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**SIEMENS**

# Configuration Guidelines for Medium-voltage Switching Devices

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## Configuration Guidelines for Medium-voltage Switching Devices




Configuration Manual

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## Legal information

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indicates that minor personal injury can result if proper precautions are not taken.
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# Introduction

## Content of the Configuration Guidelines

The Configuration Guidelines describe the selection criteria of switching devices, fuses and surge arresters. They give instructions for configuring and dimensioning the primary rated values. Uses for switching applications in normal and interrupted operations are described.

Furthermore, the Configuration Guidelines offer an overview of potential additional measures, which are provided for a number of switching tasks in the medium-voltage grid (such as overvoltage protection) and whether special rules apply for dimensioning components.

In order to select the appropriate design and configure the switchgear, the Configuration Guidelines contrast the key requirements and influencing factors with the corresponding features and properties of the switching devices and describe the dimensioning rules and requirements for overvoltage protection.

## Target group of the Configuration Guidelines

The Configuration Guidelines are intended for:

- Switchgear operators
- Planning offices
- Installers of switchgear

Here, the Configuration Guidelines provide instructions on selecting suitable equipment for the corresponding application.

The designs are based on IEC, with primarily the 62271 series of standards being used. In principle, the designs can be transferred to other ranges of standards such as IEEE C37, GB, DL, GOST. However, ratings are sometimes different there, which needs to be considered for the application.

## Applicable documents

You will find further information on the products described in the respective product catalogs.





## Safety notes

These Configuration Guidelines only provide instructions for configuring and dimensioning switching devices, fuses and surge arresters for the described applications.

For the design and installation in special applications, the appropriate operating instructions, safety regulations and product standards are to be observed.

### Working on live parts

In order to implement the described applications, work is required which sometimes needs to be executed with hazardous voltages present. For this reason, the work must only be carried out by qualified personnel who are familiar with and follow the safety regulations and precautions.

Wear the prescribed protective clothing. Observe the general equipment regulations and safety regulations for working on high-voltage installations (for example, DIN VDE, NFPA 70E as well as national and international regulations).

Prior to commencing work on live parts, a de-energized state must be established. As such, the Five Safety Rules must be observed:

- Isolate
- Secure against reclosing
- Verify safe isolation from supply
- Earth and short-circuit
- Cover adjacent live parts

### Standards and certifications

The products and systems listed in these Configuration Guidelines are manufactured and distributed using a certified management system (according to ISO 9001, ISO 14001 and ISO 45001).

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## Terms, features and definitions

### Switching devices

Switching devices are used in circuits for the following switching functions:

- Connecting parts from circuits as well as conducting voltage and current
- Breaking (switch-off) and isolation (ensure isolating break) of circuits

#### Stress

- De-energized switching on and switching off
- Switching of operational currents
- Switching of short-circuit currents
- Conducting the current (operational or fault current)
- Establishing a defined isolating distance

#### Requirements

- In a closed state, the switching device should pose as little resistance as possible to the flow of operational and short-circuit currents. This feature must also remain in place during fault currents and the associated mechanical shear stress.
- In an open state, the open contact gap must be able to reliably withstand or isolate the voltages that occur there.
- All live parts must be sufficiently isolated against earth and between the phases when the switching device is open or closed.
- The switching device should be able to close the circuit with applied voltage. Depending on the operating condition, the following states may occur:
  - No current or only a very low current flowing (no-load line or charging current of the line or cable)
  - Flow of an operational current
  - Presence of a short-circuit current
- The switching device should be able to open the circuit with flowing current. This requirement does not extend to disconnectors.
- The switching device should induce switching overvoltages which are as low as possible.

### Device types and their tasks

#### Circuit-breakers

Circuit-breakers are able to activate and deactivate currents both in interrupted and uninterrupted operation. The range extends from small inductive and capacitive load currents

to short-circuit currents. Circuit-breakers work under all fault conditions on the grid, such as earth fault and phase opposition.

Outdoor circuit-breakers have the same fields of applications but are designed in such a way that they withstand weather conditions. They are mounted on the ground, on poles or directly on overhead lines.

### **Reclosers**

The recloser is a special device for application in overhead lines. Its breaking capacity corresponds to that of a circuit-breaker, but also features a transformer and a control unit.

Reclosers can be switched off and on again several times in the event of an error, meaning that operation can be resumed in the event of a temporary error. This means that extended grid interruptions and downtimes can be avoided.

### **Load switches**

Load switches must be able to switch operational currents on and off up to their rated operational current and switch on with existing short-circuits (up to their rated short-circuit making current). They also have a limited short-circuit breaking capacity, depending on the quenching principle and manufacturer.

### **Disconnectors**

Disconnectors are used for de-energized switch-off and switch-on. Their role is to "isolate" downstream equipment to enable work on these.

### **Switch-disconnectors**

A switch-disconnector is to be understood as the combination of a load switch and a disconnector, or a load switch with isolating distance.

### **Contactors and combinations of contactors and fuses**

Contactors are load-breaking devices with a limited making and breaking capacity. They are used for high switching rates. If a contactor is combined with a fuse, the fuse restricts and breaks the short-circuit current.

### **Earthing switches**

Earthing switches earth de-energized circuits.

### **Make-proof earthing switches**

Make-proof earthing switches earth circuits in a safe manner, even with voltage present, i.e., in the case that the circuit to be earthed was accidentally not isolated.

### **Fuses**

Fuses protect devices and systems once by disconnecting short-circuit currents, which the actual switching devices can no longer process themselves. Fuses consist of the fuse base and the fuse link. With the fuse base, in the case of de-energized removal of the fuse link (such as for the disconnector), an isolating distance can be established.

## Overvoltage protection

Surge arresters protect the insulation of the equipment (such as transformers, circuit-breakers and bushes) in electrical power systems against overvoltages. These overvoltages may be caused by nearby lightning strikes, electromagnetic impulses, electrostatic discharges and switching operations in the grid and have a very high level of energy.

The current is discharged by the arrester (generally to earth). Effective overvoltage protection calls for the use of different arrester types, tailored to the specific application and situation.

## 3.1 Rated values

### Rated insulation level or withstand voltage

The rated insulation level is the dielectric strength from phase to earth, between phases and across the open contact gap, or across the isolating distance. The dielectric strength is the capability of an electrical component to withstand overvoltages. These can be operating voltages or higher-frequency voltages caused by switching operations or earth faults (internal overvoltages), as well as lightning strikes (external overvoltages).

The dielectric strength is defined by the rated lightning impulse withstand voltage and the rated short-duration power-frequency withstand voltage. Both values are verified by type tests; a power-frequency withstand voltage test is also an integral part of the routine test.

The dielectric strength is demonstrated using standardized rated lightning impulse voltages (standard shock wave 1.2/50  $\mu$ s) for external overvoltages and rated alternating voltages (50 or 60 Hz for 1 min) for internal overvoltages or to ensure the dielectric strength throughout the entire service life.

### Rated voltage

The rated voltage is the upper limit of the operating voltage the device is designed for. It must be equal to or greater than the maximum appearing operating voltage under consideration of the permissible voltage fluctuations. The ratio between the rated voltage and the necessary withstand voltage values is defined in the product standards (such as IEC 62271-100).

The maximum operating voltage is the most important dimensioning criterion. It defines the electrical stress of the switching device when switching off through transient voltage recovery and recovery voltage.

### Rated operational current

This is the current the device can continuously carry under defined ambient conditions. The dimensioning criterion is the maximum permissible temperature rise, which must not exceed the defined temperatures. If a device is mounted in a switchgear, the maximum permissible operational current is determined by the temperature-rise limits when the device is operated in this switchgear.

### 3.1 Rated values

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#### Note

If a device is installed in an enclosure (switchgear), it may possibly not be loaded with its full rated current, depending on the quality of the thermal heat dissipation. The maximum permissible operating current in the enclosure (switchgear) is to be verified by means of testing.

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#### Rated short-circuit making current

The rated short-circuit making current is the peak value of the making current in case of short circuit on the load side of the switching device. Its value corresponds to the rated peak withstand current, but it represents a greater stress for the switching device, as dynamic forces work against the closing movement.

#### Rated peak withstand current

The peak withstand current arises in case of short circuit, and it is the peak value of the first half-wave of the short-circuit current after the beginning of the current flow. It is a measure for the electrodynamic (mechanical) load of an electrical component. This value is highly dependent on the time when the short circuit occurs and on the connected equipment, and it can vary with each switching operation.

The rated peak withstand current is the maximum value the device can carry in closed state. The peak withstand current is tested in accordance with the standard, which specifies a fixed ratio between the rated short-circuit breaking current and the rated peak withstand current.

A peak withstand current is not specified for switching devices with short-circuit making capacity. If a switching device is to be used for conducting a peak withstand current, the value of the corresponding rated short-circuit making current is to be used.

#### Rated breaking current

The rated breaking current defines the breaking capacity of load (operational) currents. For Siemens vacuum switching devices, this value corresponds to the operational current, and is therefore not indicated separately.

#### Rated short-circuit breaking current

The short-circuit breaking current is the maximum possible rms value of a short-circuit current, which a switching device can safely switch off. It is indicated as a symmetrical current, and corresponds to the short-circuit current after decay of a superimposed DC component.

## 3.2 Device selection according to rated values

Switching devices and all other equipment must be designed for the power system data available at the respective location of use. This power system data defines the rated values of the switching devices.

### Selection of switching devices

Device designation	Dielectric strength	Rated voltage	Rated operational current	Rated peak withstand current	Switching capacity			
					Rated breaking current	Rated short-circuit breaking current	Capacitive loads	Rated short-circuit making current
<b>Switching devices</b>								
Circuit-breakers	•	•	•	–	–	•	•	•
Reclosers	•	•	•	–	–	•	•	•
Load switches	•	•	•	–	•	–	–	•
Disconnectors	•	•	•	–	•	–	–	•
Earthing switches	•	•	–	•	–	–	–	–
Make-proof earthing switches	•	•	–	–	–	–	–	•
Contactors	•	•	•	–	•	• <sup>1)</sup>	•	• <sup>1)</sup>
Fuse	–	•	•	–	–	•	–	–
Fuse switch	•	–	•	–	–	–	–	–
<b>Non-switching devices</b>								
Short-circuit current limiting coil	•	–	•	•	–	–	–	–
Bushing	•	–	–	• <sup>2)</sup>	–	–	–	–
Post insulator	•	–	–	• <sup>2)</sup>	–	–	–	–

● Selection criterion

1) Limited short-circuit making or breaking capacity

2) Observe the minimum breaking strength for bushings and post insulators

### Selection of surge arresters

Device designation	Rated voltage $U_r$	Continuous voltage $U_c$	Rated arrester peak withstand current $I_n$	Protection level / residual voltages *)	Load discharge capacity $Q_{rs}$	Thermal rated energy absorption capacity $W_{th}$	Rated short-circuit current $I_s$	Creepage distance
Surge arrester	•	•	•	•	•	•	•	•

\*) For rated lightning impulse withstand voltage based on 8/20  $\mu$ s with a rated leakage current of 5 or 10 kA, for example. In the case of switching overvoltage based on the residual voltage of a 30 / 60  $\mu$ s wave with a leakage current of 0.5, 1 or 2 kA.

### 3.3 Other terms

A range of further terms are defined in the standards, which are used for project specifications and invitations to tender. In addition to the definitions in the individual product standards, such as IEC 62271-1, terms can be looked up in the IEC dictionary (<http://www.electropedia.org/>).



# Selection of switching devices based on switching duties

# 4

## 4.1 Switching applications with uninterrupted operation

The following table provides an overview of which switching applications may occur in normal operation and in the case of faults. These define the need to use certain switching devices, which are shown with a comparison of the switching duties.

## Selection of switching devices based on switching duties

### 4.1 Switching applications with uninterrupted operation

Occurring load				Components						
Switching application	① Current	② Special feature	③ Comment	Circuit-breakers	Contactors	Switch-disconnectors	Recloser	Fuse savers	(Make-proof) earthing switches	
<b>Switching duties in inductive circuits</b>										
Distribution transformers	unloaded	$\leq 0,03 I_r$	–	Also applies for zero point generator	■	■	■	■	–	–
	loaded	$\leq 1,2 I_r$	–	Generally no protective circuit necessary	■	■	■	■	–	–
Furnace transformers		$\leq 2 I_r$	High switching frequency	Surge protection circuit to be configured on a customized basis	■	–	–	–	–	–
Earth-fault reactors		$\leq 300 \text{ A}$	–	Surge arresters are common practice	■	–	■	■	–	–
Short-circuit current limiting coils		$\leq 2000 \text{ A}$	Transient recovery voltage with rate of rise $\leq 6 \text{ kV} / \mu\text{s}$	Surge protection circuit to be configured on a customized basis	■	–	–	–	–	–
Charging current reactors		$\leq 2000 \text{ A}$	Transient recovery voltage with rate of rise $\leq 6 \text{ kV} / \mu\text{s}$	Surge protection circuit to be configured on a customized basis	■	–	–	–	–	–
Motors	in operation	$\leq I_r$	–	–	■	■	–	–	–	–
	during start	$\leq 7 I_r$	Opening to $7 I_r$ at $\cos \varphi \leq 0,3$	For motors with $I_{an} \leq 600 \text{ A}$ 3EF surge limiters are suitable as a protective circuit. Individually compensated motors do not need protective circuit.	■	■	–	–	–	–
Generators in power plants		$\leq I_r$	Surge arrester not required	Surge protection against surge voltages from the grid is common practice	■	–	–	–	–	–
Converter transformers		$\leq I_r$	–	Overvoltage protection is common practice	■	–	–	–	–	–
Low inductive currents		$20 \text{ A} < I_r < 600 \text{ A}$	Virtual current chopping by multiple restrikes	Surge protection circuit common practice, to be configured on customized, if necessary	■	■	–	■	–	–
<b>Switching duties in capacitive circuits</b>										
Capacitor banks		$\leq 1,4 I_r$	High recovery voltage	–	■	■	■	■	■	–
Filter circuits		$\leq 1000 \text{ A}$	High recovery voltage	–	■	–	–	–	–	–
Parallel connection of capacitor banks		$\leq 20 \text{ kA}$ @ 4250 Hz	High amplitude and high rate of rise of the making current due to high frequency transient recovery voltage	> 10 kA: Inductors required, up to 10 kA: Inductors recommended	■	–	–	–	–	–
Unloaded cables		$\leq 100 \text{ A}$	High recovery voltage	–	■	–	■	■	–	–
Unloaded overhead lines		$\leq 10 \text{ A}$	High recovery voltage	–	■	–	■	■	■	–
Phase-controlled switch-on		$\leq I_r$	POW switching	Single-phase switching devices and corresponding control unit required	–	–	–	■	–	–
<b>Switching duties for other cases of operation</b>										
Disconnecting	–	–	–	Isolating distance, disconnection from power supply systems	–	–	*	–	–	–
Multiple reclosing	–	–	–	–	–	–	–	■	■	–

