on the primary distribution level. Alternatively, HRC fuses can attend to short-circuit protection (and to a very limited extent overload protection). The same degree of fine setting and grading is not however possible. That is why – with a few exceptions – HRC fuses are found on the secondary distribution level.

The frequency of switching operations depends on network operation and on the respective switching duty. In primary distribution switchgear this frequency is higher overall, because circuit-

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breakers interrupt the earth faults, short circuits or other malfunctions that occur with lesser or greater frequency, depending on the structure and quality of the distribution network. In industrial networks it is the loads that determine this frequency; with motors (for example) it can be very high. For extremely frequent switching, contactors are the most suitable option. This type of panel is therfore regarded as an item of primary distribution switchgear, even if in terms of switching capacity the contactor has more in common with a load-interrupter switch.

E 7.2 Secondary distribution switchgear

In all switchgear designs, switch disconnectors can be installed instead of circuit-breakers. This can be done in primary distribution switchgear, if a load-interrupter switch is required for individual feeders. Other demands are however made of pure secondary distribution switchgear (than are imposed on primary distribution switchgear); the main differences are

- Lower normal currents, usually only up to 630 A
- Lower short-circuit strength, up to 25 kA_{rms} / 63 kA_{peak}
- No short-circuit breaking capacity, HRC fuses provide protection
- Switching devices: With switch disconnectors there is no need for the withdrawable unit, which is always required with circuit-breakers
- Lower frequency of switching operations
- Smaller scope of secondary equipment

Switch and switch-fuse boards are used universally in distribution networks up to 24 kV: in network stations of distribution authorities and in industry, in load centres of production plants and in consumer substations (commercial installations); everywhere where energy is transformed from medium to low voltage. In conventional ring networks one can expect approximately 5 switch and fuse boards in network stations to each circuit-breaker unit in primary substations and node points.

Special demands are made on switch and fuse gear in public networks. Where tough climatic conditions are present, the equipment must withstand wide temperature ranges, high humidity and frequent condensation patterns.

E 7.3 Feeder-type construction

This – extensible – type is provided for switchgear units that have to be adjusted to many different operational duties. This means e.g. the number of feeders and the feeder types are selectable; there are

- circuit-breaker panels
- switch-disconnector panels with / without HRC fuses
- transformer panels
- metering panels (transfer and revenue metering)

Figure E-20 illustrates three examples of air-insulated switch panels:

(a) Fixed mounted design with SF_6 switch-disconnector,
Compartments: partition class PM (metallic)
Busbar tool-based accessible, switch non-accessible,

Cable and HRC fuse tool-based or procedure-based accessible
Loss of service continuity category LSC 2A

(b) Fixed mounted design with conventional switch-disconnector without partitions, thus loss of service continuity category LSC 1

(c) Withrawable circuit-breaker,
Partitions between cubicles and temporary inserted barrier to the busbar,
Partition class PI (temporary barrier is of insulating material)
Loss of service continuity category LSC 2A

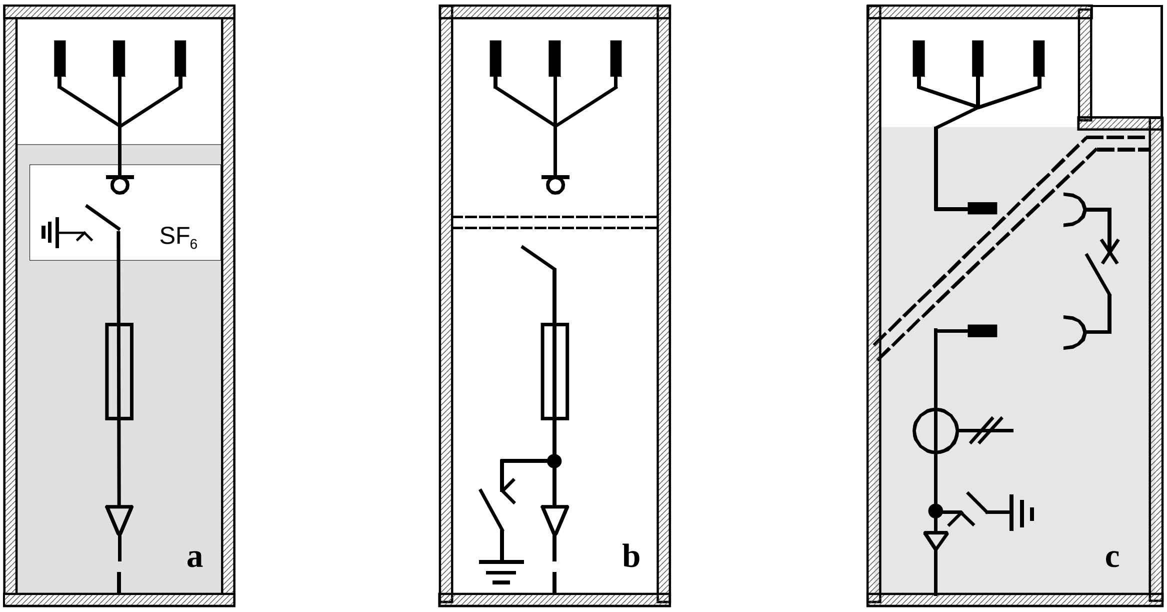

Figure E-20: Variants of feeder-type (extensible) design

The feeder-type construction is especially suitable for application in industrial systems. For example, one substation can be fed via one radial incoming feeder; the incoming feeder would then be equipped with a switch-disconnector. Feeders for distribution transformers can either be equipped with a switch-disconnector-fuse combination or with a circuit-breaker.

Moreover, almost all the auxiliaries available for circuit- breaker switchgear are also possible; interlocks, faulty switching-sequence prevention systems, instrument transformers. This makes this type of switchgear very flexible in application.

E 7.4 Block-type construction

This means that all switching devices for the incoming and outgoing feeders and for the busbars are located in one common enclosure. As a rule, only switch-disconnectors are installed; the different versions available with the feeder-type construction (circuit-breaker, metering) are not available here. This type of construction is very compact; it is economical where the number of versions required is limited. The main application lies in unit substations for power supply. Here, the hermetically sealed design is becoming more and more accepted. In most of the cases, SF_6 is used both as insulating and arc-quenching medium. The switches can have a separate arcing chamber or be located directly in the insulating compartment. To ground the feeders either separate earthing switches are provided, or the main switching device attends to earthing; various designs of three-

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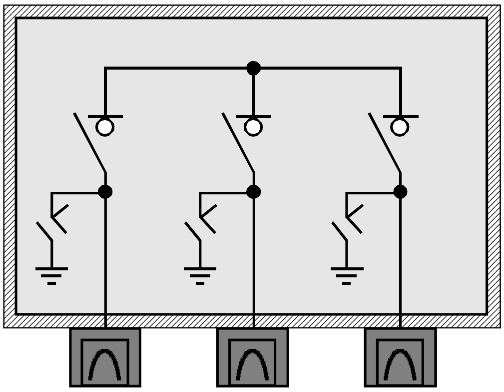
position switch are used. An example is shown in Figure E-22. Block-type construction is nowadays only used for pure secondary distribution switchgear; hybrid secordary and primary distribution feeders are currently available only in panel-type design

Instead of panel rows, several housing sizes are available. Another solution is provided by welding two housings together.



- Gas insulation
- non-accessible compartment
- Partition class PM (metal)

Figure E-21: Block-type (non-extensible) design

E 8 Switching devices

The type of switchgear influences the design of the switching devices (See chapter C for the fundamental function of such devices). A crucial factor is the insulating medium: in air-insulated switchgear practically all those variants are to be found which can be relatively simply integrated in a panel. In contrast, gas insulation calls for diligent selection of switch designs, since devices and the overall system alike require a hermetically sealed enclosure. The switching devices used and the particular features encountered with GIS are set out below.

E 8.1 Switching devices in air-insulated switchgear

The following are used in air-insulated switchgear:

- Conventional switches and switch-disconnectors,
  the quenching devices of which work with hard gas or compressed air
- SF_6 switch-disconnectors
- SF_6 transformer circuit-breakers,
  with a capacity suitable for switching transformers
- Vacuum circuit-breakers,
  these being more suitable for loads than are switch disconnectors, when switching takes place frequently (≥ 1 x per day), or the required switching performance exceeds the capacity of a switch disconnector
- Vacuum switches (rare)
- Vacuum contactors
- SF_6 contactors (rare)

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With vacuum switches, an additional disconnector or withdrawable unit is required to comply with the conditions of the isolating distance, whilst all other types of switches are usually designed as combined switch-disconnectors.

E 8.2 Switching devices in gas-insulated switchgear

Depending on the intended purpose, gas-insulated switchgear makes use of:

- SF_6 disconnectors and earthing switches
- SF_6 switch disconnectors
- SF_6 transformer circuit-breakers, with a capacity suitable for switching transformers
- Vacuum circuit-breakers
- Vacuum contactors

Disconnectors, earthing switches and load-interrupter switches are frequently combined in the form of three-position switches, whereby the earthing function can also include a short-circuit making capacity (make-proof earthing switch); Figure E-22 shows a combined switch disconnector and earthing switch with short-circuit making capacity.

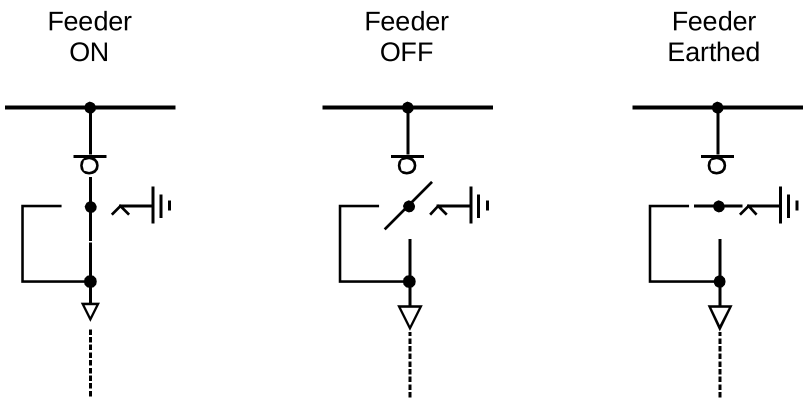

Figure E-22: Example of a three-position switch

As the list above shows, panels with vacuum circuit-breakers or vacuum contactors in gas-insulated switchgear feature the SF_6 only for insulation, whereas load-interrupter switches use the SF_6 as both insulation and quenching medium.

Why does one not use the advantages of a vacuum interrupter in gas insulated switch and fuse (secondary distribution) switchgear, when they dominate in circuit-breaker (primary distribution) switchgear? A decisive reason is cost, because the former is used in thousands in distribution substations. Exactly for that reason the two following technical aspects must be solved in the simplest way.

<u>The insulation capacity</u>

Switch disconnectors must have a contact gap which complies with the special requirements of the applicable standard. They must have:

- a higher and secure insulating capability which ensures that an overvoltage will never cause breakdown of the contact gap but, at the worst, to earth;

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- security against reduction of the insulating capability which could be caused, for example, by pollution;
- security against tracking. Any tendency to tracking (leakage current across insulators) shall not affect the isolating distance but must be deflected to earth.

Of these requirements, a vacuum interruptor fulfils only the last two. Enclosure in SF_6 prevents pollution and tracking (as long as condensation is not possible).

The increased isolation strength could be achieved by appropriate design of the vacuum interruptor but, as it exists, this is not its purpose. Therefore, to achieve the required safety level, a disconnection gap must be connected in series, usually with its own drive mechanism and interlocks.

In contrast, a suitable SF_6 three-position switch fulfils all the functions of load switching, isolation and (make-proof) earthing in one unit, with one drive mechanism, with inherent interlock.

The switching capacity

Switch-disconnectors have only to interrupt small load currents - and that not often. They are not called upon to switch fault currents. Based upon these application criteria, switch-disconnectors are designed to switch a maximum of, for example, 100 x 400 A, whereas a circuit-breaker must be able to switch, say, 10000 x 2000 A (a factor of 500). The remaining duties required of secondary switchgear are accomplished by an SF_6 switch just as well as by a vacuum interruptor.