\* Disconnectors

- ① Currents which must be switched on or off in the worst case for:
    - **Unloaded transformers:** This does not include transformers with special loads, such as motors, generators, converters and arc furnaces.
    - **Earth-fault reactors:** In the event of an earth fault, if the switching device is switched off, the full phase-to-phase operating voltage can occur at the open contact gap.
    - **Short-circuit current limiting coils:** Due to the high TRV frequency of short-circuit current limiting coils, high rates of rise are to be expected for the transient recovery voltage.
    - **Motors:** In the case of frequently switched motors, it is more economical to use contactors instead of circuit-breakers or load switches.
    - **Generators:** Generators generally behave in a similar way to an inductance, regardless of whether they are in underexcited or overexcited operation.
    - **Filter circuits:** Capacitors with current limiting reactors also represent filter circuits.
  - ② This column defines the respective particularities. If nothing is indicated, this switching application represents no problem for the switching devices to be used, and needs not be especially considered for the selection.
  - ③ This column gives general information about the measures to be observed for the application.
    - Use of switching device makes sense
    - Use of switching device does not make sense
- $I_{an}$  Motor starting current  
 $I_r$  Rated operational current

## 4.2 Switching applications with interrupted operation

Occurring load Switching application				Comonents								
				① Current	② Special feature**	③ Comment	Circuit-breakers	Contactors	Switch-disconnectors	Reclosers	Fuse savers	(Make-proof) earthing switches
<b>Switching duties during short circuits</b>												
Making on a short-circuit				$I_{ma}$	High and inductive currents	Typical case, breaking capacity verified by type tests	■	○	■	■	■	■
Opening	Terminal short circuit	$I_{sc}$	–		■	–	–	■	■	–		
	Distance short circuit	$I_{sc}$	Higher $du / dt$ than with Terminal short circuit	Not a problem for vacuum circuit-breaker	■	–	–	■	■	–		
	Generator-supplied short circuit	$I_{sc}$	Transient recovery voltage with rate of rise $\leq 2 \text{ kV} / \mu\text{s}$ , high direct current component, possibly missing zero crossings	Surge voltage protection for generators with $I''_k \leq 600 \text{ A}$	■	–	–	–	–	–		
	Brief interruption	$I_{sc}$	–	–	■	–	–	■	■	–		
	Transformer-supplied short circuit	$I_{sc}$	Transient recovery voltage with rate of rise $\leq 6 \text{ kV} / \mu\text{s}^*$	–	■	–	–	■	–	–		
	Short circuit current limiting coil	$I_{sc}$	Transient recovery voltage with rate of rise $\leq 10 \text{ kV} / \mu\text{s}$	–	■	–	–	–	–	–		
	Double earth fault	$0,87 I_{sc}$	–	–	■	–	–	■	■	–		
	Blocking motors	$\leq 5 \dots 7 I_r$	Switching off $5 \dots 7 I_r$ for $\cos \varphi < 0.2$	For motors with $I_{an} \leq 600 \text{ A}$ , 3EF surge limiters are suitable as a protective circuit. Individually compensated motors do not need protective circuit.	■	–	–	–	–	–		
	Phase opposition	$0,25 I_{sc}$	–	–	■	–	–	■	–	–		
<b>Switching duties under earth fault conditions (predominantly capacitive currents)</b>												
Unloaded cable / overhead lines Error on supply side				$\leq 5 \text{ A}$	High recovery voltage	–	■	■	–	■	■	–
Loades cable / overhead lines	Error on supply side	$\leq I_r$	High recovery voltage	–	■	■	–	■	■	–		
	Error on load side	$\leq I_r$	–	As a general rule, surge protection is not required, however there are individual cases, in which surge voltages have occurred due to the complex grid structure.	■	■	–	■	■	–		
<b>Switching duties for other applications</b>												
Protective isolation circuit (disconnection under load)				$\leq I_r$	–	–	–	–	■	–	–	–
Rapid load transfer				$\leq I_r$	Switchover in $< 100 \text{ ms}$	–	■	–	–	■	–	–

$I_{sc}$  generally describes a short-circuit current and, depending on the observed process, may include different values. This affects, for example, the opening and closing operation in the event of a short circuit  $I_k$  (as the first occurring component and therefore relevant when the

short circuit occurs for the first mechanical stress),  $I_k'$  as soon as  $I_k''$  has subsided (and is therefore frequently relevant at the time of closing following the mechanical residual time of the circuit-breaker) or  $I_k'$  as a permanent value.

- ① This column defines currents which must be switched on or off in the worst case.  
In the case of a transformer-supplied short circuit: this applies to all transformers regardless of the load.
- ② This column defines the respective particularities. If nothing is indicated, this switching application represents no problem for the switching devices to be used, and needs not be especially considered for the selection.
- ③ This column gives general information about the measures to be observed for the application.
- Application possible, but not intended
- Use of switching device makes sense
- Use of switching device does not make sense
- $I_{an}$  Motor starting current
- $I_k''$  Initial balanced short-circuit current
- $I_{ma}$  Rated short-circuit making current
- $I_r$  Rated operational current
- $I_{sc}$  Rated short-circuit breaking current
- \* Typically up to 6 kV/ $\mu$ s, in individual cases also above
- \*\* Typical values for cable connections. In the case of a direct connecting bar, the values may also be higher, which does not pose a problem for vacuum circuit-breakers.



# Switching applications with uninterrupted operation

# 5

## 5.1 Switching duties in inductive circuits

### 5.1.1 Explanations on switching duties in inductive circuits

#### 5.1.1.1 Current chopping

If when switching off very low inductive currents, the current is chopped prior to the natural zero crossing (in the figure chopping current  $i_a$ ), on the switched off side (transformer) magnetic energy is retained in the iron of the transformer corresponding to the chopping current. This magnetic energy causes an increase in voltage over the contacts. In extreme cases, this overvoltage may cause restrikes. The chopping current is however very low on vacuum circuit-breakers and the occurring overvoltage is safely controlled. It is compensated by means of the capacitances of the switched off side (stray and cable capacitance).

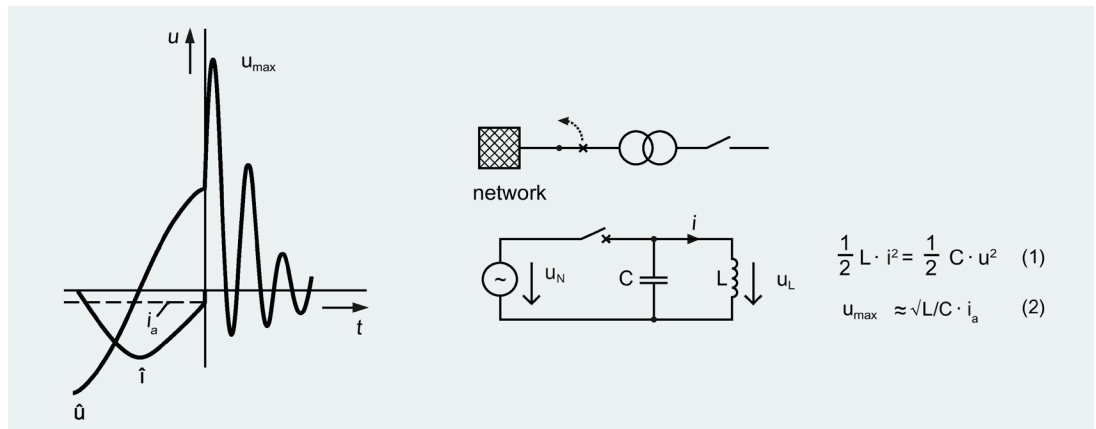
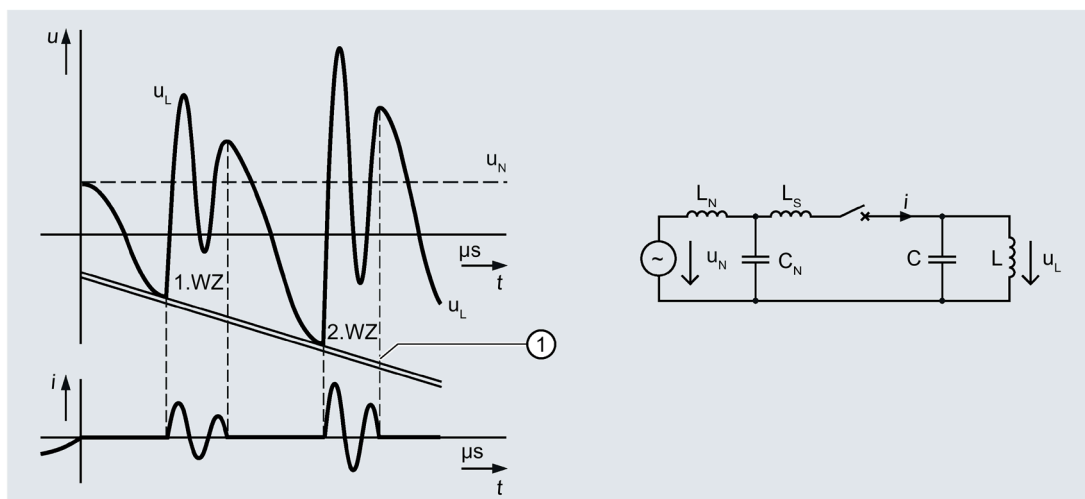


Figure 5-1 Current chopping during inductive switching

#### 5.1.1.2 Multiple restrikes

When switching low inductive currents, higher overvoltages may occur if the switch is restrieked after the first breaking of the current and it is then able to interrupt the high frequency compensating current (see next figure). This causes another overvoltage and possibly another restrike.

If this process is repeated several times, with each one causing a restrike which leads to a transient phenomenon between the line-side and load-side capacitances, one regards this as multiple restrikes.



① Increasing dielectric strength of the opening contacts

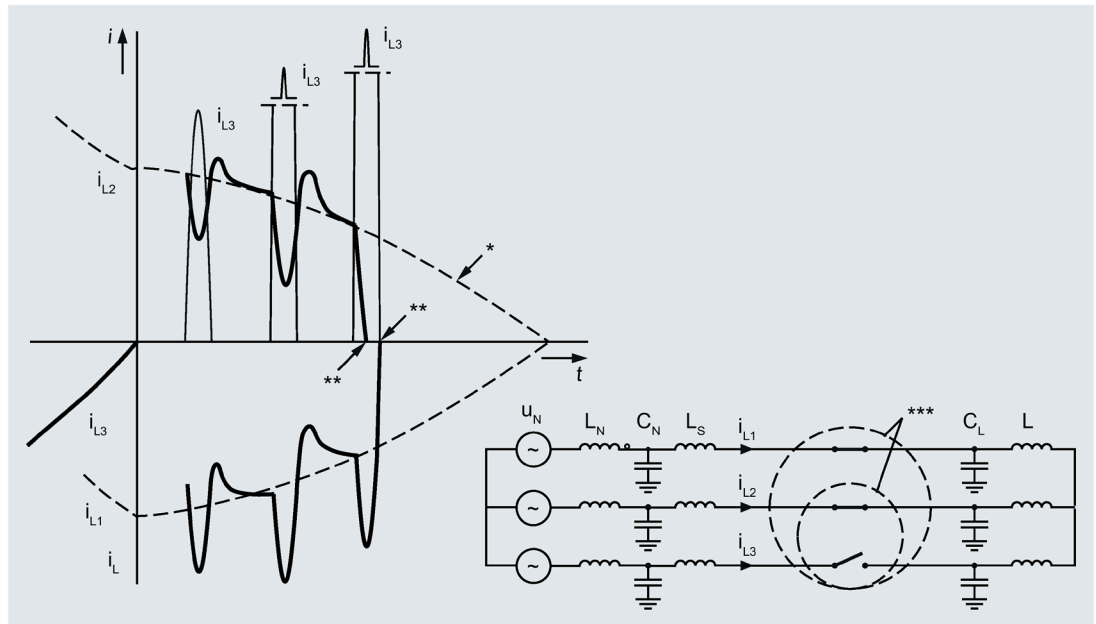
Figure 5-2 Restrikes during inductive switching

The voltage amplitude increases with each of these restrikes, in such a way that it may result in increasing overvoltages and therefore high frequency compensating currents. Please note here the section titled Virtual current chopping (Page 23).



### 5.1.1.3 Virtual current chopping

Virtual current chopping is a consequence of multiple restrikes in the contact gap of the first-pole-to-clear. It is dependent on the characteristics of the circuit to be switched, in particular, on the couplings between the phases.



- \* Currents  $i_L$  at line frequency  $f_N$
- \*\* High frequency between the individual phases (inductive) zero current transitions in the last poles L1 and L2 to be cleared by the coupling
- \*\*\* Couplings

Figure 5-3 Virtual current chopping: Coupled currents in the L1 and L2 phases for multiple restrikes in phase L3

With increasing voltage amplitude, the associated high-frequency compensating current also increases from one restrike to the next. If this compensating current (in the figure: phase current  $i_{L3}$ ) is inductively (capacitively) coupled in both other phases, into which the power-frequency current still flows at this time, high-frequency zero transitions may also occur there (with phase currents  $i_{L1}$  and  $i_{L2}$ ). If the switching device breaks in one of these zero transitions, this is regarded as virtual (=indicated or forced) current chopping. The high-frequency compensating current only flows in the area of the switchgear while the power-frequency current is still flowing in the load. The above described interruption of the current in a high-frequency zero point therefore causes actual current chopping at this point for the power-frequency current.

As this virtual current chopping can occur at relatively high instantaneous values of the power-frequency current, correspondingly high overvoltages are possible, which need to be limited by surge arresters.

## 5.1.2 Switching of distribution transformers

### Application

Distribution transformers in power supply company and industrial grids.

A distinction is made from block transformers, which are connected directly to special loads – such as motors, generators, converters and arc furnaces. For more information, see the section titled Switching of block transformers (Page 25).

### Load

	Unloaded transformer	Loaded or unloaded transformer
Current	Magnetizing current, 0.5 to 3% of the rated operational current	Up to 120% of the rated operational current
cos $\varphi$	< 0.3 inductive	0.7 to 1.0 inductive
Additional measures	<ul style="list-style-type: none"> <li>• Generally no protection circuit is required</li> <li>• With cast resin transformers and so-called dry-type transformers, due to the higher risk of premature damage to the insulation, it may be necessary to protect such transformers with RC circuits <sup>1)</sup>.</li> </ul>	

<sup>1)</sup> RC circuits are offered by a number of manufacturers as an assembly (e.g. ZORC). These can be used but do need to be checked on a case by case basis in terms of their dimensioning.

The switching of inductive 'load currents' can be critical if the short-circuit current of one of the distribution transformers is lower than 600 A on the primary voltage side. It is generally assumed that unloading shutdown initially takes place on the low-voltage side or from the switches of the downstream low-voltage side switchgear. In the case of another operating procedure or a long line between the switch and low-voltage system, for example, surge arresters should also be used.

### Unloaded transformer

With unloaded transformers (no load connected), an excitation current flows. This is highly inductive with a cos  $\varphi$  < 0.3 and less than 3% of the rated operational current. Transformers tend not to be switched. However, in order to save energy costs, these transformers can be switched more often.

### Switching on a transformer

Switching on transformers may cause an inrush current, the so-called rush. Switch-off during this process, i.e., switching off currents in the rush is generally critical. When switching off a transformer in the rush, currents occur of up to 15-times the transformer rated current with cos  $\varphi$  = 0.15, which are also heavily superimposed with harmonics.

High overvoltages are to be expected for such operations if no appropriate protective measures have been taken. The standard method for preventing overload (damage) is to use modern protection devices with an in-rush suppression function. Otherwise, surge arresters (or limiters) must be used as a minimum, if such disconnection procedures cannot be prevented by adequate protection device settings.

### 5.1.3 Switching of block transformers

Block transformers generally only feed one individual special load. The switching duty is defined by the characteristics of the load.

#### 5.1.3.1 Switching of furnace transformers

##### Use cases

Furnace transformers are block transformers. The following loads can be connected for the case described here:

- Arc furnaces
- Reduction furnaces (also known as 'submerged arc furnace')
- Induction furnaces (these are connected as 2-phase loads often via converters, refer to section Switching of converter transformers (Page 26))

##### Load

	Arc furnace as load	Reduction or induction furnace as load
Current	0.01 to 2.0 · rated operational current of the transformer	0.01 to 2.0 · rated operational current of the transformer
cos φ	0.2 to 0.9 inductive	0.5 to 0.8 inductive
Features	<ul style="list-style-type: none"> <li>• Resonance excitations in transformer windings possible due to multiple re-strikes during switch-off</li> <li>• High overvoltages possible due to virtual current chopping at currents ≤ 600 A</li> </ul>	
Additional measures	RC circuit and surge arrester on the transformer and multiple surge arresters and possibly RC circuit also on the busbar (customized configuration required).	

##### Note

Overvoltage protection must be calculated on a project-specific basis. Liability is limited if Siemens only provides the switch and an overvoltage protection calculation is not performed.

Very high requirements are posed on furnace switches from an electrical and mechanical perspective and sometimes under unfavorable environmental conditions, such as increased thermal load or accumulation of conductive dust.

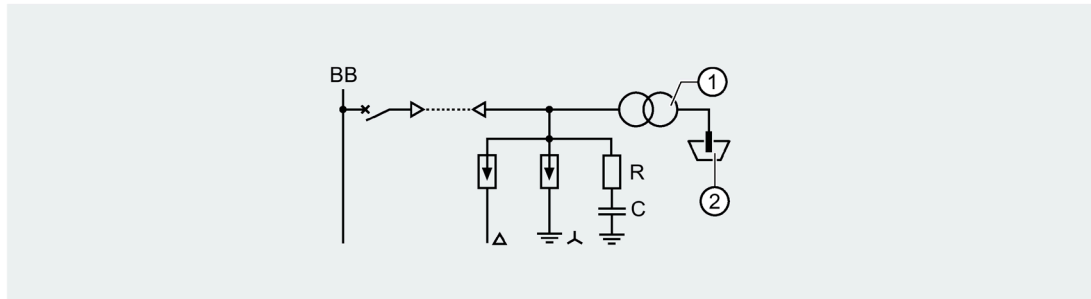
The currents to be switched are between virtually zero and two times the rated operational current of the furnace transformer. They may be asymmetrical and distorted. The switching frequency can be up to 100 switching cycles per day and in individual cases even higher.

Induction furnaces have a single-phase (crucible-earth) or 2-phase design, but are connected to the 3-phase system. This now tends to be implemented using converters. Otherwise, balancing is required by means of a Steinmetz circuit.

### Overvoltage protection circuit

Furnace switches generally need to be equipped with RC circuits and surge arresters. The RC circuits prevent internal overvoltages caused by resonance excitations in the transformer, by attenuating high-frequency compensating currents, which are produced during multiple restrikes. In the case of switched inductive currents  $\leq 600$  A, virtual current chopping may occur. This then causes overvoltages, which have to be limited by a surge arrester. Currents in this range then also occur, if the rated operational current of the transformer is  $> 600$  A, as depending on the operating mode, the operational current can be between the excitation current (idle state) and two times the rated operational current (electrode short circuit).

Depending on the neutral-point connection type, either only three arresters are required between the line and earth or also between the lines (6-arrester connection). Whether the busbar also needs a protection circuit depends on the grid conditions, predominantly on the capacitance to earth on the supply side of the furnace switch. The busbar is often still equipped with surge arresters.



- ① Furnace transformer
- ② Arc furnace

Figure 5-4 Overvoltage protection circuit on furnace transformer

The protection circuit must be custom tailored to the network conditions by means of a network calculation. This optimizes the protection for equipment and is also necessary for protecting the circuit itself. In doing so, the entire medium-voltage grid must be considered (as well as the entire grid side of the furnace switch). The circuit-breakers must also be appropriately selected in order to maintain the overvoltage level. The current values can be found in the catalog.

The arc furnace causes harmonics, which in turn drive harmonic currents through the RC circuits. The latter must be designed for the resulting thermal stress, which particularly applies to damping resistors.

For the switching of converter furnaces (medium-frequency furnaces), follow section Switching of converter transformers (Page 26).

#### 5.1.3.2 Switching of converter transformers

##### Use cases

- Controlled or uncontrolled rectifiers, for example, electrolyzer systems
- Controlled drives (converter motor)

- Voltage/frequency converter
- Static reactive power compensation (STATCOM)

## Load

	Unloaded converter transformer	Loaded converter transformer
Current	Magnetizing current, 0.5 to 3% of the rated operational current	Up to rated operational current
cos $\varphi$	0.1 to inductive	Inductive $\leftarrow \rightarrow$ capacitive
Features	Similar to distribution transformers (generally no protection circuit is required. Surge arresters are recommended, if it cannot be ruled out that switching is occasionally under load).	When switching off currents $\leq 600$ A, overvoltages may occur due to multiple restrikes and virtual current chopping.
Additional measures	Surge arrester <sup>1</sup>	Surge arrester <sup>1</sup>

<sup>1</sup> Is recommended if switching under load is possible or cannot be connected.

## Overvoltage protection circuit

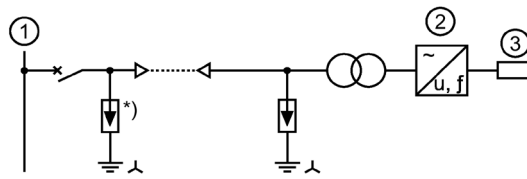
If converter transformers (previous designation: power converter transformers) are switched off in no load, a protection circuit is not required. This case of operation is also recommended as the general application, since the timing of the pulse inhibit for the converter can generally be coordinated so that it becomes active before the circuit-breaker is switched off.

If the transformer is switched off under load in the range  $\leq 600$  A, impermissible overvoltages may occur. Even if the operational current of the system  $> 600$  A, a protection circuit should be installed, since load-sensitive circuits should be possible in the critical area. Experience has shown that phase-to-phase insulation must also be protected for converter transformers, whereas otherwise the phase-to-earth insulation is more critical.

In systems with operating voltages  $\leq 15$  kV, the surge limiters in phase-to-earth circuits can also limit phase-to-phase overvoltages to permissible values, if the transformer is insulated according to the top lightning impulse voltage values.

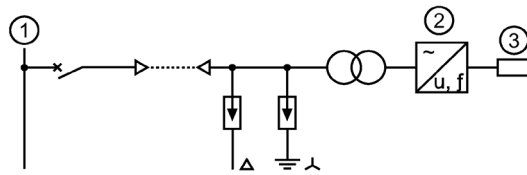
For higher operating voltages, the arresters are to be custom rated based on the line voltage, neutral-point connection type and insulation level.

Arresters are always to be installed on the transformer.



- \* ) Only an optional installation type for short cable run
- ① Busbar
- ② Converter
- ③ Load

Figure 5-5 Surge arrester in phase-to-earth star connection on the transformer for operating voltages  $\leq 15$  kV



- ① Busbar
- ② Converter
- ③ Load

Figure 5-6 Surge arrester in star connection on transformer or 6-arrester connection on transformer, design based on the neutral-point connection type, for operating voltages  $> 15$  kV

### 5.1.3.3 Switching of block transformers with motors

Similar view types apply for switching block transformers with motors as for switching motors. Please note here the section titled Switching of motors (Page 31)

## 5.1.4 Switching of earth-fault reactors

### Application

Coil between transformer neutral point and earth (earth fault-compensated networks)

### Description

If the neutral point of a transformer is earthed via a coil, we refer to an earth fault-compensated network. The coil is called an arc suppression coil.

In the case of an earth fault in the power system, a purely inductive current flows through the coil, which compensates the capacitive earth fault current at the fault location. If the earth-fault reactor is switched off during a ground fault, overvoltages may occur as a result of multiple restrikes. Surge arresters are installed for protection purposes.

## Load

	Without <b>earth fault in the network</b>	With <b>earth fault in the network</b>
Current	Approx. 1% of the rated operational current of the transformer	Typically up to approx. 60 A (exceptions possible up to 300 A)
cos $\varphi$	< 0.15 inductive	< 0.15 inductive
Features	–	Overvoltage due to multiple restrikes are possible
Additional measures	Surge arresters are common practice	

## Overvoltage protection circuit

As a general rule, no special overvoltage protection is required at the arc suppression coil. However, it may be advisable if the circuit-breaker in the case of an earth fault is switched off with a load below 600 A. The circuit is shown in the next figure and must be observed for the specific individual case.

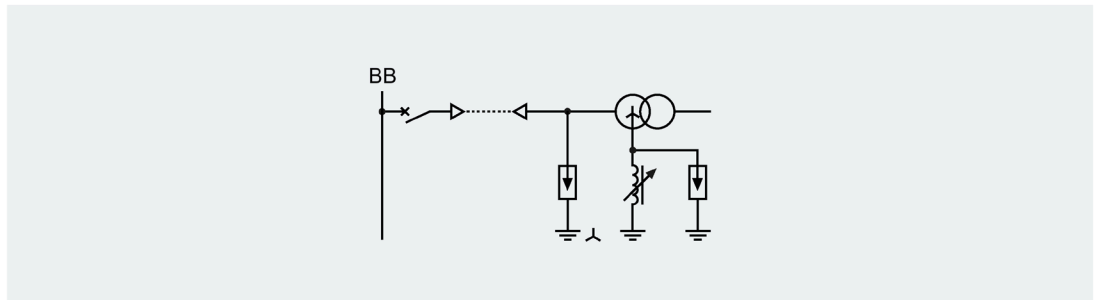


Figure 5-7 Overvoltage protection circuit on an earth-fault reactor

If the earth-fault reactor is directly switched, the surge arrester must be mounted on the primary side of the transformer or neutral point generator in the phase-to-earth star connection or in parallel to the arc suppression coil.

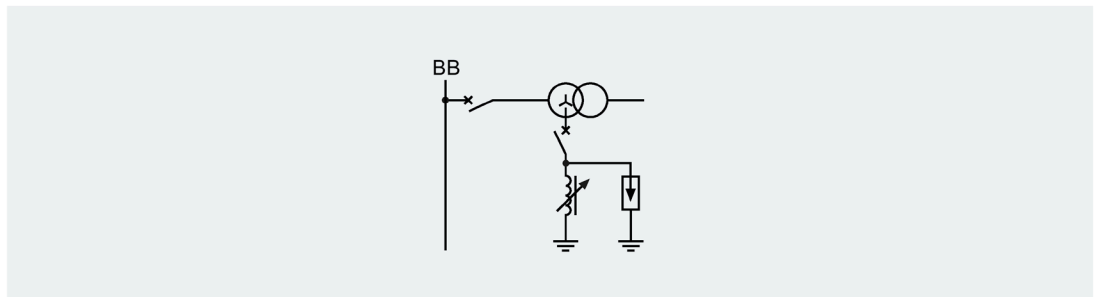


Figure 5-8 Surge arrester at the directly switched earth-fault reactor

### 5.1.5 Switching of charging current reactors

#### Application

Reactive-power compensation system, compensation of charging currents in power systems

#### Description

Charging current reactors (previous designation: 'shunt reactors') compensate the capacitive charging current of low-load and unloaded power systems. They are often connected to the tertiary winding of a transformer in order to compensate the capacitive charging power of high-voltage power systems at low load.

Charging current reactors are switched on a daily basis, therefore the circuit-breakers used reach a high number of operating cycles. Due to the high rate of rise and amplitude of the transient recovery voltage, this switching duty poses high stresses for conventional circuit-breakers. Nevertheless, special vacuum circuit-breakers are designed for such stresses.

#### Load

	<b>Compensation of the capacitive charging power of unloaded and low-load power systems</b>
Current	up to 2000 A
cos φ	0.15 inductive
Features	When switching off, multiple strikes may lead to resonance excitations in the winding, at currents < 600 A overvoltages may also occur due to virtual current chopping.
Additional measures	RC circuit is generally required. Additional surge arrester, if the coil current ≤ 600 A. The protection circuit must be custom tailored to the network conditions. For this, a network calculation is always required.

#### Overvoltage protection circuit

Short-circuit current limiting coils are always equipped with an RC circuit. When switching off, this prevents potential resonance excitation in the winding. At coil currents ≤ 600 A, arresters are used to protect against overvoltages caused by virtual current chopping.

Under certain power supply conditions, an additional circuit is required on the line side of the switch (busbar) with RC circuits and arresters.