In a sealed container in which the components are not accessible, a mechanically simple SF_6 three-position switch fulfils the duties of switching and isolation with equal reliability, better and more economically than other switching principles. For these reasons this principle has become universally adopted for switch-disconnector assemblies in compact construction.

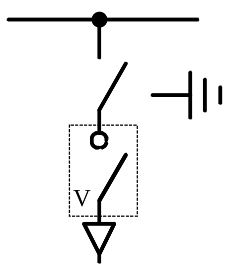
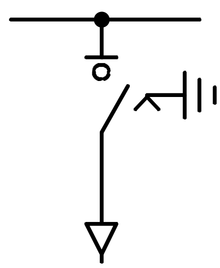
Vacuum switch	**SF_6-three-position earthing/switch-diconnector**
	
1 switching element: *load switching*	1 switching element: *load switching, isolation, earthing*
1 switching element: *isolation and earthing*	—
1 drive unit: *load switching*	1 drive unit: *load switching, isolation and earthing*
1 drive unit: *isolation and earthing*	—
1 interlock: *load switching* ⇔ *isolation and earthing*	—

Figure E-23: Consequences of the type of switching device in GIS secondary switchgear

E 9 Not typtested switchgear acc. to IEC 61936 / VDE 0101

Metal-enclosed versions still enjoy a large niche on the market, especially for partially compartmented double-busbar switchgear (Figure E-26). Due to the quality of its enclosure, modern switchgear of this design offers the same shock protection for the personnel as the corresponding type-tested switchgear.

The designs with three compartments (Figure E-24) pose no problems at least for work on the cable termination. For work on the circuit-breaker however, it is important whether the disconnector is allocated to the circuit-breaker (a) or to the busbar (b). In the former case, the disconnector is easily accessible, but the busbar has to be isolated. From this viewpoint, the partition between busbar and disconnector could be dispensed with. In the latter case, the circuit-breaker compartment can be isolated and this made accessible while the busbar is in operation; the disconnector however remains inaccessible. For disconnectors that (including their attachments) are reliable and require little maintenance, variant "b" will be preferable. Unlike these designs, cubicle-type switchgear with fixed-mounted devices (Figure E-25) makes work on the system difficult; see variants c, d and e.

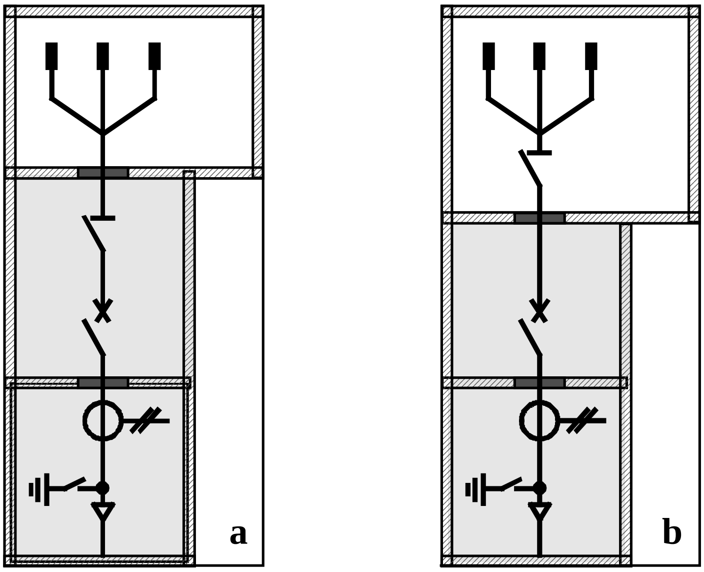


Figure E-24: Variants of compartmented "fixed mounted"designs

Also with partial compartmentalization all preparations for working can be made outside the panel, with full protection against electric shock, including the covering of adjacent live parts. For this purpose, insulating protective barriers are inserted with the front door closed; Figure E-26, variant (f). The designs (g) and (h) can even do without this, as the circuit-breaker compartment can be completely isolated safe to touch due to the partition provided below the busbar disconnectors. Furthermore, the design variants (g) and (h) protect both busbars against direct arcing effects in case of internal faults. These designs can also meet all requirements regarding the resistance to internal faults. For example, one type of the design (g) has been successfully tested up to 50 kA / 1 s for its resistance to internal faults.

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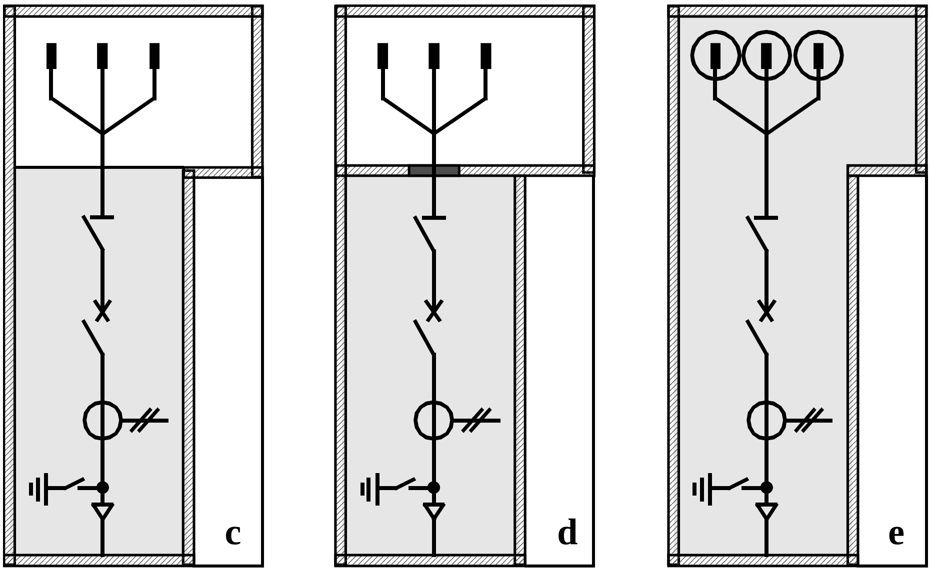

Figure E-25: Variants of „fixed mounted"cubicle designs

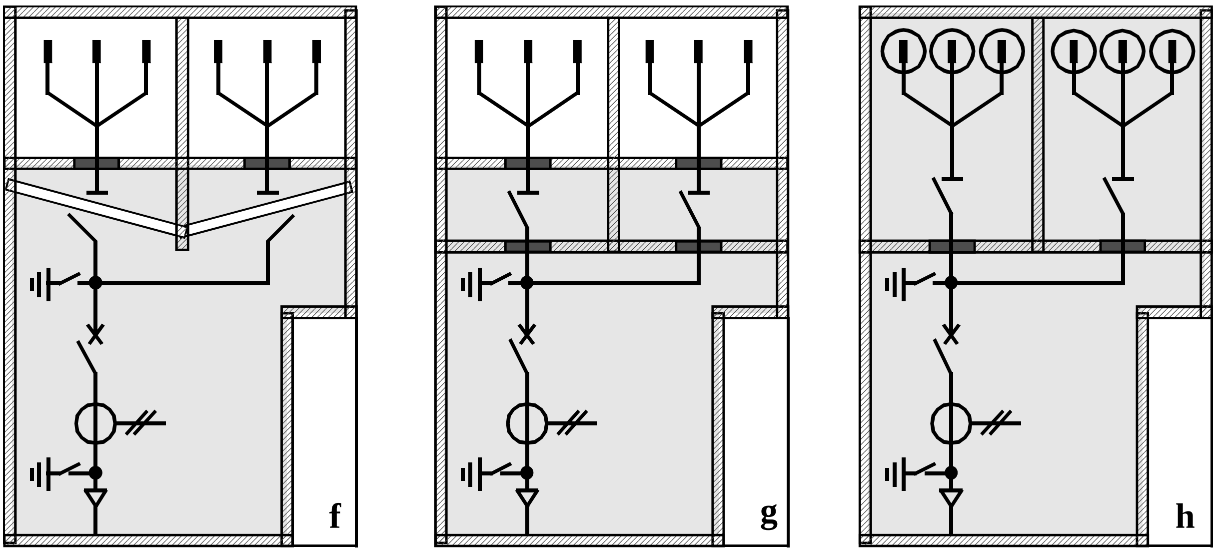

Figure E-26: Cubicle design double busbar switchgear

These non-withdrawable switchgear types have also been aligned to the quality standard of the type-tested types regarding other points of view:

- the use of reduced maintenance components
- complete switchgear interlocking systems
- operating mechanisms without l.v. components in the h.v. compartment.

Moreover, in contrast to most of the type-tested switchgear types, they offer some special features:

- They require a smaller room width, but they are higher. So, in most cases they can be installed without problems in existing switchgear rooms.
- They are flexible regarding component selection and dimensions as they do not have to be tested.
- After faults, they are quickly reconditioned again, as the damage can often be repaired with simple means that are immediately available (no special parts).

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F ACCESSORIES FOR SWITCHGEAR

F 1 Connection and wiring technology

Metal-enclosed switchgear offers high operational reliability and personnel safety. In addition, hermetically sealed gas-insulated switchgear provides full protection against environmental influences, and this almost excludes disturbances coming from outside. The same features must apply for connections and links, otherwise the reliability of the complete system would be questionable.

F 1.1 Survey and requirements

Interconnections within the switchgear and to transformers are performed by means of

- cables
- solid-insulated bars
- gas-insulated bars

The cables and bars themselves as well as their terminations have to match to the switchgear. Depending on the switchgear type and the site, this means:

- shock-proof
- climate-proof
- maintenance-free

The connection zone (e.g. cable compartment) should guarantee shock protection not only during operation, but also during work. This means, for example:

- Verifying safe isolation from the supply with the panel closed
- Doors and shutters to the cable compartment to be integrated in the feeder-related interlocks
- Partitions to adjacent cable compartments.

These demands are partly also made on the switchgear itself. For verifying safe isolation with the switchgear closed, there are capacitively coupled indication systems. They are connected to capacitive layers of the cable plugs or bars, or appropriate equipment is installed in the switchgear. Interlocks make sure that the cable compartment can only be opened when the feeder has been isolated, and that reclosing during work is prevented.

Resistance to climate means insensitivity against pollution and humidity, also against small animals and plant growth. Creepage currents and partial discharges must not occur. Compliance with these requirements is decisive especially in unit substations, as these are subject to the hardest conditions.

F 1.2 Cable or bar?

Apart from the electrical data, the space conditions within the switchgear are decisive for this question. In most cases, the following table applies

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Current	„Short“ connection	„Long“ connection
up to 1250 A	cables	cables
more than 1250 A	bars	parallel cables

Table F-1: Criteria for cable or bar connections in switchgear installations

"Short connections" are those up to 50 m, rather below this value in practice. The limit for using cables or bars also depends on economical aspects.

F 1.2 a Cables

Single cables are used up to 1250 A. They:

- are flexible to lay
- need only 2 sealing ends
- are easy to transport and to install
- enable simple exchange in case of faults, if plug-in terminations are used.

"Flexible to lay" means, in the double sense of the phrase, the mobility of the cable on its route; thus, it is easy to overcome planning inaccuracies. In contrast to bars, cables do not consist of single sections; so they do not require any straight joints except the sealing ends. If the switchgear is equipped with plug-in sockets, the cable can be transferred to a spare feeder in the event of a feeder fault; or to an adjacent feeder, if this one has an additional spare socket.

Currents above 1250 A can be transmitted through parallel cables. For short distances this is not recommended, as it increases

- the expenses for sealing ends
- the space required for connection within the panel
- the risk of faults

The failure rate of conventional sealing ends is still high compared with the switchgear, as the VDEW[11] statistics show. With n parallel cables, the risk also increases n times. Moreover, parallel installation also leads to a reduction of the current carrying capacity due to the temperature rise; as a consequence, larger cross-sections are required. For long interconnections, however, there is no alternative to cables.

F 1.2 b Bars

Gas-insulated or solid-insulated bars are used for currents above 1250 A. Solid-insulated bars have already been manufactured for more than 10,000 A; for normal medium-voltage switchgear, the field of application ranges up to 4000 A. These bars offer:

- high thermal and dynamic strength
- shock protection
- reduced space requirements
- narrow bending radii

[11] VDEW = the association of German electricity producers

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- simple installation

The high current carrying capacity is only achieved by the corresponding conductor dimensions. The fault withstand capability depends on the support spacing; it is much higher than that of cables. Narrow bending radii enable a route that is exactly adjusted to the building - cables have increasing bending radii in proportion to the cross-section.

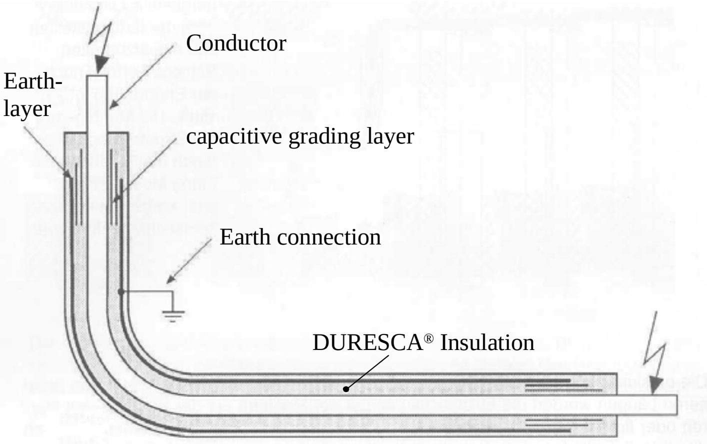
The following table compares some characteristics of gas and solid insulated bars with an air insulated busbar system.

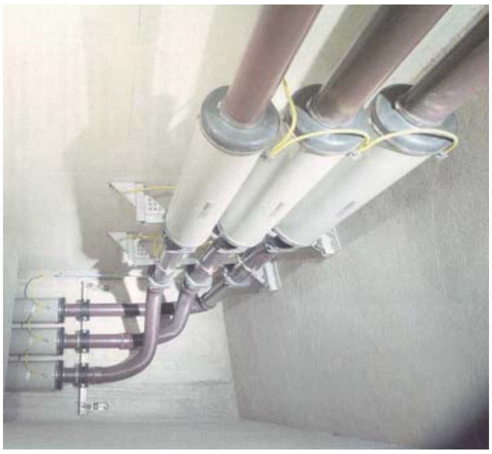
Characteristic	**System**		
	Solid insulation	**Gas (SF_6)**	**Air**
Insulation self healing?	No	Yes	Yes
Dimensions	Small	Small	Clearances to IEC 61936 => large
Type testes	Yes	Yes	No
Phase segregation	Yes	Yes	No
Earthing of the enclosure	No resistance to short-circuit	Resistant to short-circuit	Resistant to short-circuit
Shock protection	Earthed screen	Metal enclosure	Metal enclosure
Connection technology	Plug (standard)	Plug (standard)	Bolts (custom built)
Current & voltage measurement	Toroidal core CT capacitive layer	Toroidal core CT capacitive electrode	Cast resinn CT capacitive support
Design and manufacture	Individual	Modular	individual
Modification/extension	New bars	Possible	possible

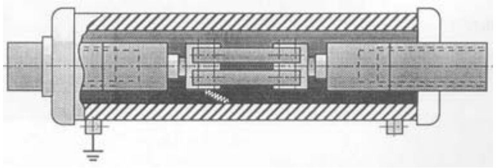
Table F-2: Comparison of solid bar connection methods

Solid-insulated bars (Figure F-1) consist of individually manufactured sections with a length of approx. 10 to 12 m. Straight joints couple the sections and also serve for the linear expansion, which is required for thermal and constructional tolerances. Re-routing, conversion or extension of this made-to-measure system is not possible; new bar sections would be necessary.

The insulation is composed of several cast-resin vacuum impregnated paper layers, with additional control and earthing layers. The earthing layer provides the shock protection, but will not carry earth fault currents.







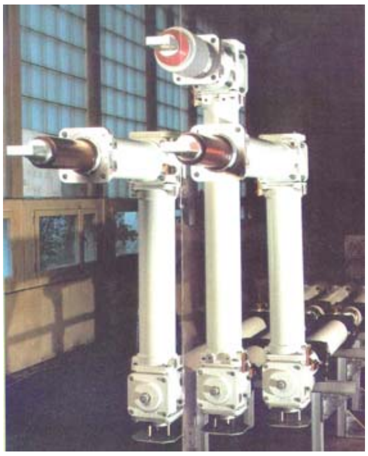
⇖ Construction principle

← Connector with length compensation

Source: Moser-Glaser

Figure F-1: Solid insulated bar

Gas-insulated bars can be compared with the busbar of a SF_6 insulated switchgear. Due to the single-pole, hermetic encapsulation, they are not only shock-proof, but also completely protected against external influence. The bar connection consists of standard components that are installed at site and then filled with SF_6. Thus re-routing or extension is possible by replacement or addition of modular components.



Source: Moser-Glaser

Figure F-2: Gas-insulated bar with various terminal types

Gas and solid insulated systems require less space than air insulated types. They allow modern plug-in connections to equipment. External ring type c.t.s can be used, with the winding at earth potential so that it is not subject to electrical stress; whereas air insulated bars, in a common metal trunk, require post or bushing type c.t.s and v.t.s. For voltage measurement, a capacitive layer is provided in the solid dielectric and an electrode can be fitted in gas insulated ducts.

Both types of bars require an exact spatial planning. The solid- insulated bar also requires accurate manufacturing. For short connections with high currents, bars are the best solution.

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F 1.3 Cable connection systems

Sealing ends are one component for the connection between the switchgear and the cable. They perform various functions:

- line terminal
- control of the electric field
- insulation against earth
- protection of the cable against environmental influences
- balancing and control of the liquid level in mass-impregnated cables

Today, switchgear is mostly connected by thermoplastic-insulated (solid dielectric) cables. If required, straight joints couple these cables with mass-impregnated cables, which are not examined further here. Usual sealing ends for thermoplastic-insulated cables are

- the shrink-on sealing end
- the cast-resin sealing end
- the push-on sealing end
- the plug-in termination.

The shrink-on system utilizes pre-stretched material (sleeves and bands), which returns to its original size by heating it up to 150°C. In this way, the sleeve shrinks onto the cable. Between the sleeve and the cable sheath, there is a fusible adhesive; it melts due to the heat, thus sealing the joints when the sleeve shrinks on.

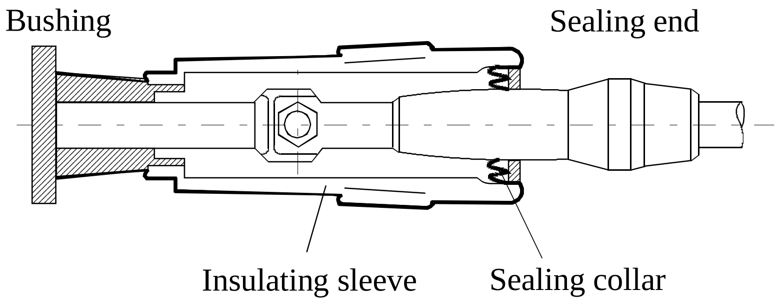

Figure F-3: Sealing end with insulation sleeve

Push-on sealing ends consist of pre-assembled parts; the material is usually silicone rubber. They are pushed onto the prepared cable.

Conventional cable sealing ends can also be installed so as to be safe against environmental influences. Figure F-3 shows an installation for gas-insulated switchgear. A sealing collar is fixed on the sealing end and an insulating sleeve is pushed onto it, which is also fixed at the bushing. The insulating sleeve is made of silicon rubber. It seals one pole completely in all directions.

F 1.4 Plug-in cable terminations

These are detachable plug connections between cables and switchgear panels or devices. They serve for simple installation of cables and can be detached easily in case of fault or for working. This should not be confused with a plug-in contact for frequent plugging in and pulling out. Cable plugs are:

- metal-enclosed, shock proof
- or with earthed conductive layer (contact protection by enclosure)
- climate-proof, even submersible
- maintenance-free
- space saving

This makes them the only connecting elements that suit the concept of hermetically sealed switchgear. In conjunction with the connectors at the terminals (bushing pockets for insertion of the plug) the following systems are distinguished according to EN 50181

- the outside-cone system
- the inside-cone system

Figure F-4 shows the two systems schematically.

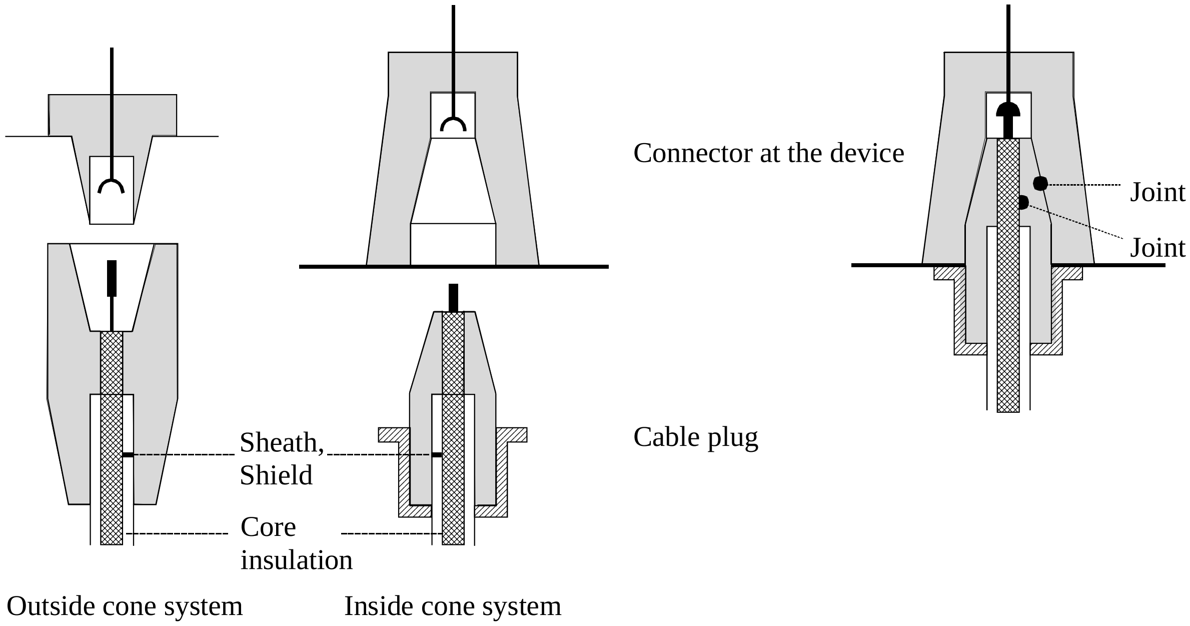

Figure F-4: Scheme of inside and outside cone system

There are clear differences when comparing the two systems under consideration of the criteria insulation, sealing and space requirements. Each connection has two joints: one between the plug and the socket and one between the insulating body of the plug and the cable sheath. Both joints must be allround mechanically and electrically sealed in order to ensure the insulating capacity required.

In the **outside-cone system**, the plug is pulled over the bushing of the terminal. The joints are only sealed by the prestressing force of the insulating body of the plug. Damages (fissures) in the material can reduce the insulating capacity. Here, the installation must be carried out very carefully. On plugs with metal housings – which are more expensive – this risk does not apply. Outside cone

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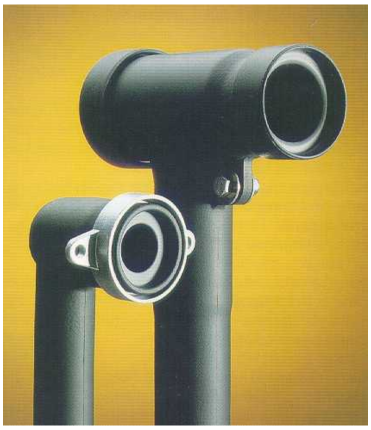
plugs are available for up to 630 A rated normal current; for higher currents up to three T and elbow plugs can be placed on top of each other (“piggyback arrangement“). T-plugs also allow a surge arrester to be fitted, or also plugs for voltage tests.