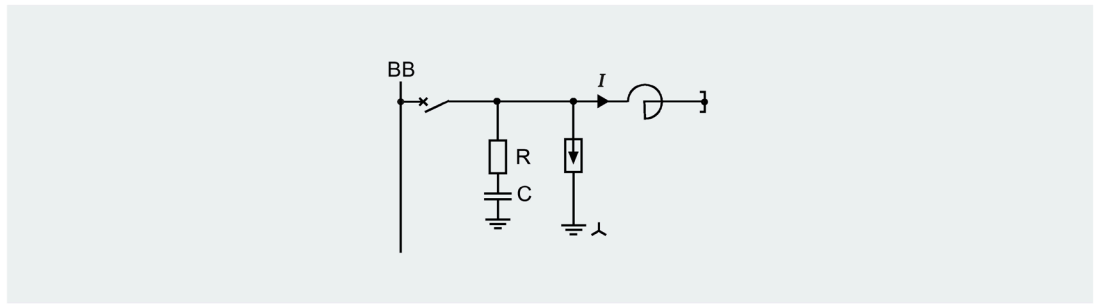


Figure 5-9 Overvoltage protection circuit on a short-circuit current limiting coil

I	Wiring
$\leq 600$ A	RC circuit and arresters (phase-to-earth arresters with earthed or compensated neutral point, additional phase-to-phase arrester required for isolated neutral point)
$> 600$ A	RC circuits

## 5.1.6 Switching of motors

### Use cases

- Asynchronous motors (squirrel-cage rotor and slip-ring rotor)
- Synchronous motors with asynchronous start-up
- Motor with block transformer
- Motor with transformer starter
- Motor with customized reactive power compensation
- Controlled drive (converter motor, you will find additional information in the section Switching of converter transformers (Page 26))

### Load

	Motor during start	Motor in normal operation (no-load operation to full load)
Current	Squirrel-cage rotor: $5$ to $7 \cdot I_{rMot}$ slip-ring rotor: $1$ to $2 \cdot I_{rMot}$	$0.1$ to $1.2 \cdot I_{rMot}$
$\cos \varphi$	$0.2$ to $0.3$ inductive	$0.8$ to $0.9$ inductive
Features	Switching off $I_{an} \leq 600$ A <sup>1)</sup> : Overvoltages possible as a result of multiple restrikes and virtual current chopping	Switching off in normal operation: Impermissible overvoltages do not occur
Additional measures	Overvoltage protection for motors with $I_{an} \leq 600$ A <sup>1) 2)</sup>	

1) In the case of motor-transformer combinations, the switching device current is decisive

2) Motors with individual reactive power compensation do not need a protection circuit.

## Overvoltage protection circuit

The overvoltage protection of motors is primarily aimed at protecting the insulation of motor windings. However the quality of the insulation tends to be lower in both older and inexpensive motors. With this in mind, greater demands need to be placed on the overvoltage protection circuit and a lower residual voltage level must be achieved. In the past, the overvoltage protection circuit was implemented with surge limiters from the 3EF series. Today, surge arresters of the 3EJ0 or 3EJ9 series are used with an accordingly reduced residual voltage level.

Surge arresters or surge limiters are used if the starting current to be switched is  $\leq 600$  A. In motor-transformer combinations, the current that flows through the switching device is decisive. The length of cable connections to the motor and other parameters have a negligible influence on the protection circuit. In the case of transformers, the protection (arrester) is always to be installed on the transformer.

**Exception:** Individual reactive power-compensated motors do not require a protection circuit, if the capacitors are permanently connected to the motor and do not include any reactors switched in series. The capacitor capacitance reduces the frequency of the transient recovery voltage for the first-pole-to-clear below the limiting value for multiple restrikes. As a result, overvoltages no longer occur. Alternatively, an individual power factor correction can thus also be applied with inductorless capacitors instead of surge limiters. You will find additional information in the section 'Motors with individual power factor correction'.

---

### Note

If several directly compensated motors are operated in parallel and each is switched with a switch, high inrush currents may occur due to the capacitors being positioned in parallel. Information on this (also referred to as back-to-back) case of operation can be found in section Switching of capacitors and filter circuits (Page 39).

---

### Note

Premature damage to the motors can be avoided if commissioning is performed in a careful manner and the correct protection settings are specified.

---

The following figures show the connection points for surge limiters in different layouts with motors:

#### Directly switched motors

For directly switched motors of the 12 kV level, surge arrester 3EJ9 012-0CC71-4B (previously surge limiter 3EF3 120-1) must be used in order to ensure the necessary protection level.

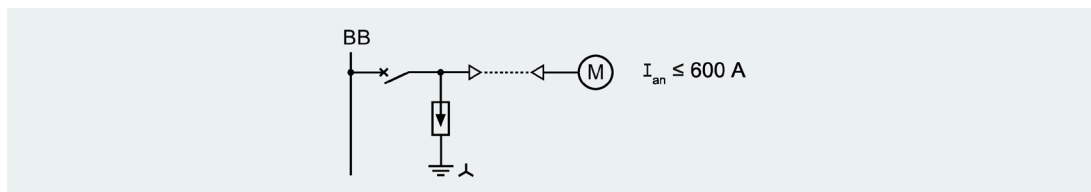


Figure 5-10 Surge arrester/limiter in phase-to-earth star connection on the circuit-breaker

### Motors with block transformer

For motors with block transformers and operating voltages  $\leq 15$  kV with the upper values of the rated insulation level according to IEC 60071, surge arresters are respectively switched between phase and earth (see next figure). Layout of the surge arresters directly at the switch should be avoided, as traveling wave processes lead to doubled overvoltage values at the transformer. Only with lower operating voltages and a sufficiently high dielectric strength of the equipment does the installation location become less critical.

#### Note

**Disconnecting motors frequently takes place within the scope of commissioning. In order not to provoke overvoltages or premature damage, disconnection during early start-up or so-called jog mode (fast ON-OFF switching) should be avoided.**

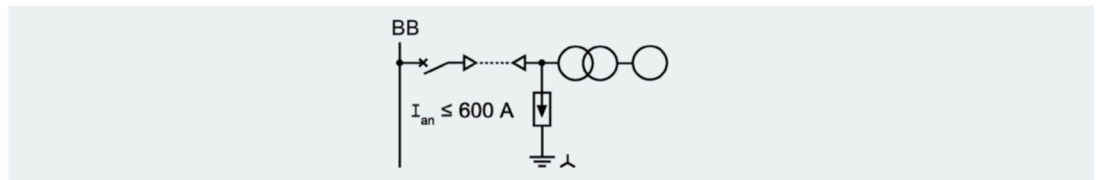


Figure 5-11 Surge arrester in phase-to-earth star connection on the transformer

At operating voltages  $> 15$  kV or a lower value of the rated insulation level according to IEC 60060, additional arresters are added (see next figure). This connection method is often used for older equipment or motors, whose insulation capacity is reduced by its design or aging. In such cases, a 6-arrester connection must be used.

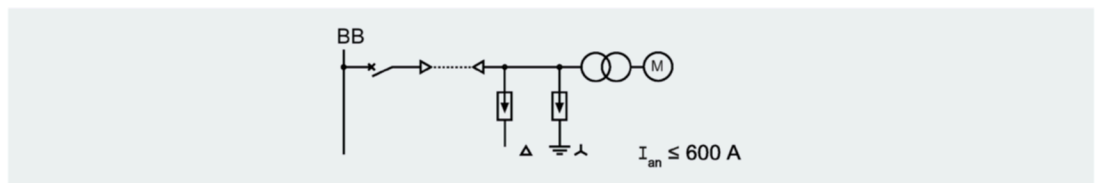


Figure 5-12 6-arrester connection at the transformer - with respectively phase-to-earth arrester and phase-to-phase arrester

### Motors with transformer starter

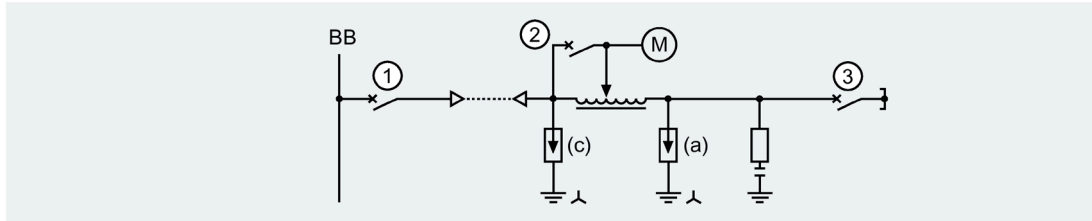
The insulation of transformer starters often does not correspond with the standardized rated insulation levels according to IEC 60060. Therefore only surge limiters or accordingly designed surge arresters of the 3EJ series should be used on the transformer, as shown in the following figure. They ensure the necessary low limiting voltages, which cannot be achieved by standard surge arresters.

All surge arresters, including those on the neutral point (a), are selected according to the rated voltage (or corresponding rated overvoltage values) of the transformer. An additional RC circuit generally needs to be implemented on the neutral point terminals. All circuit

5.1 Switching duties in inductive circuits

measures (arresters and RC circuit) should generally be installed at the transformer. Otherwise, problems may occur due to space restrictions or a smooth mode of operation cannot be ensured.

$I_{an}$	Connection of the surge arresters
$\leq 600$ A	Layout at the neutral point of the transformer (a) and layout at the transformer (c)
$> 600$ A	At the neutral point of the transformer (a)



- ① Circuit-breaker (main switch)
- ② Circuit-breaker (override switch)
- ③ Neutral-to-ground switch

Figure 5-13 Layout of surge arresters for transformer starters

See also

Switching of motors (Page 31)

**Motors with individual power factor correction**

A protection circuit is not required. Alternatively, an individual power factor correction can thus be applied with inductorless capacitors instead of surge limiters. Typically around 90% of the no-load input of the motor is to be compensated.

**Note**

This layout may lead to connecting the capacitors in parallel. Please note here the section titled Switching of capacitors and filter circuits (Page 39)

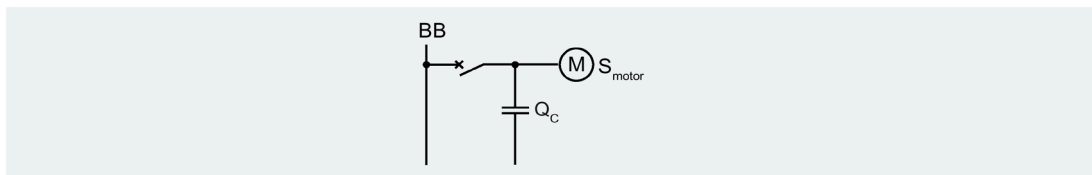


Figure 5-14 Motor with individual power factor correction (without overvoltage protection)

## 5.1.7 Switching of generators

### Use cases

- Directly switched generators
- Generator-transformer in unit connection

Direct switching of generators is generally identical to switching motors, whereby the normal switching application, in a similar way to motors, does not produce overvoltages. The short circuit in the grid or on the busbar, to which the generator is connected corresponds to the motor start.

### Load

	Generator idle and load operation
Current	Up to $1.2 \cdot I_{RG}$
$\cos \varphi$	0.8 to 1.0 inductive and capacitive possible (during excitation)
Features	Switching off in normal operation: No impermissible overvoltages
Additional measures	Overvoltage protection circuits are often available due to operational safety reasons, since various types of overvoltages can be transmitted from the grid.

### Overvoltage protection circuit

Surge arresters are implemented as shown in the following figure. As the basis, the 'transient short-circuit current' ( $I_k'$ ) is to be applied as the limiting value for the virtual current chopping. This is lower than  $I_k''$ , as the time constant for  $I_k''$  is very low (generally  $< 50$  ms), meaning that the current is in the transient range when switching off the switch (therefore at  $I_k'$ ).

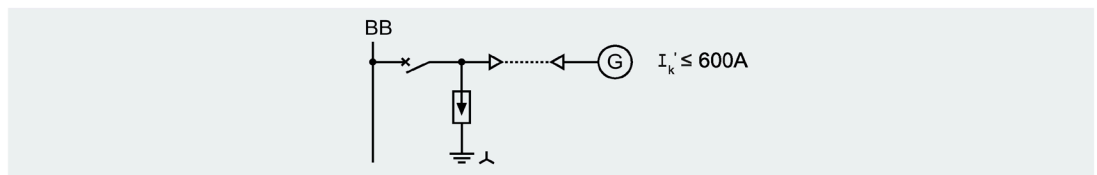


Figure 5-15 Surge limiters in phase-to-earth star connection on the circuit-breaker

Refer to the Switching applications with interrupted operation (Page 47) section for selecting the circuit-breaker.

## 5.2 Switching duties in capacitive circuits

### 5.2.1 Explanations on switching duties in capacitive circuits

#### 5.2.1.1 Single-pole opening of a capacitor

Vacuum circuit-breakers work as so-called zero-current interrupters, meaning that they switch off the current at zero point. When switching off at time  $t_1$ , the capacitor remains charged at the peak value of the driving voltage ( $u_c$ ). The system voltage ( $u_N$ ) changes sinusoidally, and reaches its opposite peak value after a half-wave. Initially, the recovery voltage (difference between  $u_c$  and  $u_N$ ) only rises slowly; the load in this case is not the rate of rise, but the absolute value of the voltage. In the case of a re-ignition within a quarter-wave following arc quenching, one refers to restriking. This kind of restriking is not dangerous.

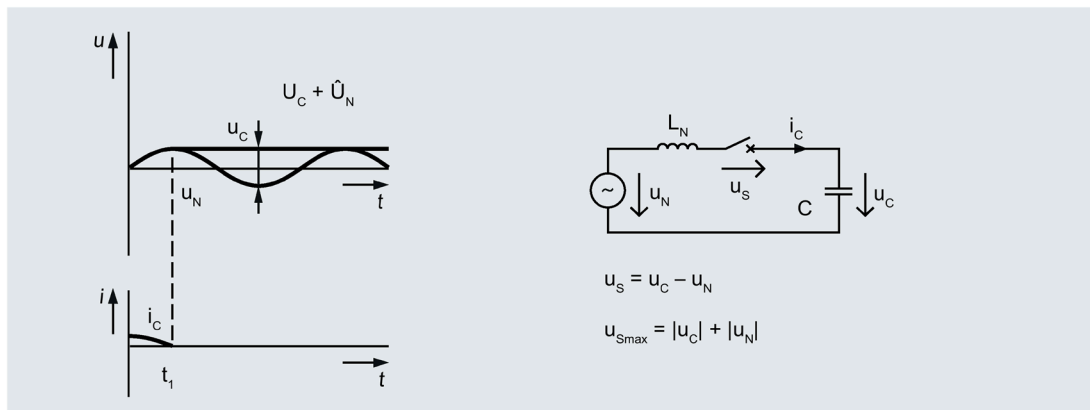


Figure 5-16 Switching off a capacitive current

If re-ignition takes place after a current-free pause of more than a quarter-wave, this is referred to as restrikes. These may cause high overvoltages. They are caused by the following: Such restrikes start a charge reversal of the energy remaining within the capacitor. This makes the voltage with opposite polarity move to a value corresponding to the capacitor voltage and instantaneous value of the system voltage (in the following figure, time  $t_2$ ). If multiple charge reversals occur (further restrikes), the arising switching overvoltages can be so high that this can overstress the insulation. This may lead to flashover at a system component with the lowest electrical strength. Just the contact gap (i.e., the switch itself), but also the housing of the switchgear may be affected. This can cause an internal arc in the switchgear.