← Outside cone socket



Sectional view →

Source: Pfisterer

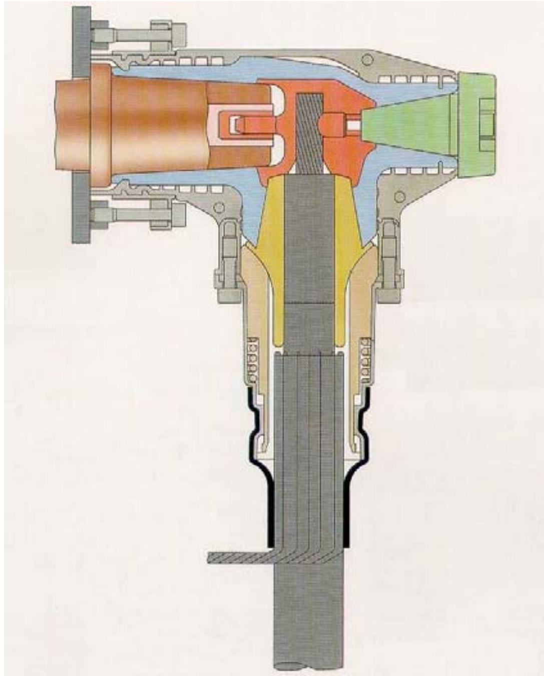
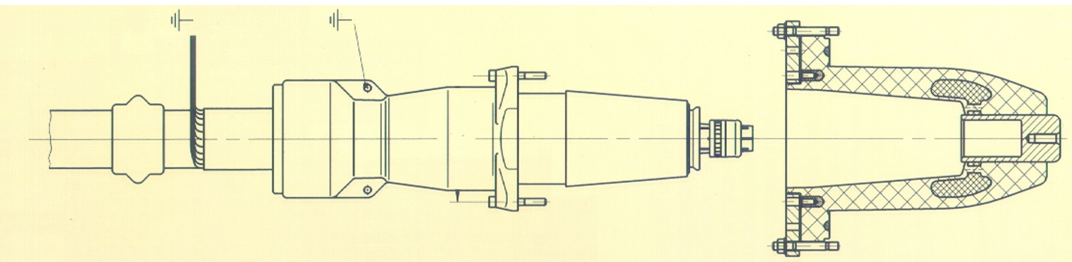


Figure F-5: Examples of outside cone cable plugs

In the **internal-cone system**, the plug is inserted inside the bushing of the terminal. Here, both joints are automatically sealed at the same time; first by the elastic force of the insulating material and then by a spring in the plug body. The internal-cone system is the most compact plug connection. It is available in standard versions up to a rated current of 1250 A, sometimes even for higher currents.



Source: Pfisterer

Figure F-6: Inside cone cable plug and socket (sectional drawing)

🡩 Inside cone plug

🡨 Socket (at the switchgear)

Source: Pfisterer

Figure F-7: Examples of the inside cone system

The plug-in cable system offers still further possibilities:

- straight or elbow plugs
- T-plugs with test connection
- plug sockets and straight joints
- plug-in surge arresters
- plug-in voltage transformers

Cable testing is possible without detaching the cables. For this purpose, the test voltage is applied through a T-plug or through a supplementary spare socket on the switchgear. Or, the socket of the plug-in surge arrester is used, as the surge arrester has to be removed anyway for a voltage test.

Moreover, cable plugs can be equipped with a capacitive layer, which can serve as a coupling capacitor for a voltage indication system.

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F 2 Voltage detecting systems

F 2.1 Purpose and requirements

Enclosed switchgear meets the requirements regarding personnel safety. Thus, opening the enclosure – as long as there is danger of contact – would be a violation of the safety regulations; but this would be necessary if conventional portable high-voltage detectors are used for verification of safe isolation from supply as required by EN 50110. Furthermore, it is clearly impossible to verify the safe isolation in this way in hermetically sealed switchgear.

Other methods to verify safe isolation as required by EN 50110 are rather impractical. The following would still be admissible:

- Fixed-mounted measuring instruments, when the pointer falls to zero during switching off. For this purpose, every panel must be equipped with three voltage transformers and indicating instruments, and personnel must already be present at the instant of switching off.
- Earthing, as long as this is not dangerous for the personnel in charge of it, i.e. with a suitable switching device. If it has been dimensioned correctly, this represents no danger for the switchgear, but service breakdowns are possible if the wrong feeder was earthed by mistake.

A permanent voltage indication system that could be easily installed in every panel would solve the problem. Such a system should:

- have a clearly recognizable display
- be easy to use
- be easy to test
- be similar for all switchgear types
- be equally suitable for all rated voltages
- also enable phase comparison

F 2.2 Mode of operation

The standards distinguish between voltage testing systems as follows

- **Plug-on voltage testing systems**, in which a relocatable indicator can be connected via an interface with a built-in coupler. Plug-on systems are themselves distinguished according to various designs (For details see chapter F 2.4)
  - HR system
  - MR system
  - LR system
  - LRM system
  - LRP system.

- **Integrated voltage testing systems**, built into and forming part of the equipment.

Figure F-8 and Figure F-9 show the principle of the voltage detecting system: the capacitances of the coupling electrode and the coupling system divide the phase voltage U_{LE} from kilovolts to a few volts (U_2) at the interface, where there is the connection facility for a plug-in indicating device. This measures U_2 and signalises the condition of the primary voltage, e.g. "voltage present" by a flashing LED. In a multi-phase circuit, such a detector system is provided for each phase.

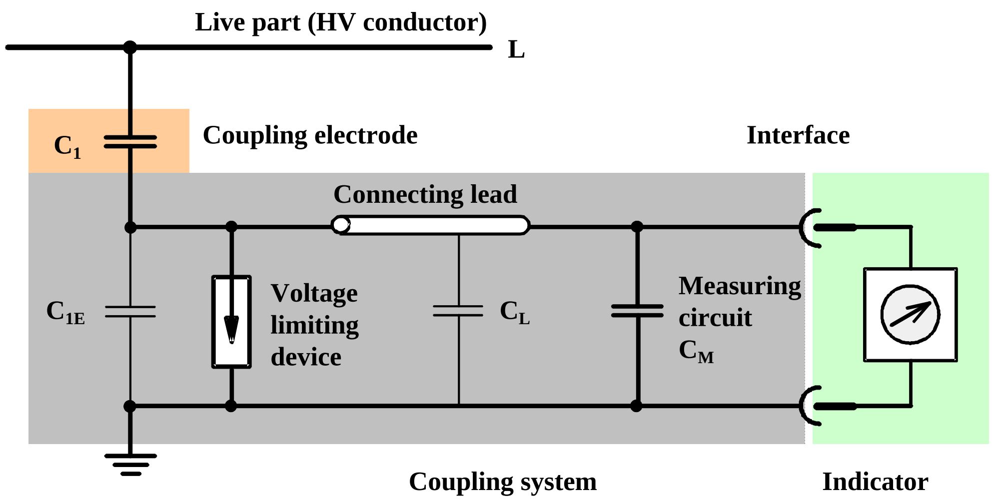

Figure F-8: Scheme of a separable voltage detecting system

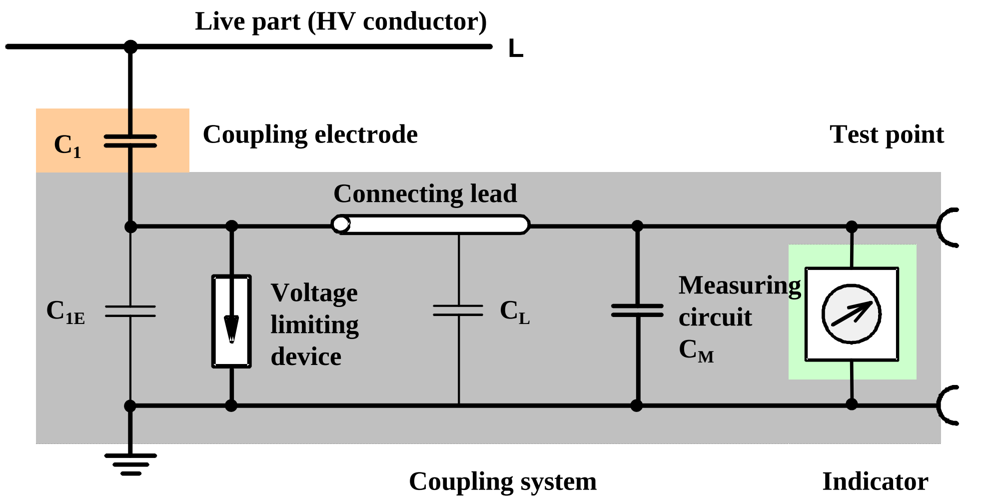

Figure F-9: Scheme of an integrated voltage detecting system

The coupling electrode gives, via the coupling dielectric, the measuring capacitance C1 (coupling capacitance) to the active part of the circuit. Built permanently into the switchgear, the coupling system contains a number of components: conductors between coupling electrode and interface, a voltage limiting device (voltage diverter) and, when required, a capacitor (measuring circuit component).

Coupling electrodes can be incorporated into various components, each suitable for installation in specific switchboard types. A discrete coupling capacitor is practically never seen but for simplification of description, the term "coupling capacitor" is nevertheless used in the following. A coupling electrode can, for example, be provided by a capacitive field layer in

- a cable connection plug

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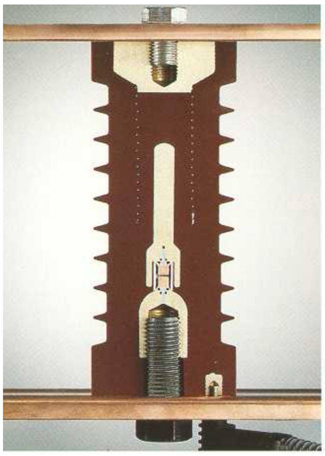
- a cable connection socket
- a solid insulated bar

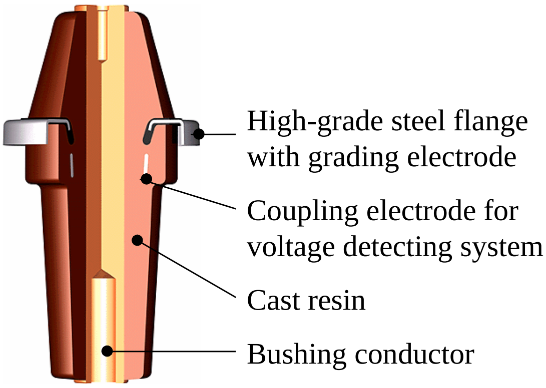
Such layers are always present and can perform the joint function of coupling capacitor. Further coupling electrodes may be formed by electrodes of metal or conductive material included for this specific purpose in

- a current transformer
- a support insulator (divider support)
- a support insulator (divider support
- a gas insulated switchboard

With the exception of capacitors surrounded by insulating gas, coupling dielectrics are cast resin, resin impregnated paper or silicon.



Divider post insulator



Weldable outer cone bushing (sectional view) for gas-insulated switchgear

Outer cone socket

Figure F-10: Examples of coupling electrodes

For protection of personnel – the connection sockets at the point of measurement (the interface) can be touched – the standard requires that the current out of the coupling capacitor, in the most unfavourable case, shall not exceed 1 mA (awareness threshold). The most unfavourable case is the state of direct short circuit of coupling capacitor to earth, at the highest permissible network voltage; which must include any voltage displacement in a three-phase network during earth fault. All conventional coupling capacitors fulfil this; the current even remains far below the limiting value. The safety requirements go even further: in the extremely rare case of a breakdown of the coupling dielectric; a voltage limiting device must prevent the resulting fault current from reaching the outside, through the measuring point.