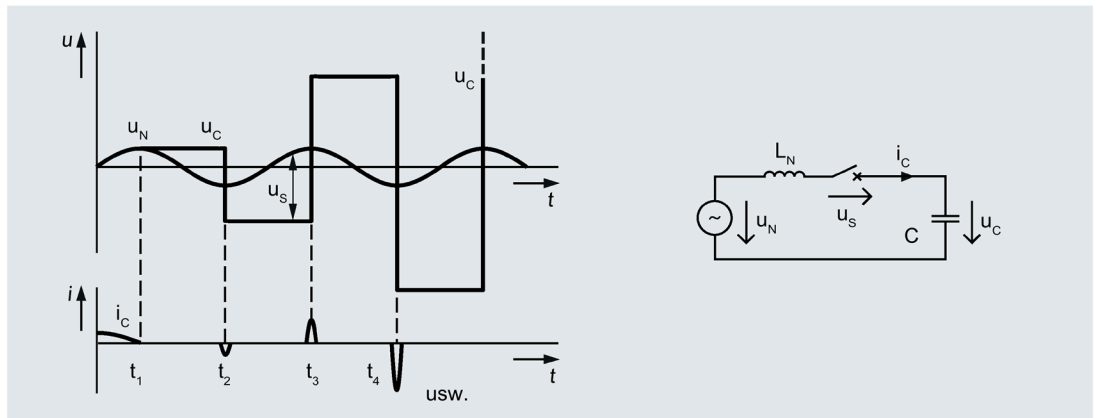


Figure 5-17 Restrikes when switching off a capacitive current

### 5.2.1.2 Three-pole switch-off of a capacitor bank

If system and capacitor neutral points are earthed, all currents are switched off at their natural zero crossings. The phase functions like a single-pole circuit. However if one of the neutral points is free or if both neutral points are not earthed, a neutral-point displacement occurs as the current in the first-pole-to-clear is interrupted. This increases the recovery voltage by 1.5 times the phase voltage in the first-pole-to-clear and occurs until the simultaneous disconnection of currents in the last-poles-to-clear has taken place, in the time  $t_1$  (current interruption in Phase L1) to  $t_2$ .

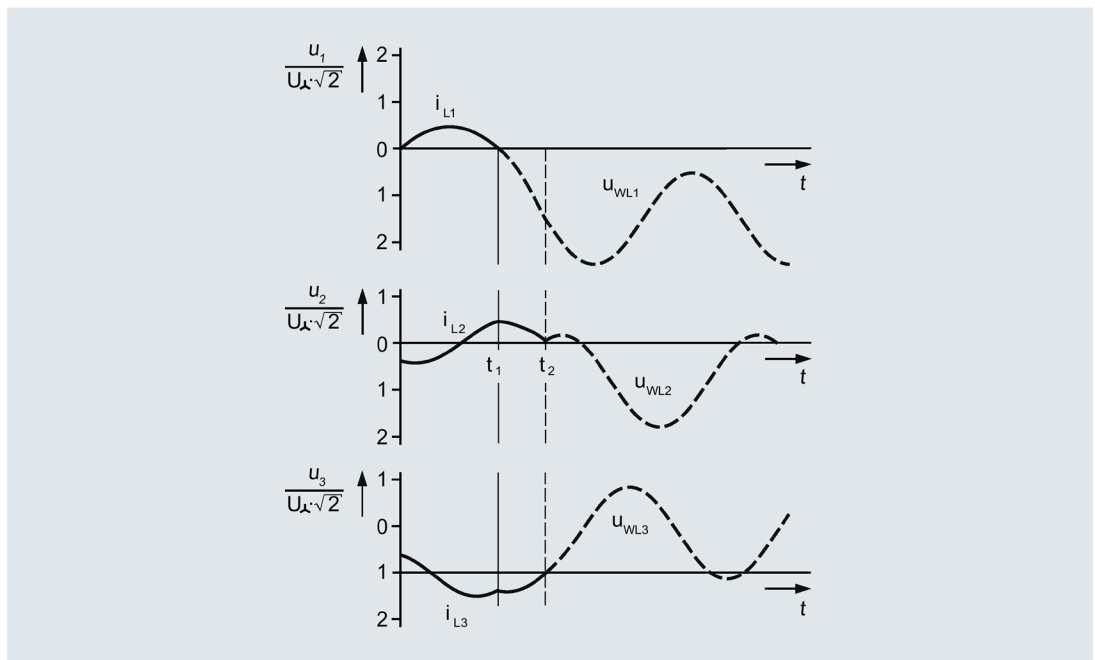


Figure 5-18 Idealized three-pole switch-off of capacitive circuits

The following maximum recovery voltages occur in the individual phases in the period following current interruption:

$$u_{WL1} = \sqrt{2} \cdot \left[ \frac{u}{\sqrt{3}} + \left( \frac{3}{2} \cdot \frac{u}{\sqrt{3}} \right) \right]$$

$$u_{WL2} = \sqrt{2} \cdot \left[ \frac{u}{\sqrt{3}} + \left( \frac{\sqrt{3}}{2} \cdot \frac{u}{\sqrt{3}} \right) \right]$$

$$u_{WL3} = \sqrt{2} \cdot \left[ \frac{u}{\sqrt{3}} + \left( \frac{\sqrt{3}}{2} \cdot \frac{u}{\sqrt{3}} \right) \right]$$

In order to safely switch capacitive currents, it is imperative that the switching devices are free from restrikes! With this in mind, class C2 switches are to be selected.

### 5.2.1.3 Switching on a capacitor bank

The permissible inrush current is based on the characteristics of the switch and the capacitor bank. For the capacitor bank, the peak value of the inrush current must generally (depending on the switch) not exceed 100-times the rated current of the capacitor, in order to limit the electrodynamic stress for the capacitor. The main limiting factor here is the system impedance. The 100 factor is a guide value, during a high switching frequency the inrush current should be limited to lower values.

Capacitor banks tend to be equipped with discharge resistors or transformers. If cycles with opening and re-closing of the capacitor bank can occur, the discharge time constant should be selected in such a way that the capacitor is fully ( $\leq 10\%$ ) discharged prior to being closed again. Otherwise too high inrush currents may occur, if the polarity of the line voltage is opposite the residual charge at the time of closing.

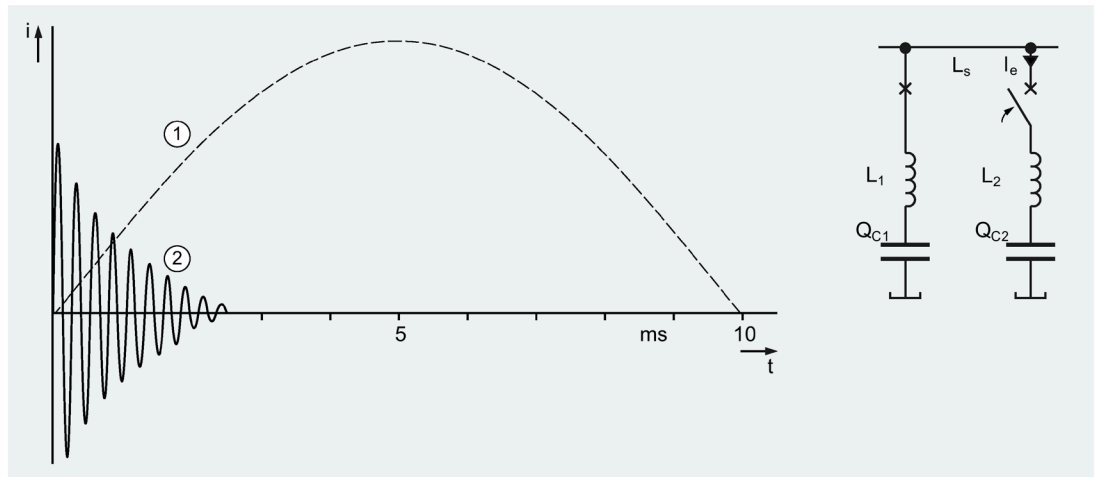
Due to harmonics, inductorless capacitor batteries should not be used in power systems, in order to prevent parallel resonances. Another benefit of the inductor is that the inrush current is limited.

### 5.2.1.4 Switching on parallel capacitor banks

This case describes the switch-on of a capacitor bank if one or more capacitor banks are already in operation (switched on) on the same busbar.

During contact approach, before galvanic touching of the contacts, pre-arcing occurs across the open contact gap, whereby the current begins to flow. Depending on the driving voltage, pre-arcing takes place in most cases 0.5 to 2 ms prior to galvanic touching of the contacts. At this point, a transient phenomenon occurs between the capacitors. Here, the capacitor that is already switched on discharges into the capacitor that is to be switched on. A resonant circuit is formed, due to the inductance between the two capacitors, caused by the supply lines and loop inductance of the switchgear. The inrush currents emerging here can be up to 10 kA and have frequencies of up to several kHz (see following figure).





- ① Current characteristic when closing onto a short circuit in 50 Hz network
- ② Compensating current when connecting a second or additional capacitor bank (simplified drawing, without gassing current from the power system)

Figure 5-19 Current characteristic when closing a parallel capacitor bank

Switching devices, which are used for parallel switching of capacitors (back-to-back), need to be accordingly tested for this purpose (for example, according to IEC 62271-100 with 20 kA at a frequency of 4250 Hz).

As a general rule, current limiting reactors should be used to reduce inrush currents and frequencies.

## 5.2.2 Switching of capacitors and filter circuits

### Use cases

Capacitor banks and filter circuits place similar requirements on the switch. Critical points are the inrush current and the voltage load.

- Capacitor banks for reactive power compensation
- Capacitors with current limiting reactors for reactive power compensation
- Filter circuits for filtering harmonics from the network. These are used for the reduction of harmonics, which mostly arise in cases when converters operate in the network.

When used as a capacitor bank for reactive power compensation, the aim is to achieve the total impedance in the power system to the greatest extent with resistance. In this way, voltage losses are compensated, in such a way that the operating voltage is kept within the tolerance range. Reactive-power compensation systems are therefore used in the following areas:

- As capacitor banks in transformer substations, in order to compensate the inductive character of a network section. This can be either a single capacitor (capacitor bank), or several capacitor banks that can be switched individually or in parallel in order to achieve a certain grading.
- As single capacitors directly at the motor (direct compensation).
- As capacitor banks in the run of long overhead lines. These are frequently mounted directly on an overhead-line pole. There may also be several plants available in the run of an overhead-line feeder.

SVCs (static VAR compensators) or TCR (thyristor controlled reactors) are increasingly being installed in order to enable stepless compensation. Here, the capacitors are not directly connected to the network, but controlled via converters.

### Capacitor banks

A distinction is made between the following designs of capacitor banks:

- Single capacitor bank
- Several capacitors in parallel, each of which is individually switched by its own switch.

Capacitors connected in parallel, which are switched with one switch, are referred to as a capacitor bank.

Load	Switching on a capacitor bank	Parallel connection <sup>1)</sup> of capacitor banks
Application	Capacitor bank (single bank)	Parallel capacitor banks
Current	Up to $1.4 \cdot I_c$	Up to $1.4 \cdot I_c$
$\cos \phi$	capacitive	capacitive
Features	High inrush currents. Permissible peak value of the capacitor often lower than the permissible value of the switch.	Very high, high-frequency (several kHz) inrush currents up to several kA with high rate of rise possible. The switching device must be selected according to the maximum occurring peak values.
Additional measures	–	At inrush currents $\hat{I}_e \leq 10 \text{ kA}$ : Additional measures are not usually required, provided the switch is designed for this application. At inrush currents $> 10 \text{ kA}$ : the suitability of the switch is to be checked. If this cannot be demonstrated, or the inrush currents are $> 20 \text{ kA}$ , a current limiting reactor is required.
Opening	Circuit-breakers are usually able to open capacitive currents of up to 70% of the rated current.	

<sup>1)</sup> Connecting other capacitors to an existing capacitive circuit

**Permissible inrush current**

The permissible inrush current depends both on the capacitor bank and the switching device.

**Capacitor bank**

The peak value of the inrush current must not exceed  $\max. 100 \cdot I_C$ . This factor is a guide value and must be checked on a case-by-case basis using capacitor data.

When closing, it is presumed that the capacitor is discharged. For this purpose, capacitor banks tend to be equipped with discharge resistors or transformers. Furthermore, the capacitor banks are predominantly fitted with a lockout, so that they can only be connected following full discharge.

If cycles with opening and re-closing are intended without a corresponding discharge lockout, the discharge time constant should be selected in such a way that the capacitor bank is discharged prior to being closed. Otherwise higher inrush currents may occur if the polarity of the line voltage is opposite the residual voltage at the time of closing.

**Switching device**

With regard to the vacuum switching device, the rated peak value of the inrush current  $\hat{I}_e$  must be greater than the maximum occurring inrush current. Typical values are 10 kA or 20 kA and are determined and tested by the manufacturer.

**Note**

The permissible inrush current can be found in the respective product catalog.

Some switching devices do not have a permissible inrush current and are therefore not suitable for this application.

If the inrush current is greater, an appropriate reduction (by reactors, for example) must be ensured on the line side.

When switching on a single capacitor bank onto the grid, the power-frequency inrush current usually remains  $< 10$  kA due to the limited short-circuit power. The maximum value of the inrush current  $\hat{I}_e$  approximately results from the equation:

$$\hat{I}_e = I_C \cdot \sqrt{2} \cdot \sqrt{\frac{S_{k''}}{Q_C}}$$

or:

$$\hat{I}_e \leq I_C \cdot \sqrt{2} \cdot n \quad \text{with } n = \frac{t_F}{t_N}$$

This maximum value occurs if the connection takes place at the maximum voltage and the capacitor bank is discharged.

The TRV frequency can be determined with the following equation:

$$f_F = \frac{1}{2 \cdot \pi \cdot \sqrt{L \cdot C}}$$

**Measures for limiting the inrush current**

- The most common measures for limiting inrush current are with a current limiting reactor. This should be taken into consideration in every system design.
- Reduction of the time constant with ohmic resistance and additional inductance in parallel with a current limiting reactor. However, this measure is only advisable for inductor-capacitors. Reactors and parallel dampings are configured on a customized basis.

**Note**

If a current limiting reactor is used to reduce the inrush current, an inductor-capacitor unit functions in a similar way to a filter. As such, the voltage load of the circuit-breaker is also to be checked when closing.

**Capacitors with current limiting reactor**

Load	Switching on a capacitor bank (individually or switched in parallel)
Current	up to $I_c$
$\cos \varphi$	capacitive

**Note**

After opening, the voltage on the capacitor side is greater than the line voltage. The rated voltage of the switching device must not be exceeded here. The calculation of the applied voltage is the same as described in the 'Filter circuits' section.

**Filter circuits**

Load	Switching of filter circuits
Current	Rated current of the filter (combination of capacitor and reactor). When connecting parallel filter circuits, high-frequency transient currents occur. The frequency of these currents corresponds to the combination of the tuning frequencies of the filters.
$\cos \varphi$	capacitive
Switching off a filter circuit (features)	After switching off, the voltage on the filter circuit is greater than the line voltage. The recovery voltage verified by capacitive tests must not be exceeded.
Additional measures	If the rated current of the circuit-breaker is exceeded, a circuit-breaker of the next highest rated voltage must be used or two circuit-breakers switched in series. In this case, please consult your respective contact partner at Siemens.

### Permissible voltage load of the switching device when switching off

When filter circuits or inductor-capacitor banks are switched off, the stress for the circuit-breaker caused by the recovery voltage is higher than with other consumers. This is due to the properties of the series connection of the inductor and the capacitor. If the same current flows through both components, the voltages at the capacitor and the inductor are phase-shifted 180°. The capacitor voltage  $U_C$  is higher than the driving line voltage by the value of the inductor voltage  $U_L$ . After switching off, the higher voltage  $U_C$  is applied at the switching device because the capacitor stores the electric charge. The capacitor voltage – and thus also the voltage across the switch – depends on the tuning frequency of the filter circuit, whereby any harmonics may increase this voltage.

If the capacitor voltage  $U_C$  exceeds the rated voltage of the circuit-breaker, a switch of the next highest voltage series needs to be used; for example, a 24 kV circuit-breaker instead of a 17.5 kV circuit-breaker. If the limit of 36 or 40.5 kV is exceeded on the 36 / 40.5 kV circuit-breakers, circuit-breakers from the 3AH3/4 or 8DA/DB series can be used, if corresponding test results are available. Otherwise, two circuit-breakers must be used in series.

### Calculation of the voltage load from filters and inductor capacitors

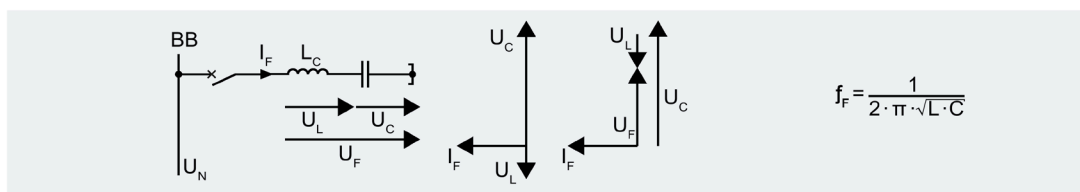


Figure 5-20 Filter circuit and vector diagrams

In the closed state of the switching device, the filter and line voltage are equal ( $U_F = U_N$ ). After opening, the full voltage  $U_{F0+}$  (amplitude) is applied at the capacitor side, because the capacitor stores the electric charges.

The filter voltage after opening  $U_{F0+}$  is calculated using the ordinal numbers:

$$U_{F0+} = U_N \cdot \frac{v^2}{v^2 - 1}$$

whereby  $n = \frac{f_F}{f_N}$

#### Example

For the ordinal number  $v = 5$  at a filter frequency of 250 Hz:

$$U_{F0+} = U_{C0-} = U_N \cdot \frac{5^2}{5^2 - 1} = U_N \cdot 1,042$$

This means that the rated voltage of the corresponding circuit-breaker must be at least 4.2% above the max. rated voltage in the power system. Harmonics are not considered here and may even increase this value.

### 5.2.3 Switching of unloaded cables and overhead lines

Cables and overhead lines have a capacitance per unit length. This is significantly higher for the cables. This is the reason why no load cables and overhead lines are switched according to the described principles. Switching devices must be designed for this load, which is regularly confirmed by a type test.

#### Load

	Unloaded cables and overhead lines
Current	See pullout from IEC 62271-100 standard, table 9
cos $\varphi$	capacitive
Features	In reality, the occurring values have a high fluctuation range. The type test values required according to the standard are representative and also cover non-standard values (higher and lower).
Additional measures	None

All Siemens switching devices comply with the values specified in the IEC 62271-100 standard, Table 9 for switching unloaded cables and overhead lines. Excerpts of these are listed in the following table.

Rated voltage [kV]	Overhead line	Cable	Single capacitor battery
	Rated power charge breaking current $I_l$	Rated cable charge breaking current $I_c$	Rated capacitor bank breaking current $I_{sb}$
7.2	10	10	400
12	10	25	400
15	10	25	400
17.5	10	31.5	400
24	10	31.5	400
36	10	50	400
38	10	50	400

### 5.2.4 Switching of ripple control systems

The ripple control systems enable audio-frequency impulses to be fed into the energy supply networks. The control frequencies are between 160 Hz and 1.6 kHz, whereby in the lower frequency range serial coupling is common and in the upper range only parallel coupling is. In both cases, the switching device switches a capacitive current, which consists of a superimposition of network and control (audio)-frequency parts. Vacuum circuit-breakers are free from restrikes with class C2 and therefore well suited for this switching duty.

**Load**

	<b>Ripple control systems during transmission mode</b>
Current	up to 20 A
cos $\phi$	capacitive
Features	A high-frequency current (160 Hz to 1.6 kHz) is superimposed on the net current (50/60 Hz). Air and hard-gas switch-disconnectors are not suitable for this switching application.
Additional measures	If necessary, a higher rated voltage is recommended if disconnections occur during transmission mode.

**5.3 Switching duties for other cases of operation****5.3.1 Operational switching (mechanical, electrical)**

A distinction is made between the mechanical number of operating cycles and the electrical service life in accordance with the standard. The most important classes for mechanical switching are M1 (2000 switching cycles) and M2 (10000 switching cycles).

The electrical service life is specified by class E. Siemens circuit-breakers are developed for the highest E2 class. Irrespective of this, the switching capacity (short-circuit making and breaking operations) is proven by performance tests. The test sequence differs from the E2 test.

The mechanical and electrical switching capacity is shown in the respective product catalogs in the switching cycle diagrams.

**5.3.2 Multiple reclosing**

Faults and short circuits in overhead lines are often only temporary and can, for example, be caused by storms, strong wind or animals. Vacuum circuit-breakers for auto-reclosing (AR) leave such short dead times between closing and opening that the de-energized time interval is hardly appreciable for the power supply to the consumers, but leaves enough time for the fault to disappear.

In case of unsuccessful auto-reclosing, there is a new breaking operation and the faulty feeder is shut down definitively. Vacuum circuit-breakers are also suitable for multiple-shot reclosing, which is mainly applied in English speaking countries under the designation "Reclosing".

Typical switching sequences include O - 0.3 s - CO - 15 s - CO or O - 0.3 s - CO - 3 min - CO or above 40 kA O - 3 min - CO - 3 min - CO. Special devices for even more frequent automatic reclosing are referred to as reclosers. The switching sequence here is, for example, O - 0.2 s - CO - 2 s - CO - 2 s - CO.

### 5.3.3 Synchronizing

The switching device must have a constant, short and defined closing time (= time from when the command is given to closing the contacts in all poles). Devices with a spring-operated mechanism are not suitable; one usually uses circuit-breakers with a stored-energy mechanism.

### 5.3.4 Switching coupler circuit-breakers

When switching coupler circuit-breakers, adjacent busbar sections are activated or deactivated. The stresses are therefore comparable with those of input or output switches.

This application is suitable for both uninterrupted operation and in the case of power system faults.

### 5.3.5 Earth and short-circuit

For earthing and short-circuiting active parts of power installations, mechanical switching devices, such as earthing switches can be used, among other things. However a combination of disconnectors and circuit-breakers can also be used, with the disconnector designed as a three-position switch. The electrical connection with the earth is established via the circuit-breaker with the appropriate position of the disconnector.

### 5.3.6 Disconnecting

For safety reasons, isolating distances must have higher insulation levels than other parts of a system. The relevant values are defined in the respective product standards. In addition to this, leakage currents must not be able to flow across the isolating distances.

Bypassing the isolating distance with insulating materials is only permitted if effective protection against pollution (gas insulation) or leakage current dissipated to earth is guaranteed. These conditions are not met by circuit-breakers, since they are designed for high electrically dynamic stresses and frequent switching. Vacuum tubes, in particular, cannot be used as an isolating distance.

In circuit-breaker switchgear, either a separate disconnector is provided or the circuit-breaker can be pulled out on a withdrawable part and therefore establish a disconnection.

In the case of load switches with lower currents and switching frequencies, the combination of both functions (= load switching and disconnection) is rather common.



# Switching applications with interrupted operation

## 6.1 Explanatory notes for interrupted operation - switching capacity

### 6.1.1 Characteristic values of the short-circuit current

#### Characteristic values of short-circuit currents with different fault types

Prior to the short circuit occurring, the phase offset between the current and voltage is low ( $\cos \varphi \geq 0.9$ ), as the loads are predominantly resistive or when connecting larger inductive loads they are accordingly compensated.

In the event of a short circuit, from this moment the phase sequence is defined by the short-circuit circuit. Since for lines, transformers and generators the inductive part is significantly higher than the resistive part, one generally only considers the inductive part of the circuit for short-circuit calculations. This means that if a short circuit occurs from a predominantly resistive current, this becomes a purely inductive current.

If one assumes the worst case in which the short circuit occurs in the voltage zero crossing, the current would need to jump to the peak value of the initial balanced short-circuit current  $I_k''$  due to the phase offset occurring there. However, this is not possible due to the inductance of the circuit. The short-circuit current can only start with a finite rate of rise and reaches its peak value after a quarter-wave. The occurring current offset in relation to the zero line and the subsequent decay process to zero is referred to as the DC component of the short-circuit current.

You will find additional information in the Section Breaking of short-circuit currents (Page 50), (Figure 6-4 Short circuit near the generator (Page 51), Figure 6-5 Short circuit near the generator with no zero transitions (Page 52) and Figure 6-6 Short circuit far from generator (short circuit in the power system) (Page 52).

The alternating current decays from the initial balanced short-circuit current  $I_k''$  to the uninterrupted short-circuit current  $I_k$ . The peak value of the initial balanced short-circuit current with the superimposed D.C. component is referred to as the peak short-circuit current  $I_p$ . This is the maximum instantaneous value of the short-circuit current.

#### D.C. component

The direct current generally decays in the ratio of reactance  $X$  to the ohmic resistance  $R$  of the circuit within a few periods. The direct current can only decay very slowly near the generator, as the ohmic resistance of the generators is very low and the  $X/R$  ratio is therefore very high.

The typical decay time constant  $\tau$ , which is also used as standard for circuit-breakers, is 45 ms. Depending on the network configuration, different values may occur. Conversion is needed of the short-circuit breaking capacity determined during type tests to the correspondingly different time constant.

### Initial balanced short-circuit current

The initial balanced short-circuit current  $I_k''$  is the rms value of the short-circuit alternating current at the moment the short circuit occurs.

### Impulse short-circuit current

The impulse short-circuit current  $I_p$  is the highest instantaneous value of the current after the short circuit occurs. It is defined as the peak value.

### Uninterrupted short-circuit current

The uninterrupted short-circuit current  $I_k$  is the rms value of the short-circuit alternating current, which remains after all the balancing processes have decayed.

### Short-circuit breaking current

The short-circuit breaking current is the current, which flows across the switch at the time of the first contact separation. It is composed of the AC component at this time and, if necessary, the DC component still available at this time. In the case of a short circuit near the generator,  $I_k''$  is  $> I_k$ . In the case of short circuit far from the generator,  $I_k''$  is  $\approx I_k$ . This means that the switching device must be able to switch off a current, which still runs asymmetrically to the zero line (DC component) and its AC component has not yet decayed to the uninterrupted short-circuit current  $I_k$ . The following factors are decisive here:

- Short-circuit location (near the generator/far from the generator)
- Short circuit occurrence (for example, in voltage zero crossing)
- Opening instant (relay and opening time of the switching device)

## 6.1.2 Short-circuit current interruption and recovery voltage

The following figure shows how after breaking the short-circuit current, the voltage is recovered across the contact gap.

It is assumed that the contact separation takes place at time  $t_1$  (phase angle  $\omega t_1$ ). The short-circuit current continues flowing via an arc and is then interrupted in the next zero crossing at time  $t_2$  (phase angle  $\omega t_2$ ), initially in one of the three poles (L3 first-pole-to-clear in the figure).

The  $L_1$  and  $L_2$  currents continue flowing into both other poles approx.  $90^\circ$  el. (therefore approx. 5 ms at 50 Hz) up to a common zero crossing (in a power system with free neutral point) and are then also interrupted.