The total undercapacitance of the voltage divider is made up of various components:

•	Leakage capacitance:	coupling electrode against earth C_{1E} indicator against earth
•	Coupling system:	connecting lead C_L measuring circuit component (additional capacitor) C_M
•	Load	indicator

Coaxial cables are conventionally used for the connecting cables – their inherent capacitance lies mostly in the order of 50 to 100 pF/m. Design, panel type and the conductor routing inside the panel determine the length and thus the capacitance; e.g. in double busbar systems lengths of up to 6 m are required.

The interface, of which one pole is connected to the measurement voltage and the other to earth, is the connecting point (interface) for an indicator, a phase comparator or a combination device with both functions.

The indicator evaluates the measurement voltage and displas the condition of the primary circuit by, for example, the blinking of an LED.

F 2.3 Threshold values for indication

The signal "voltage present" MUST appear within an exactly prescribed range of the operating voltage and SHALL NOT appear below a prescribed value. The threshold determines the phase-to-earth voltage at the detector system; see Fig. E4. The base value in each case is the rated (operational) voltage of a network. The threshold values allow for the fact that the rated voltage in a multi-phase system is always that between the phases, whereas the voltage at the detectors is that between phase and earth.

The values are determined so that the signal "voltage present" appears at over approximately 80% of the normal operating voltage. Converted for various networks, we see that for a

3-phase system the signal must appear at a phase-earth voltage

- from 45 % and up to 120 % of rated voltage (between phases), but
- shall not appear at under 10 % of rated voltage;

single pole earthed single-phase systems the signal must appear at a phase-earth voltage

- from 78 % and up to 120 % of rated voltage (between phases), but
- shall not appear at under 17 % of rated voltage.

symmetrically earthed single-phase systems the signal must appear at a phase-earth voltage

- from 39 % and up to 60 % of rated voltage (between phases), but
- shall not appear at under 9 % of rated voltage;

The lower window "signal SHALL NOT appear" ensures that weak, induced voltages from neighbouring systems will not erroneously simulate the condition "voltage present". DC voltages, e.g. from residual charges on cable conductors shall equally not be signalled. The upper window "signal MUST appear" covers that voltage range of a network which is possible in normal operation. In between, there is a range in which the signal may begin. This middle window gives design freedom for the choice of the divider ratio.

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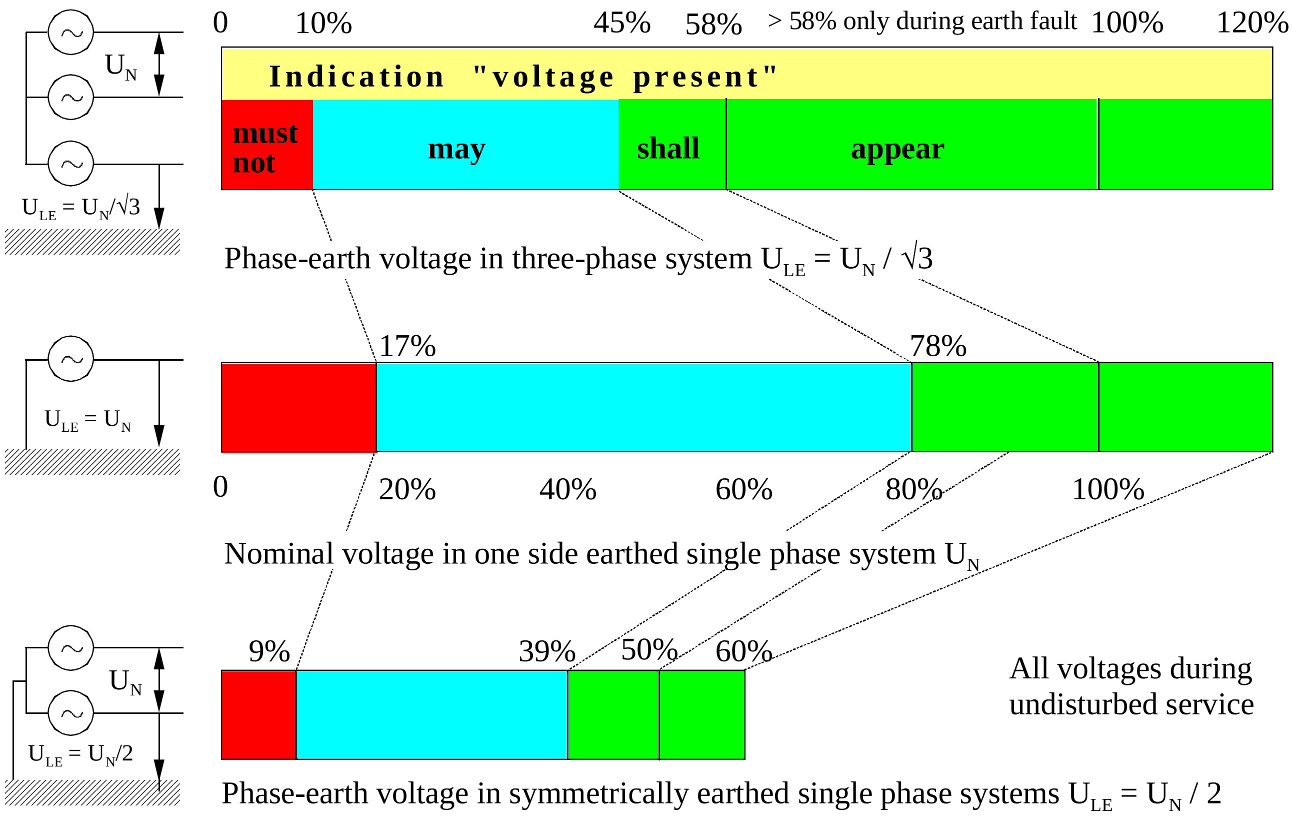

Figure F-11: Threshold values

F 2.4 Separable System (VDS)

There are detecting systems with plug-in (separable) and such with integrated indicators. Different plug-in systems differ at the interface, that is, at the electrical and mechanical interface to the indicator.

F 2.4 a HR-System

The HR system (high-resistance system) has a voltage of 90 V at the interface and a measuring current of 2.5 µA when the operating threshold is reached. The indicator provided incorporates a glow-lamp which does not need a supplementary auxiliary voltage.

Characteristic	**System**		
	HR	**LRM**	**LR**
Voltage at the interface	70 … 90 V	4 … 5 V	4 … 5 V
Threshold current	2.5 µA	2.5 µA	2.5 µA
Available energy at the interface	225 µW	12.5 µW	12.5 µW
Impedance of indicator	36 MΩ	2 MΩ	2 MΩ
Min. insulation resistance	400 MΩ	20 MΩ	20 MΩ

Characteristic	**System**		
	HR	**LRM**	**LR**
Interface	19 mm Europlug	Pin centres 14 mm similar Europlug	6.3 mm latch-in-plug
Test of indicator before use	Neighbour cubicle or test adapter + socket	Neighbour cubicle or test adapter + socket	Built-in testing element
Indicator signals „Voltage present“ „Voltage not present“	Flashing or steady light No light	Flashing or steady light No light	Red flashlight + sound Green flashlight + sound
Duration of indication	As long as indicator is plugged in, continuous	As long as indicator is plugged in, continuous	As long as test button is pressed, <u>not</u> continuous
Phase comparison	With separate device	With separate device	With combined device
Maintenance of indicator	None	None	Battery
Use of an indicator in a different detection system	Not possible	With adapter possible in HR- and LR-System	With adapter possible in HR- and LR-System

Table F-3: Characteristics of separable VDS

F 2.4 b LR-System

The LR system (low-resistance system) has a voltage of 5 V at the interface and a measuring current of 2.5 µA when the operating threshold is reached. The indicator provided needs a battery. Mostly, combined indicator and phase comparator devices are used.

F 2.4 c LRM-System

The LRM system (low-resistance modified system) differs from the LR system with a latch-in plug, in that it has a modified interface with two plug pins at 14 mm centres (otherwise similar to the 19 mm Europlug). The deliberately selected 14 mm dimension prevents accidental insertion of the plug into a mains socket. At the operating threshold, 5 V / 2.5 µA appears at the interface. The indicators have a blinking LED, without auxiliary voltage.

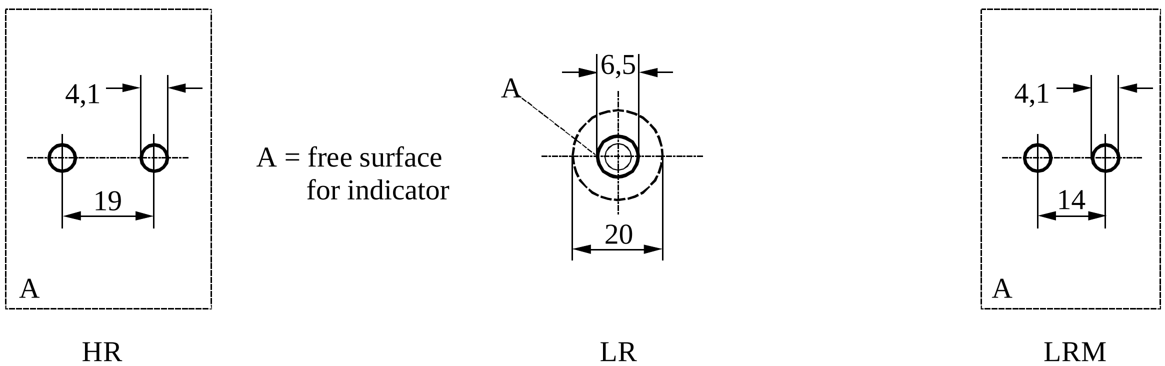

Figure F-12: Interfaces of separable VDS

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F 2.4 d Application of separable systems

To test for presence or absence of voltage in the cubicle, the indicator device is inserted sequentially into the sockets; if it does not blink, the feeder is de-energized. Alternativly, three indicators may be permanently left in the sockets - the systems are suitable for continuous use.

To test the indictors of all systems, there are adaptors which can be inserted into a mains socket. These replicate the threshold voltage (5V or 90 V). With such adapters it is possible to check the indicators for proper function at any mains socket (230 V). HR indicators can directly be inserted into a mains socket, without test adapter. This often used method, however, does only check the glow-lamp but not whether the indicator works properly at 90 V threshold voltage. This is not an approved method of test according to the standard.

Interface test devices, which one can insert into the interface socket instead of the indicator, test correct functioning of the coupling circuit. They give a "go", "no go" signal, indicating "in order" or "not in order". When the electrical threshold voltage values lie within the correct range, this will be signalled by a green LED; otherwise a red signal appears.

F 2.5 Integrated systems (IVDS)

Integrated systems with fixed-mounted indicator have no interface. They can work internally with any current or voltage levels. Only for phase comparators is a measuring point provided in the form of an external connection; it is usually compatible with an LRM interface.

Integrated systems use – with few exceptions – LC display, creating considerable scope for showing operating states. Dead state can be actively indicated, as well as readiness for operation and the to-standard state of the interface (repeat test).

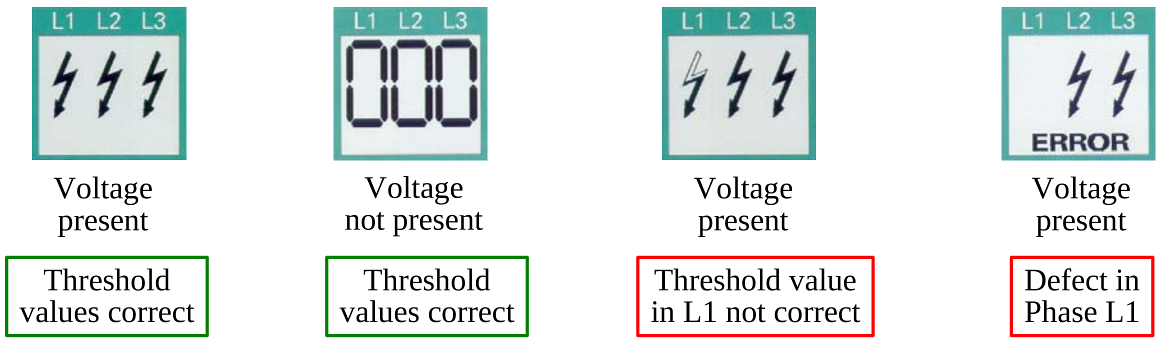

Figure F-13: Indication data with a LC-Display

G MATERIALS

G 1 Sulphur Hexafluoride SF_6

G 1.1 Characteristics for electrotechnical usage

SF_6 is a gas, of which the molecule comprises one sulphur atom surrounded symmetrically by six fluorine atoms in a saturated state.This structure makes the molecule very stable and inert. SF_6 does not react with other materials, is non-toxic and non-flammable, cannot oxidise lubricants or metals, e.g. contacts or connections.

The following physical, chemical and electrotechnical characteristics are of particular importance for switchgear applications:

- colour and odourless, non flammable
- inert at room temperature => non-toxic
- 5 times heavier than air
- good heat conductivity
- thermal dissociation between 1500 and 3000 K
- complete ionisation above approx. 4000 K
- electro-negative (electron attractive character)
- dielectric strength 2.5 times that of air
- good arc-quenching characteristics

G 1.2 Application as insulating medium

Every insulating gas fills the whole available space. In contrast to solid insulating materials, a gas allows no inconsistencies which may lead to faults, does not suffer from pre-stressing (ageing) nor residual damage after any event (self-healing).

Compared with air, SF_6 is the better insulating gas. Its electro-negativity causes it to attract free electrons, so that the molecule readily becomes an ion. Free electrons, by contrast, are very mobile; in an electrical field they take on high energies; can then form further charge carriers by impulse ionisation and initiate a breakdown. Ions are however notably slower than electrons in the electric field and therefore hardly likely to cause flashovers. The capture of electrons by SF_6 molecules reduces the number of free electrons and makes the gas more dielectrically stable.

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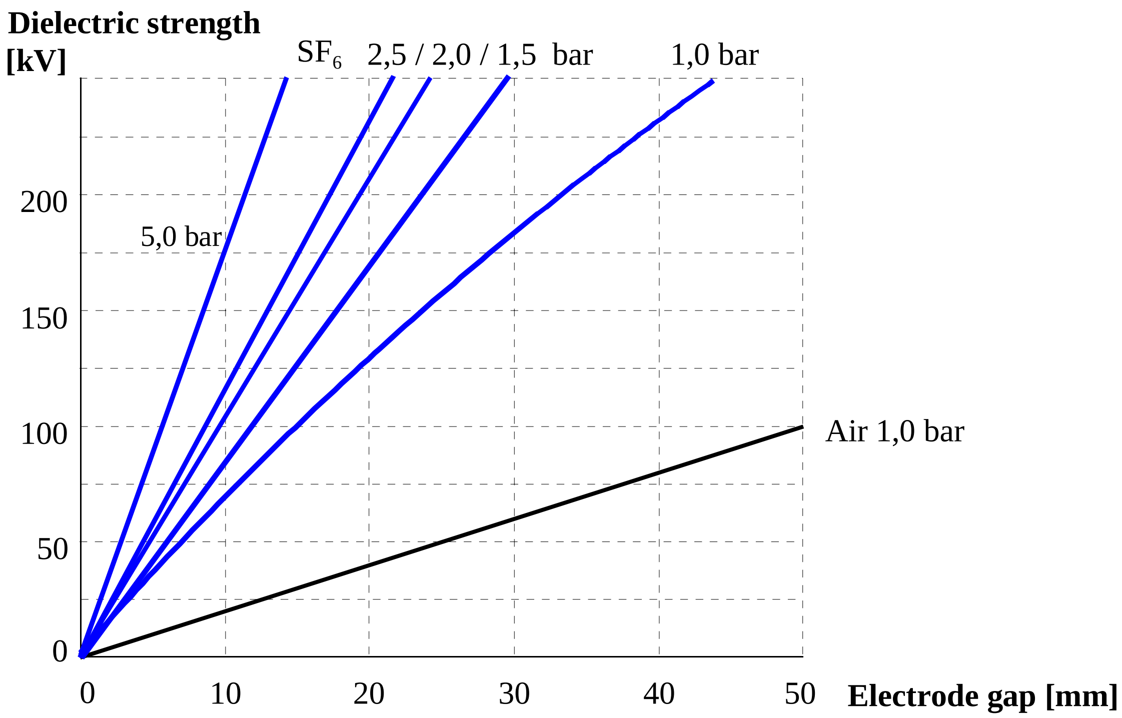

Figure G-1: Breakdown voltage at 50 Hz in homogeneous fields – air and SF_6

Above a critical field strength E0, of 89 kV/cm·bar, however, more free electrons are formed than are attached, charge carriers multiply like an avalanche and breakdown is initiated. In air, the critical value is 25 kv/cm·bar. The dielectric character of SF_6 is better by the same ratio (Figure G-1). This allows much more compact enclosures. Nevertheless, the necessity to maintain a more or less homogeneous electrical field remains. Sharp corners, surface irregularities and free particles must be avoided by appropriate forming of conductive surfaces and by field control at critical locations.

The high density and low viscosity of the gas explain its good thermal conductivity. Despite compact enclosures, heat losses are rapidly dispersed. Even at high operating temperatures, the gas remains stable because thermal dissociation first begins at 1500 K – far above the permissible temperature in electrical equipment.

G 1.3 Application as arc extinction medium

SF_6 has a much better arc extinction capability than air; due to its thermal and ionisation characteristics, which are shown in figure Figure G-2.

Commencing at about 1500 K, SF_6 starts to separate in its atomic constituents. From approximately 4000 K this dissociation is complete. This process requires a large amount of energy, which is taken from the arc. Beyond the arc, in the area of lower temperatures, the atoms recombine into SF_6 and the energy is again released. Through this process, large amounts of energy are rapidly transported from the arc and there remains only a thinner, hotter core which alone is conductive. At a current zero, this core can be rapidly cooled to below 3000 K so that the gas is no longer conductive.

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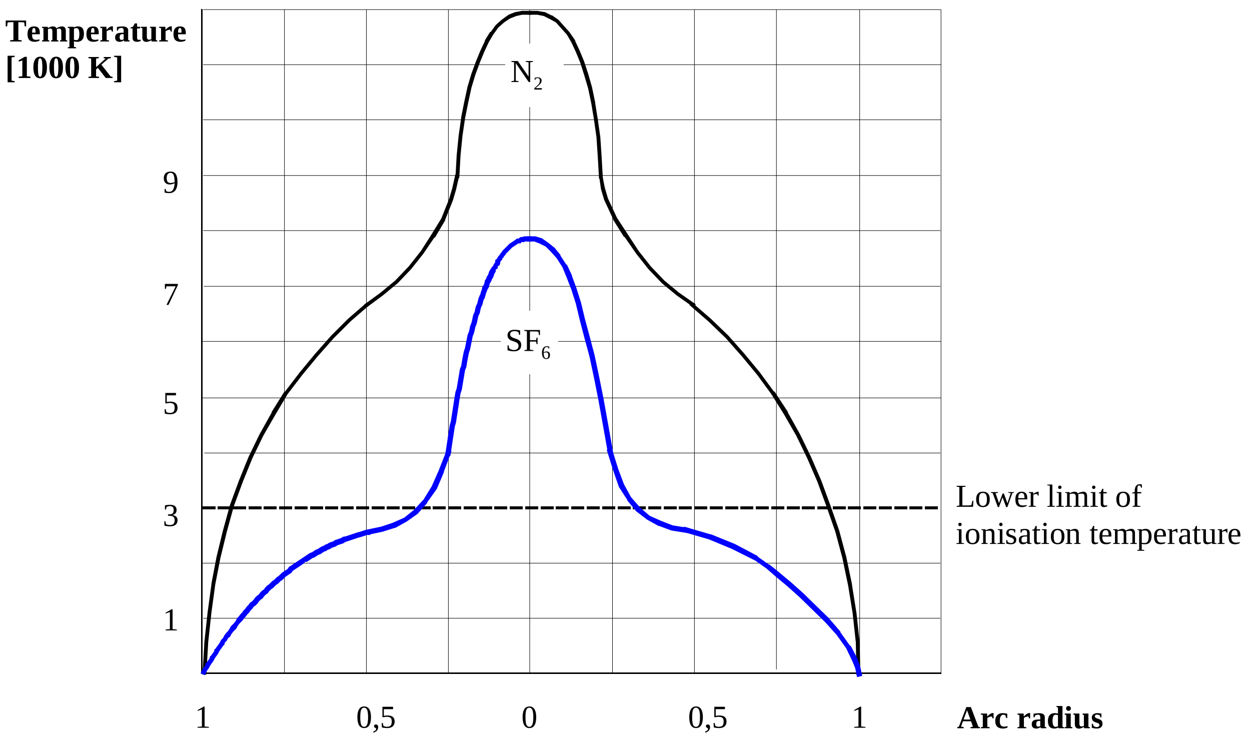

Figure G-2: Radial temperature distribution within an arc in SF_6 and N_2

In contrast, an arc in nitrogen gas is cooled only by convection and radiation. The diameter and the volume of the hot conductive core is many times greater. De-ionisation takes correspondingly longer and requires a strong blasting system.

For the application of SF_6 in switchgear, see also chapters C 1.1 arc-quenching, C 1.7 circuit-breakers and E 6 gas-insulated switchgear.

G 1.4 SF_6 and the environment

SF_6 has been used as an insulating and arc quenching medium for high and medium-voltage switchgear since 1960. The excellent electrical, chemical and physical properties of the gas have had a major influence on the design of switchgear in general [47] and SF_6 had hitherto gradually been replacing many of the other commonly-used and more costly media such as oil and compressed air. Therefore, SF_6 technology has greatly improved the efficient utilization of technical and financial resources (and manpower) in power transmission and distribution. At the same time SF_6 has also reduced the hazard risk for personnel and the environment (compared with oil).

In Germany at present almost 50% of new medium-voltage switchgear being installed at the primary distribution level (i.e. transformer substations) is gas-insulated; at the secondary level (i.e. main substations, distribution substations and secondary substations with RMU[12]) the figure is almost two-thirds.

In the case of high-voltage switchgear, i.e. over 52 kV, approximately 40% of new switchgear being installed is metal-enclosed and gas-insulated (GIS). Although the remaining 60% is air-insulated (AIS), almost all circuit-breakers now employ SF_6 exclusively as the arc quenching medium. This is

[12] Ring Main Unit, load-break switchgear with (ring-)cable and transformer feeders.

particularly true for rated voltages over 170 kV, so other forms of arc quenching in new equipment are so insignificant that they can be disregarded.

Despite the many years of excellent results with SF_6 and the well-proven guidelines which regulate its use, there is still a great deal of political discussion (viz. the Kyoto Summit) of the technology involved with regard to the greenhouse gas problem. Overall, however, taking into account all the ecological, economic, safety and technical aspects, there is no doubt that SF_6 is still the best insulating and arc quenching medium for switchgear. Present SF_6 technology in power transmission and distribution is the end-result of many decades of optimization, which is why Siemens (and most other major manufacturers) are totally committed to it.

G 1.5 Environmental compatibility

The properties of SF_6 relevant to the environment:

- No ecotoxic potential
- Harmless to the ozone layer
- High relevance to greenhouse potential
- Persistent (slow to degrade)

Pure SF_6 is physiologically completely harmless and, in fact, is even used by the medical profession directly on humans for such procedures as lung examinations.

SF_6 is a greenhouse gas [56]. Although its greenhouse potential – quoted as a CO_2 equivalent with the GWP factor[13] – is 23,900 times greater than that of CO_2 [57], the proportion of SF_6 already in the atmosphere and contributing to the greenhouse effect is less than 0.1 %. This is a very low figure compared with the contribution from carbon dioxide (CO_2) which is reckoned to be 50%. More recent studies place the figure for GWP factor at 22,200 [58]. This means that the proportions of SF_6 contributing to greenhouse gas emissions are even less than had previously been thought.