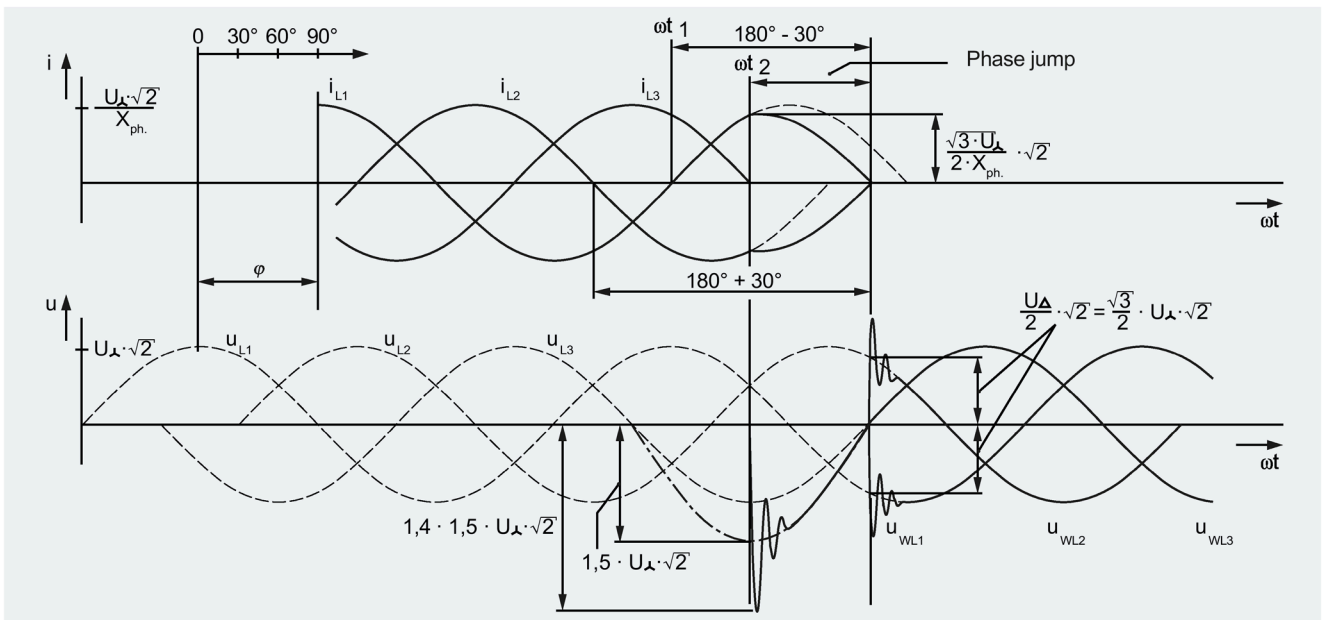
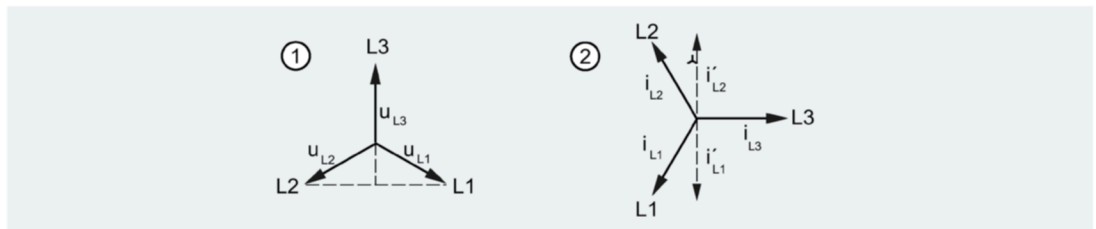


Figure 6-1 Idealized three-pole short-circuit disconnection

As shown in the following illustration, the recovery voltage jumps in the first-pole-to-clear L3 in the system with free neutral point to the triangular side between conductor L1 and L2 and is therefore higher than the phase-to-earth voltage by a factor of 1.5 ( $1.5 \cdot U_{\Delta} \cdot \sqrt{2} / \sqrt{3}$ ). This is how the term 'first pole to clear factor' is formed in English and is described in the standard with first-pole-to-clear = 1.3. This operating-frequency recovery voltage is also superimposed by a higher-frequency transient event. The standards assume that this transient recovery voltage exceeds the operating-frequency recovery voltage by a factor of 1.4. The total transient recovery voltage is therefore in the first-pole-to-clear L3 (as the peak value)  $u_c = 1.4 \cdot 1.5 \cdot \sqrt{2} \cdot U_{\Delta} / \sqrt{3}$  (IEC 62-271-100).

The two other poles then oscillate  $90^\circ$  to the first-pole-to-clear (following a reduction in the current to  $\sqrt{3}/2$ -times) as well as to  $\sqrt{3}/2$ -times the phase voltage.



- ① Voltage vector diagram
- ② Current vector diagram

Figure 6-2 Vector diagrams in cases of a short circuit in the power system

In the case of a rigidly earthed neutral point (with an earth fault factor of 1), the voltage in this first-pole-to-clear oscillates to the phase voltage. In the same way, the other two phases follow  $60^\circ$  or  $120^\circ$  first-pole-to-clear (figure 'Idealized three-pole short-circuit disconnection').

In effectively earthed systems, earth fault factors of up to 1.4 can occur. This results in a lower voltage in the first-pole-to-clear with a factor of 1.3 as well as an increased current in

the second-pole-to-clear. A test with first-pole-to-clear = 1.3 has thus also been included in the latest version of the circuit-breaker standard.

## 6.2 Transient recovery voltage

The following figure shows the recovery voltage, also known as the transient recovery voltage, across the contact gap after the short-circuit current has been broken. It is assumed that the contact separation takes place at time  $t_1$ . This corresponds to the clearing in the first pole according to section Short-circuit current interruption and recovery voltage (Page 48). Due to its short-term characteristics, this is called transient recovery voltage (TRV) in English.

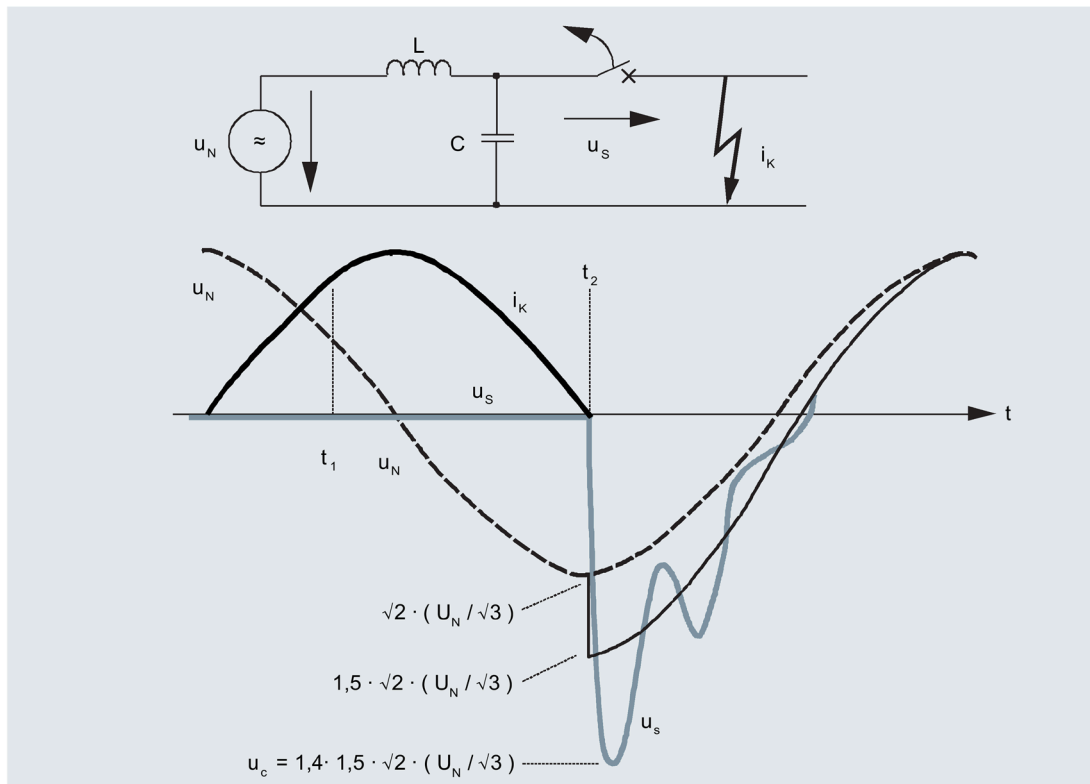


Figure 6-3 Transient recovery voltage following short circuit in the power system

## 6.3 Breaking of short-circuit currents

In the case of short circuits, a distinction is generally made between a short circuit near and far from the generator. The distinction is based on the different supply system inductances involved and the resulting different current characteristics or decay behavior of the direct-current component.

A short circuit is regarded as near the generator if the ratio from the initial balanced short-circuit current to the sustained symmetrical short-circuit current  $I_k'' / I_{RG}$  is  $> 2$ . The direct-current component (DC component) means an asymmetry of the short circuit and therefore

an additional load of the switch. Extremely high or slowly decaying DC components (in comparison to the alternating current component) can lead to a complete displacement of the short-circuit current. In extreme cases, zero current transitions are no longer available (missing zero transitions at DC components > 100%).

The large DC component of the short-circuit current is typical of the short circuit near the generator.

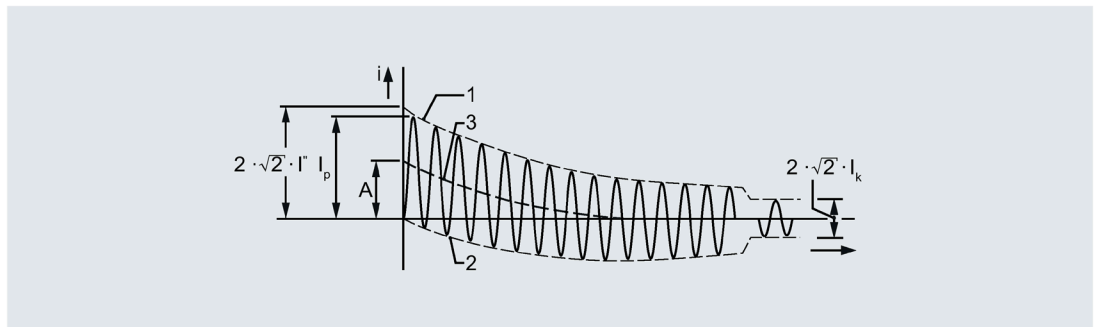
The breaking capacity of a circuit-breaker must be tailored to the magnitude of the current to be interrupted. Here, the temporal course of the current and the magnitude of transient recovery voltage occurring on the switching device terminals following the interruption (zero transition) are to be considered.

The following short-circuit currents may occur in the three-phase current system:

- Three-pole short circuit (highest current load) with or without earth contact
- Two-pole short circuit with or without earth contact
- Single-pole earth fault (in power grid with earthed neutral point)

### Short circuit near the generator

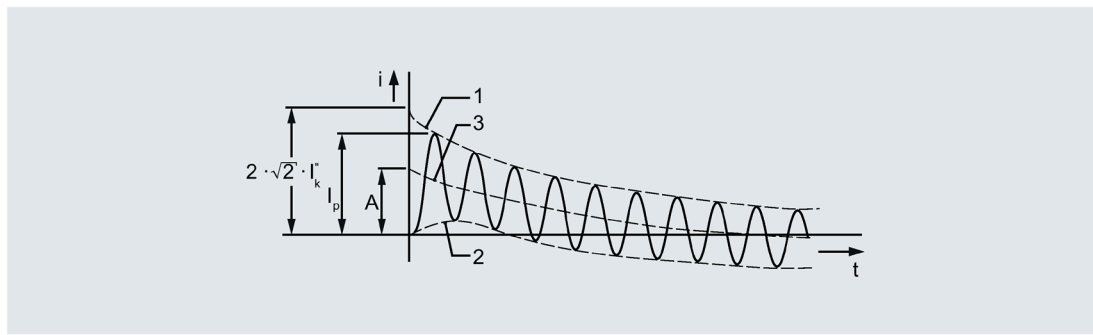
A short circuit near the generator occurs if in addition to the DC component, the AC component is also decremented. It occurs if in the case of a 3-pole short circuit, the proportion of initial balanced short-circuit current for a synchronous machine exceeds at least two times its continuous loading current.



- (1) Upper envelope
- (2) Lower envelope
- (3) Decaying DC current with initial value A

Figure 6-4 Short circuit near the generator

Under extreme conditions in short circuits near the generator, the AC component of the short-circuit current may decay faster than the DC component, in such a way that zero transitions do not occur.

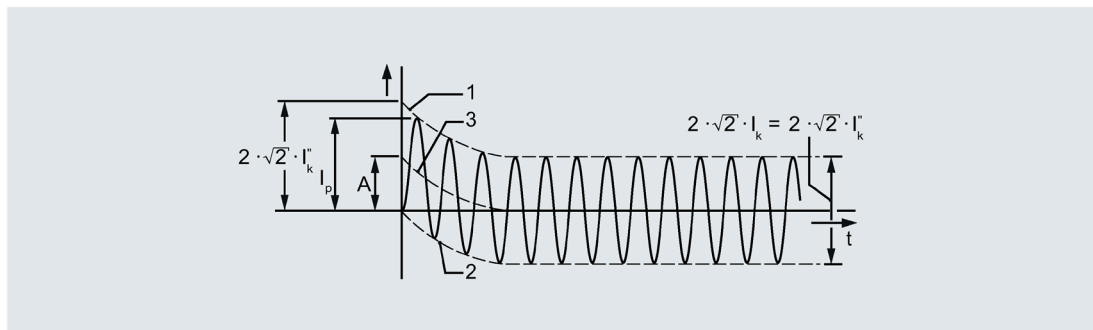


- (1) Upper envelope
- (2) Lower envelope
- (3) Decaying DC current with initial value A

Figure 6-5 Short circuit near the generator with no zero transitions

### Short circuit far from generator (short circuit in the power system)

A short circuit far from the generator occurs if its AC component practically does not decay, meaning that the short-circuit alternating current remains virtually permanently constant ( $I_k'' = I_k' = I_k$ ).



- (1) Upper envelope
- (2) Lower envelope
- (3) Decaying DC current with initial value A

Figure 6-6 Short circuit far from generator (short circuit in the power system)

### 6.3.1 Terminal short circuit

A terminal short circuit is the short circuit on the load side in the direct vicinity of the connection terminals for a switching device. It is not influenced by an additional line or cable length and therefore represents the most extreme load case for the switching device. Circuit-breakers are type tested on this basis.

### 6.3.2 Double earth fault

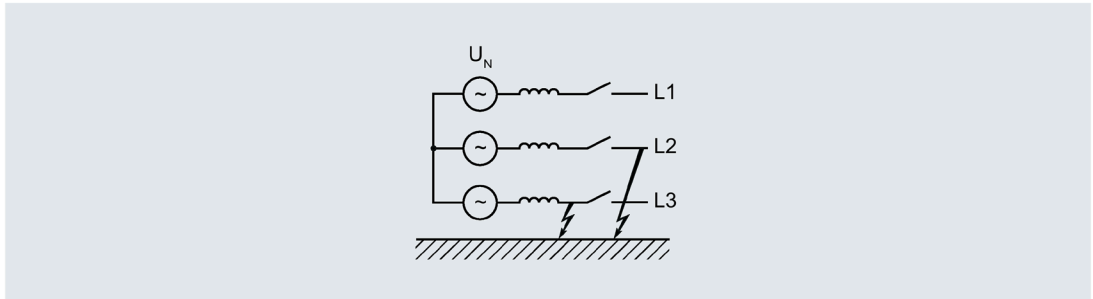


Figure 6-7 Double earth fault in the network

The double earth fault occurs in systems with a free neutral point or earthed systems. A double earth fault occurs if an earth fault exists at two spatially isolated points of the system in different phases. Due to the free neutral point, only a limited fault current flows, whereas a short-circuit current flows between the affected phases.