The contribution from all high-voltage and medium-voltage applications of SF_6 (manufacture and operation) to the total greenhouse potential in Germany (1998) was less than 0.05%.

The great majority of SF_6 emissions originate from other, open applications such as

- Aluminium and magnesium castings
- Soundproof windows
- Motor car tyres
- Aerospace industry
- Military uses

According to [59] approximately 8500 tonnes of SF_6 are manufactured every year worldwide, of which 6200 tonnes are eventually released into the atmosphere[14] and largely come from open and semi-open applications, i.e. motor vehicle tyres, soundproof windows, etc.).The European proportion of these emissions due to energy-related applications is 210 tonnes per annum[15] arising from accidental release during development, manufacture and installation and leaks from switchgear during normal service. Most of the releases due to leakage come from the older installations which,

[13] GWP Global Warming Potential, obtained for 100 years.
[14] Figures in year 1995
[15] Figures for the European Union („EU 15“).

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however, are gradually being replaced by new equipment. When one remembers that the global emission rate of all synthetic greenhouse gases will have increased to approximately 50,000 Mt/a CO_2 equivalent by 2010 [55], the proportion of SF_6 emissions from electrical engineering sources will be 23 Mt/a, i.e. only ≈ **0.04%**.

Modern high-voltage switchgear has leakage rates of only around 0.5% p.a. whereas with medium-voltage equipment it is less than 0.1% p.a. The figure for welded medium-voltage switchgear is once again significantly lower, i.e. a leakage rate of almost zero.

Measurements taken in the atmosphere have shown that annual SF_6 emissions since 1995 have already fallen [60]. In total, the amount of SF_6 contributing to the greenhouse effect is small enough to be negligible [59]. This is also clear in relation to the contribution from CO_2: compared with the 6200 tonnes of SF_6 the annual world-wide release of CO_2 is approximately 22 billion tonnes. In CO_2-equivalent that is approximately 150 Mt, or 0.7%.

G 1.6 Responsibility in the use of SF_6

The major manufacturers of SF_6-insulated switchgear have researched the whole field of SF_6 - from its manufacture to eventual recycling - very thoroughly indeed in conjunction with a range of independent environmental organizations, the manufacturers of SF_6, professional institutions and approval authorities. Manufacturers and users are also playing an active role in the European Climate Control Program ECCP [50]:

- The quantities of SF_6 used in switchgear are carefully monitored and registered in the various fields of development, manufacture, operation and disposal [51], [50]. For this purpose many countries employ a system of obligatory self-declaration by manufacturers and users [52], [53] which are negotiated with and approved by the national ministries of environment. The implemented procedures used in actual practice, in Germany have been integrated into the climate control programs of the Federal German Government [54].
- Despite the very small overall proportion of switchgear involved in the greenhouse effect, both manufacturers and users are still continuing to work hard on new ways of reducing emissions as well as keeping a close eye on developments elsewhere in the world [55].

For users there is no risk at all arising from the use of SF_6 equipment. All major manufacturers are clearly committed to SF_6 technology and are happy to assure plant operators of its risk-free characteristics, which are as follows:

- A design of installation whose primary feature is the use of the absolute minimum quantity of SF_6 gas necessary for insulation purposes and with a standard of leak-proofing that can be sustained for decades;
- In the case of medium-voltage equipment, sealed pressure systems have become established which require no attention at all to the gas throughout the entire service life of more than 30 years. For such equipment Siemens uses stainless steel chambers welded with automatic laser machines to produce a hermetic seal. In this case the leakage rate is practically zero. All equipment used at the secondary distribution level is built in this way and the same techniques are gradually working their way through into the primary distribution level.
- Extremely sensitive automatic leak detection equipment is used during production to ensure maximum possible leak-tightness for the chambers and enclosures.
- The leakage rate of such systems is less than 0.1% pro Jahr.

- At the end of the equipment's service life the SF_6 and all the other materials are either recycled or disposed of by the manufacturer or an appropriately qualified company.
- The used SF_6 is pumped out, reconditioned and used again so that, in effect, the whole process is a closed loop in which the use of modern maintenance equipment with a lower evacuating pressure helps achieve a sustained reduction in emissions throughout the process.

The switchgear industry has clearly acted in a quite exemplary fashion, as acknowledged by environmental authorities and institutions all over the world. The decisions recorded in the minutes of the Kyoto Climate Conference on reducing greenhouse gas emissions mainly apply to major sources of emissions in other still very widespread uses, and not to manufacturers and operators in the power industry who are showing an outstanding sense of responsibility. Therefore, restrictions on the use of SF_6 in switchgear would not produce any noticeable effect in reducing world-wide emissions. On the other hand, of course, any old and/or leaking installations which still exist in some countries should be replaced by modern, properly-sealed equipment.

In actual fact, the European switchgear industry actively supports a program of reduction in SF_6 emissions. The only factor always open to discussion is precisely where any improvements can be implemented most effectively.

Thanks to their safe sealing – in the best cases they are totally welded – and the establishing of a sustainable closed loop of usage, modern electrical switchgear is both ecologically harmless and economically essential. Therefore, future generations will certainly not be inheriting any problems from the use of new SF_6-based technology. On the other hand, however, the modernization of old, leaking equipment and restrictions on the use of SF_6 for applications other than switchgear should be a world-wide aim where high emissions are evident.

G 1.7 SF_6 and external or internal faults

The term "fault" can mean many different things, depending on the particular situation. Here, therefore, we are going to differentiate between external faults (where the switchgear is the "victim") and internal faults where the fault originates in the switchgear itself. When a fault occurs, for the SF_6 to have no chance whatever of causing any problems for either persons or the environment, it must be able to escape from the switchgear. However, this only occurs when there are severe mechanical or thermal effects on the system, which means that they must be serious events. Even when a fault occurs during which parts of the system are damaged and start leaking, only a small amount of SF_6 will be able to escape because the installations are always subdivided into a number of separate compartments. Should SF_6 escape, there can be no further damage unless there is heat involved (coming from either fire or arcing) and decomposition products arise. This is because SF_6 is inert and physiologically harmless, as described in section G 1.5.

In the event of an external fault during which there is an escape of gas, e.g. due to a fire, the SF_6 does not make any additional contribution to the fire load because it is non-flammable. In contrast to oil, which was widely used in the past as an insulating and arc quenching medium and is still used in almost all types of transformer, there are no secondary dangers involved due to oil fires or explosions. So the measures taken to deal with fires in no way differ from those for other types of equipment.

Internal faults are extremely rare: The switchgear standard IEC 62271-200 / VDE 0671-200 (metal-enclosed switchgear up to 52 kV) expressly recognizes the reliable characteristics of gas-insulated switchgear; it recommends the use of gas-filled compartments as a way of avoiding internal faults in the switchgear resulting from external influences. Operating experience confirms this tactic;

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faults – the worst case being an arc inside the switchgear – have become rarer precisely thanks to the use of gas-insulated switchgear.

With gas-insulated medium-voltage equipment the statistical probability of fault arcing is approximately 10^{-5} per panel per annum (i.e. one fault a year will occur in 100,000 panels or in one panel every 100,000 years), and therefore is substantially better than in alternative insulating systems that are subject to aging and external factors of influence.

Should, nevertheless, a fault arc ever occur in SF_6-insulated switchgear, the gas will initially split into its primary constituents (single fluorides) under the effect of the arcing. If they succeed in escaping from the switchgear, their exposure to water vapor in the form of humidity in the air will produce secondary products, mainly

- highly volatile constituents (HF derivatives)
- hydrofluoric acid (HF)
- thionyl fluoride SOF_2
- SO_2
- S_2F_2

Research studies [62] have shown that, in actual practice, the risk to humans is no greater than that from the combustion of other materials in air-insulated and solid-insulated switchgear exposed to fault arcing.

To cope with fault situations, a number of rules [61], [63] and [64] have been laid down for the procedures to be adopted to deal with the fault and to ensure safety for the operating staff.

With medium-voltage systems the amounts and pressures of SF_6 used are so small that, in the view of German professional associations - and compared with a fault in an air-insulated installation - there is no additional hazard for the operating staff. The same work safety regulations apply to both types of equipment (AIS and GIS). For this reason medium-voltage equipment does not come under the professional association regulations that apply to SF_6 switchgear [64]. However, an operator can still use the information as a guide fot the correct procedures to adopt.

G 1.8 Operational experience

SF_6 was first launched on to the market several decades ago and, in the years since, the technology of its use throughout its whole life-cycle has been safely mastered - from its manufacture to eventual recycling or disposal. Siemens has been building SF_6 switchgear for more than 30 years and so far has supplied and commissioned more than

- 8.000 HV bays
- 33.000 HV circuit-breakers
- 300.000 MV panels with switches and circuit-breakers

The advantageous characteristics of SF_6 and its associated technology (as described and explained above) are the main reason for its popular acceptance by the market.

H STANDARDS

The following list names the most important standards or specifications; it is structured according to

- Statutory regulations for medium-voltage equipment
- Generic standards for switching devices and switchgear
- Product standards for switching devices
- Product standards for switchgear and accessories

Generally, the IEC standards concur with the relevant national standards. A standard uses the symbols customary in the respective technical field. It is consequently possible for the same physical variable to be differently designated.

H 1 Statutory regulations for medium-voltage equipment

International	**Germany**	**Title** (English / German)
	BGV A3	Unfallverhütungsvorschrift – Elektrische Anlagen und Betriebsmittel
	BGV B11	Unfallverhütungsvorschrift – Elektromagnetische Felder
	BGV A8	Unfallverhütungsvorschrift – Sicherheits- und Gesundheitsschutzkennzeichnung am Arbeitsplatz
1999/519/EC [16]		Council recommendation of 12 July 1999 on the limitation of exposure of the general public to electromagnetic fields (0 Hz to 300 GHz)
	26. BImSchV	EMVU-Verordnung – 26. Verordnung zur Durchführung des Bundes-Immissionsschutzgesetzes (Verordnung über elektromagnetische Felder - 26. BlmSchV) Vom 16. Dezember 1996
89/336/EEC [17]		Council directive 89/336/EEC – EMC Directive of 3 May 1989 on the approximation of the laws of the Member States relating to electromagnetic compatibility; amended by 92/31/EEC; 93/68/EEC
	EMVG	Gesetz über die elektromagnetische Verträglichkeit von Geräten Vom 18. September 1998
	BGI 766	Instandsetzungsarbeiten an elektrischen Anlagen auf Brandstellen
	BGI 559	Handlungsanleitung zur Anpassung von Hochspannungsanlagen - DIN VDE 0101 (05/89) -

Note on BGV[18]: Accident prevention regulations issued by the statutory industrial accident insurance institutions (Berufsgenossenschaften: BGs) are legally binding, according to the 7th code of social law, §15.

Note on BGI[19]: BG information describes typical solutions for applying BG regulations. Unlike UVV rulings, BG information does not have to be obligatorily applied.

[16] An EU Council Recommendation need not obligatorily be implemented in applicable law in EU member states. In Germany this has taken place in the form of 26. BImSchV.
[17] An EU Directive must be implemented in national law in EU member states. However, only respective national legislation is legally binding.
[18] BGV = BG regulation
[19] BGI = BG information

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H 2 Generic standards for switching devices and switchgear

=> Listed according to the number of the international standard

International standard	**German standard**	**Title** (English / German)
EN 50110	VDE 0105-100 [20]	Operation of electrical installations Betrieb von elektrischen Anlagen
IEC 60071	VDE 0111	Insulation coordination Isolationskoordination
IEC 60376	VDE 0373-1	Specification and acceptance of new sulphur hexafluoride Bestimmung für neues Schwefelhexafluorid SF_6
IEC 60480	VDE 0373-2	Guide to the checking of SF_6 taken from electrical equipment Prüfung von aus elektrischen Geräten entnommenem SF_6
IEC 60529	VDE 0470-1	Degrees of protection provided by enclosures (IP Code) Schutzarten durch Gehäuse (IP-Code)
IEC 60694	VDE 0670-1000	Common specification high-voltage switchgear and controlgear standards Gemeinsame Bestimmungen für Hochspannungs-Schaltgeräte-Normen
IEC 60865	VDE 0103	Short-circuit currents - Calculation of effects Kurzschlußströme – Berechnung der Wirkung
IEC 60909	VDE 0102	Short-circuit current calculation in three-phase a.c. systems Kurzschlußströme in Drehstromnetzen
IEC 61634		High-voltage switchgear and controlgear - Use and handling of sulphur hexafluoride (SF_6) in high-voltage switchgear and controlgear
IEC 61936-1	VDE 0101 [21]	Power installations exceeding 1 kV ac Starkstromanlagen mit Nennwechselspannungen über 1 kV

[20] Part 1 of EN 50110 contains minimum requirements applicable in all CENELEC countries. The respective currently valid safety requirements for the individual countries are described in national addenda. In Germany, the details of Parts 1 and 100 (VDE 0105-1 and -100) are significant.

[21] The January 2000 edition also contains specifications for earthing systems (formerly VDE 0141)

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H 3 Product standards for switching devices

=> Listed according to the number of the international standard

International standard	German standard	Title (English / German)
IEC 60044		Instrument transformers
	VDE 0414	Meßwandler
IEC 60099		Surge arresters
	VDE 0675	Überspannungsableiter
IEC 60265-1		High-voltage switches - Part 1: Switches for rated voltages above 1 kV and less than 52 kV
	VDE 0670-301	Hochspannungs-Lastschalter – Teil 1: Hochspannungs-Lastschalter für Bemessungsspannungen über 1 kV und unter 52 kV
IEC 60282		High-voltage fuses - Current-limiting fuses
	VDE 0670-4	Hochspannungssicherungen –Strombegrenzende Sicherungen
IEC 62271-105		High-voltage alternating current switch-fuse combinations
	VDE 0671-105	Hochspannungs-Lastschalter-Sicherungs-Kombinationen
IEC 60470		High-voltage alternating current contactors and contactor-based motor-starters
	VDE 0670-501	Hochspannungs-Wechselstrom-Schütze und -Motorstarter mit Schützen
IEC 60644		Specification for high-voltage fuse-links for motor circuit applications
	VDE 0670-401	Anforderungen an Hochspannungs-Sicherungseinsätze für Motorstromkreise
IEC 60787		Application guide for the selection of fuse-links of high-voltage fuses for transformer circuit applications
	VDE 0670-402	Wechselstromschaltgeräte für Spannungen über 1 kV – Auswahl von strombegrenzenden Sicherungseinsätzen für Transformatorstromkreise
IEC 62271-110		High-voltage alternating current circuit-breakers - Inductive load switching
IEC 62271-100		High-voltage switchgear and controlgear - High-voltage alternating-current circuit-breakers
	VDE 0671-100	Hochspannungs-Wechselstrom-Leistungsschalter
IEC 62271-102		High-voltage switchgear and controlgear - High-voltage alternating current disconnectors and earthing switches
	VDE 0671-102	Wechselstromtrennschalter und Erdungsschalter

H 4 Product standards for switchgear and accessories

=> Listed according to the number of the international standard

International standard	German standard	Title (English / German)
IEC 62271-200		A.C. metal-enclosed switchgear and controlgear for rated voltages above 1 kV and up to and including 52 kV
	VDE 0671-200	Metallgekapselte Wechselstrom-Schaltanlagen für Bemessungsspannungen über 1 kV bis einschließlich 52 kV
IEC 60466		A.C. insulation-enclosed switchgear and controlgear for rated voltages above 1kV and up to and including 38 kV
	(VDE 0670-7) [22]	Isolierstoffgekapselte Hochspannungsschalt- und -steuergeräte für Nennspannungen über 1 kV bis einschließlich 38 kV
IEC 61219		Live working – Earthing or earthing and short-circuiting equipment using lances as a short-circuiting device – Lance earthing
	VDE 0683-200	Arbeiten unter Spannung – Erdungs- oder Erdungs- und Kurzschließvorrichtung mit Stäben als kurzschließendes Gerät – Staberdung
IEC 61230		Live working – Portable equipment for earthing or earthing and short-circuiting
	VDE 0683-100	Arbeiten unter Spannung – Ortsveränderliche Geräte zum Erden oder Erden und Kurzschließen
IEC 61243-1		Life working – Voltage detectors Capacitive type to be used for voltages exceeding 1 kV a.c
	VDE 0682-411	Arbeiten unter Spannung – Spannungsprüfer Kapazitive Ausführung für Wechselspannungen über 1 kV
IEC 61243-2		Life working – Voltage detectors Resistive type to be used for voltages of 1 kV to 36 kV a.c.
	VDE 0682-412	Arbeiten unter Spannung – Spannungsprüfer Resistive (ohmsche) Ausführungen für Wechselspannungen von 1 kV bis 36 kV
IEC 61243-5		Live working - Voltage detectors Voltage detecting systems (VDS)
	VDE 0682-415	Arbeiten unter Spannung – Spannungsprüfer Spannungsprüfsysteme (VDS)
IEC 61330		High-voltage/low-voltage prefabricated substations
	VDE 0670-611	Fabrikfertige Stationen für Hochspannung/Niederspannung
EN 50187		Gas-filled compartments for a.c. switchgear and controlgear for rated voltages above 1 kV and up to and including 52 kV
	VDE 0670-811	Gasgefüllte Schotträume für Wechselstrom-Schaltgeräte und –Schaltanlagen mit Bemessungsspannungen > 1 kV bis einschließlich 52 kV

[22] VDE 0670-7 is withdrawn

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International standard	German standard	Title (English / German)
	VDE 0681	Geräte zum Betätigen, Prüfen und Abschranken unter Spannung stehender Teile mit Nennspannungen über 1 kV
	-1	- Allgemeine Festlegungen für DIN VDE 0681 Teil 2 bis Teil 4
	-2	- Schaltstangen
	-3	- Sicherungszangen
	-5	- Phasenvergleicher
	-8	- Isolierende Schutzplatten

H 5 New numbers of IEC standards for switching devices and switchgear

In the next few years the numbers of standards applicable to switching devices and switchgear will change; some have already done so. This will affect documentation (type plates, operating instructions, catalogs etc.). IEC will in future group all the standards of a committee under one number, making it easy to find the standards for a particular technical field.

Standards for switching devices and switchgear are drafted in the IEC technical committee TC 17 and will in future be given the group number IEC 62271. This means that all medium-voltage switching device and switchgear standards will begin with this number; this will be followed by a hyphen and the number of the relevant part (e.g. a product standard). For example, the circuit-breaker standard - formerly IEC 60056 – is now called IEC 62271-100.

IEC 62271 entitled "High-voltage switchgear and controlgear" will comprise a number of sub-groups, numbered:
- as of 001: generic specifications (IEC 60694)
- as of 100: switching device standards, responsibility lying with IEC subcommittee SC 17A
- as of 200: switchgear standards, responsibility lying with IEC subcommittee SC 17C
- as of 300: guidelines, drafted jointly by both subcommittees SC 17A and SC 17C.

The new numbering principle is already being worked on. It will not however be applied to existing standards until after a revision. This means that the changeover for all devices and switchgear will take until about 2010.

Note: Since the new number is not used until after a revision of the standard, it is possible that the content may have changed. Characteristics and tests according to an existing standard may not necessarily correspond with the new standard.

The following table shows old and new numbers listed opposite each other.

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IEC 62271 Part …	High-voltage switchgear and controlgear – *Original title*	Old IEC number
1	Common specifications	60694
100	High-voltage alternating current circuit-breakers	60056
101	Synthetic testing of high-voltage alternating current circuit-breakers	60427
102	Alternating current disconnectors and earthing switches	60129
103	Switches for rated voltages above 1 kV and less than 52 kV	60265-1
104	High-voltage switches for rated voltages of 52 kV and above	60265-2
105	High-voltage alternating current switch-fuse combinations	60420
106	High-voltage alternating current contactors and contactor-based motor-starters	60470
107	High-voltage alternating current switchgear-fuse combinations	New
108	Switchgear having combined functions	New
200	A.C.-metal enclosed switchgear and controlgear for rated voltages above 1 kV and up to and including 52 kV	60298
201	A.C.-insulation-enclosed switchgear and controlgear for rated voltages above 1 kV and up to and including 38 kV	60466
202	High-voltage/low-voltage prefabricated substations	61330
203	Gas-insulated metal-enclosed switchgear for rated voltages of 72,5 kV and above	60517; 61259
204	Rigid high-voltage gas-insulated transmission lines for rated voltages of 72,5 kV and above	61640
300	Guide for seismic qualification of high-voltage alternating current circuit-breakers	61166
301	High-voltage alternating current circuit-breakers - Inductive load switching	61233
302	High-voltage alternating current circuit-breakers - Guide for short-circuit and switching test procedures for metal-enclosed and dead tank circuit-breakers	61633
303	High-voltage switchgear and controlgear - Use and handling of sulphur hexafluoride (SF_6) in high-voltage switchgear and controlgear	61634
304	Additional requirements for enclosed switchgear and controlgear from 1 kV to 72,5 kV to be used in severe climatic conditions	60932
305	Cable connections for gas-insulated metal-enclosed switchgear for rated voltages of 72,5 kV and above- Fluid-filled and extruded insulation cables – Fluid-filled and dry type cable-terminations	60859
306	Direct connection between power transformers and gas-insulated metal-enclosed switchgear for rated voltages of 72,5 kV and above	61639
307	High-voltage switchgear and controlgear - The use of electronic and associated technologies in auxiliary equipment of switchgear and controlgear	62063
308	High-voltage alternating current circuit-breakers - Guide for asymmetrical short-circuit breaking test duty T100a	62215

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I APPENDIX

I 1 Abbreviations

AIS	Air-insulated switchgear
BG / BGFE	Professional association (precision and electrotechnical engineering) Berufsgenossenschaft (Feinmechanik und Elektrotechnik)
CENELEC	European Committee for Electrotechnical Standardisation (Comité Européen de Normalisation Electrotechnique)
CIGRÉ	International onference for High Voltage Installations (**C**onseil **I**nternational des **G**rands **R**éseaux **É**lectriques)
DIN	German Standards Institute (Deutsches Institut für Normung)
EN	European Standard (Europäische Norm)
GIS	Gas-insulated Switchgear
IEC	International Electrotechnical Commission
IP	International Protection (Schutzgrad)
ISO	International Organisation for Standardisation
KEMA	High Voltage and High Power Testing Laboratory for Electrical Equipment and Systems; Arnheim / Niederlande
PEHLA	Association for Testing of High Power Apparatus in Germany; member of the short-circuit testing liaison (STL) (**P**rüfung **e**lektrischer **H**och**l**eistungs**a**pparate)
VDE	Association of German Electrical Engineers Verband der Elektrotechnik, Elektronik und Informationstechnik
VDEW	German Electricity Association, trade association of the electricity supply industry; Vereinigung deutscher Elektrizitätswerke
VDN	Association of German (electricity) network operators Verband der Netzbetreiber
ZVEI	German electrical and electronic manufacturers' association Zentralverband Elektrotechnik und Elektronikindustrie

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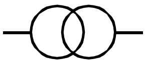
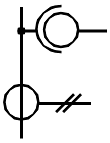
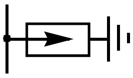
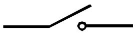
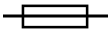
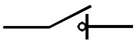
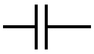
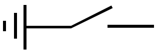
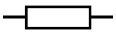
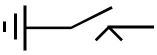
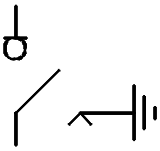
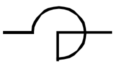
I 2 Graphical symbols

	Transformer		Voltage transformer, VT Current transformer, CT
	Circuit-breaker		
	Disconnector		Surge arrester
	Contactor		Spark gap
	Switch		Fuse
	Switch-disconnector		Capacitor
	Earthing switch		Resistor
	Make-proof earthing switch		Reactor
	Three-position switch-disconnector and make-proof earthing switch		Shunt reactor

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