The current affected by the earth fault and flowing in the conductors via earth does not exceed the magnitude of the two-pole short-circuit current.

When opening a double earth fault with a fault in front of and behind the switching device, the recovery voltage is higher than in a three-pole short circuit. During the double earth fault, the phase-to-phase voltage occurs as the power-frequency recovery voltage, whereas only the phase-to-earth voltage occurs during a three-pole short circuit. During a double earth fault, both failure points are behind the switch, meaning that the same power-frequency recovery voltage occurs as for a three-pole short circuit in the two last-poles-to-clear. In medium-voltage systems with neutral point treatment, the amplitudes and rates of rise of the transient recovery voltage are below the values of the terminal short circuit when opening double earth fault currents.

### 6.3.3 Auto-reclosing (AR) with automatic restart

Experience has shown that more than 80% of all faults in overhead distribution systems are temporary, as they were triggered by external influences. This means that the fault disappears after a short while. It is not necessary to disconnect the system for repairs.

If a short circuit occurs, the circuit-breaker first of all breaks it – excited by a protection device, such as SIPROTEC. The circuit-breaker is generally automatically reclosed after around 300 ms. If the fault no longer exists, the auto-reclosing (AR) was successful. The circuit-breaker then remains in the closed state (O - C operating sequence).

If the fault persists (unsuccessful AR), this is finally interrupted by the circuit-breaker (operating sequence: O - CO). This means that the circuit-breaker opens and closes the short-circuit current once within a few milliseconds. Reclosers are the preference for this special case in overhead distribution systems. They can repeat the auto-reclosing up to four times. Auto-reclosing is not used in cable systems;

### 6.3.4 Transformer-fed short circuits and short-circuit current limiting coils

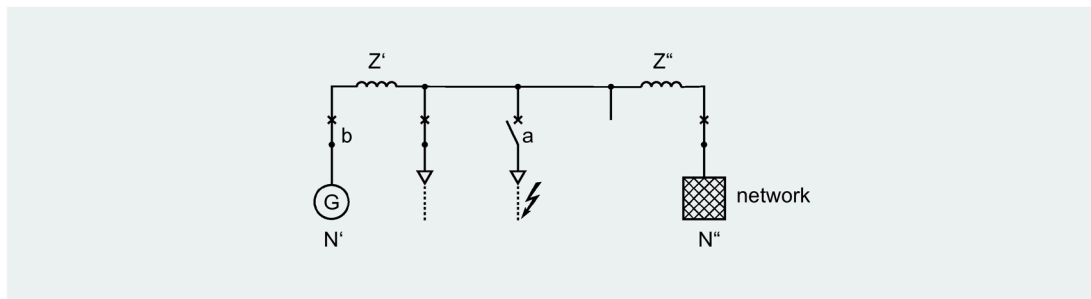
When opening a short circuit behind a short-circuit current limiting coil or a transformer – viewed from the supply direction – the circuit-breaker has a transient recovery voltage with a very high rate of rise to handle (due to the high natural frequencies of transformers and in particular short-circuit current limiting coils). High rates of rise of recovery voltage are controlled in particular by circuit-breakers in vacuum switching technology.

### 6.3.5 Blocked motors

When opening blocked motors, the switching device must be able to handle a relatively high current (around 5 to 7-times the rated motor current). In addition, there is a risk of switching overvoltages, as described in the Switching applications with uninterrupted operation (Page 15) and Switching applications with interrupted operation (Page 18) sections when switching motors during start-up.

### 6.3.6 Switching during phase opposition

Opening under phase opposition occurs predominantly when operating generators and means a high voltage load of the circuit-breaker (circuit-breaker b Figure 6-8 Example with in-plant generation and grid supply (Page 54)). This process is illustrated in the following example: In the feeder there is a 3-pole short circuit behind circuit-breaker a. As such, the generator changes its speed and therefore frequency. The power subsystem with the generator (marked as 'N' here) and the distribution grid N'' with the system impedances  $Z'$  and  $Z''$  are asynchronous. In medium-voltage systems, this case may occur if in-plant generation (system N') exists alongside the grid connection or distribution grid (grid N''). Once circuit-breaker a has opened the short circuit, a compensating current flows between N' and N'' due to the asynchronous position of the systems.

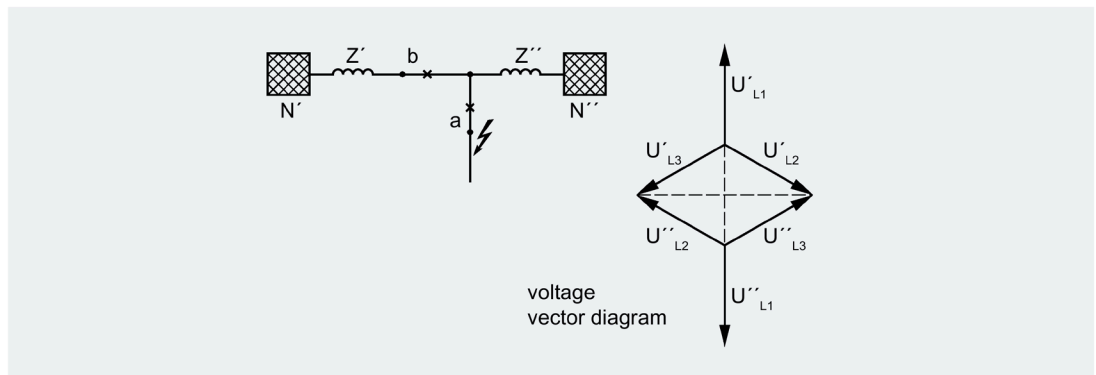


a and b Circuit-breakers

Figure 6-8 Example with in-plant generation and grid supply



The overcurrent protection of circuit-breaker b trips this circuit-breaker. The circuit-breaker now opens under the conditions of the phase oppositions, meaning the voltage load for circuit-breaker b is significantly higher than when opening under normal short-circuit conditions. In the worst case, (phase offset by  $180^\circ$ ) the voltages can be doubled (see Figure 6-9 Equivalent circuit and vector diagram for opening with phase opposition (Page 55)): The power-frequency recovery voltage can reach the value  $2 \cdot 1.5 U_N / \sqrt{3}$  and the transient recovery voltage the value  $2 \cdot 1.4 \cdot 1.5 \cdot \sqrt{2} \cdot U_N / \sqrt{3}$ .



a and b Circuit-breakers

Figure 6-9 Equivalent circuit and vector diagram for opening with phase opposition

The compensating current, which flows following the breaking of the short circuit, may in the worst case and with the same high system impedances  $Z'$  and  $Z''$  be 0.5-times the short-circuit current in the feeder (circuit-breaker a). In practice, the compensating current is generally considerably lower, provided the system impedances  $Z'$  and  $Z''$  are different and an unfavorable phase position virtually never occurs in practice. The standards also take this into account, determining the compensating current during phase opposition at 25% of the rated short-circuit breaking current.

### 6.3.7 Switching of generators

Circuit-breakers, which are used for switching generators, are exposed to the highest demands. As such, a special product standard is in place for circuit-breakers in this application (IEC / IEEE 62271-37-013: 'High-voltage switching devices and switchgear units - Alternating-current generator circuit-breakers', in order to ensure the safe functioning even under high demands.

#### Use cases

- Directly switched generators
- Generator-transformer blocks

**Selection of the circuit-breaker**

A customized design is required for generator circuit-breakers. The selection of the appropriate circuit-breaker depends on the specific operating conditions. Generally, circuit-breakers specially tested according to IEC / IEEE 62271-37-013 are to be used.

In the case of lower generator power ratings, standard circuit-breakers may also be used. However, these must also be custom designed. Ensure that the circuit-breaker is suitable for asymmetries (DC component) of the short-circuit current as well as for higher transient recovery voltages (TRVs).

**Overvoltage protection circuit**

The switching of generators in relation to transient switching operations is similar to motor switching. The transient short-circuit current  $I_k'$  of the generator during busbar short circuiting serves as a criterion for switch-based overvoltage protection. If this is  $\leq 600$  A, surge limiters or arresters are used.

However overvoltage protection is usually required if generators feed directly into an overhead distribution system. Surge arresters then provide protection against overvoltages from the system.

When it comes to planning the protection circuit, a distinction is made between the following groups:

$I_k'$	Overvoltage protection at the supply	
	In a cable system	In an overhead distribution system
$\leq 600$ A	Surge limiters or arresters, section 'Generators with $I_k' \leq 600$ A'.	Surge limiters or arresters, section 'Generators with $I_k' \leq 600$ A'.
$> 600$ A	Not necessary, it is common however that overvoltage protection is independent from the circuit-breaker, see section 'Generators with $I_k' > 600$ A'.	Machine arresters and surge capacitors, section 'Generators with $I_k' > 600$ A when fed into an overhead distribution network via a generator transformer'.

**Generators with  $I_k' \leq 600$  A**

**Directly switched generator**

In this application, the arrester is located on the switch. Additional surge arresters on the busbar side are advisable when feeding into an overhead distribution network, in order to protect against lightning surges.

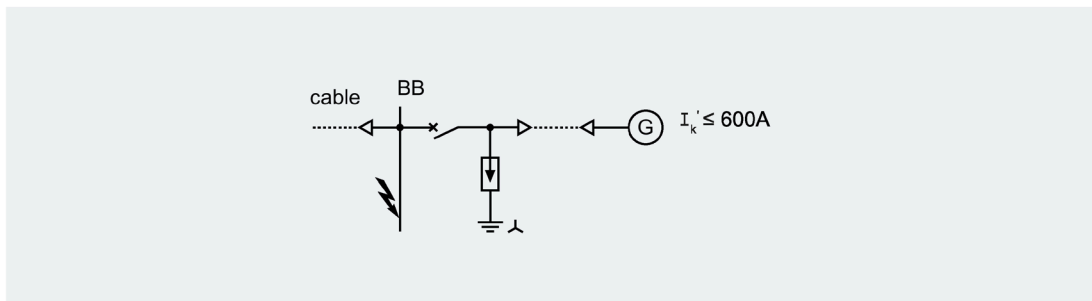


Figure 6-10 Surge arrester in phase-to-earth star connection on the circuit-breaker

### Generator with transformer

In this application, the voltage level and dielectric strength of the transformer used criteria are decisive when it comes to the overvoltage protection circuit.

The arrester is installed on the transformer at operating voltages  $\leq 15$  kV **and** at systems according to the upper values of the rated insulation level in accordance with IEC 62271-1 (see the following figure).

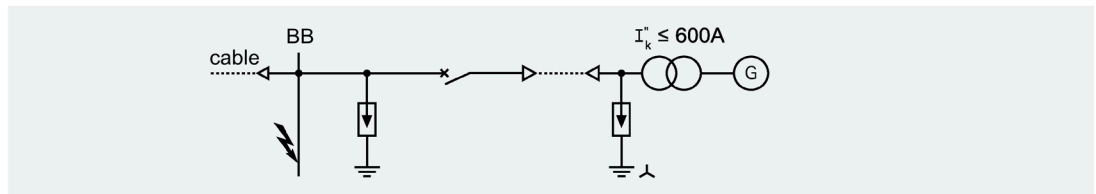


Figure 6-11 Surge arrester in phase-to-earth star connection on the transformer

Operating voltages  $> 15$  kV **or** systems with a lower value of the rated insulation level according to IEC 62271-1.

An increased level of overvoltage protection is required for this application. This comprises a combination of arresters between the phases (delta) and phase to earth (star configuration).

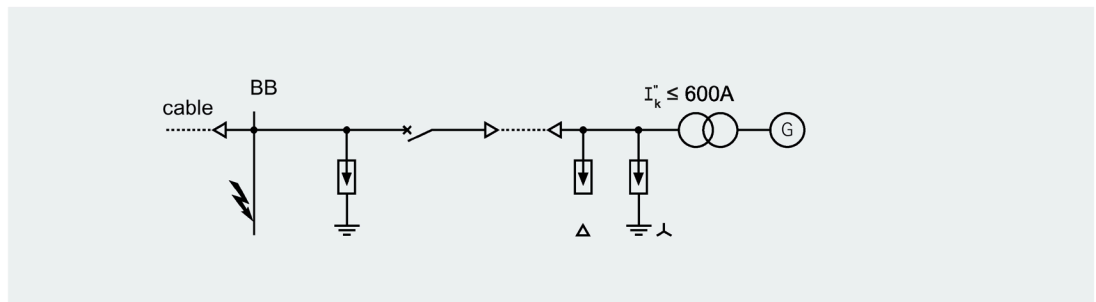


Figure 6-12 Overvoltage protection in 6-arrester connection on the transformer

Lightning protection must also be installed at the end of the overhead line when feeding into an overhead distribution system.

### Generators with $I_k' > 600$ A

Irrespective of the type of circuit-breaker, surge arresters are common for larger generators and are required when connecting to the overhead line. They provide protection against overvoltages from the system. As a general rule, devices with a high energy absorption capacity are used. They are installed directly on the generator.

### Directly switched generator

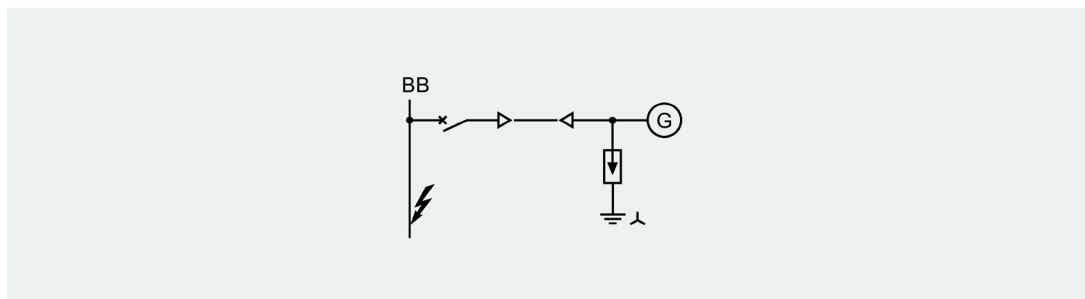


Figure 6-13 Surge arrester in phase-to-earth star connection on the generator

### Generator with transformer

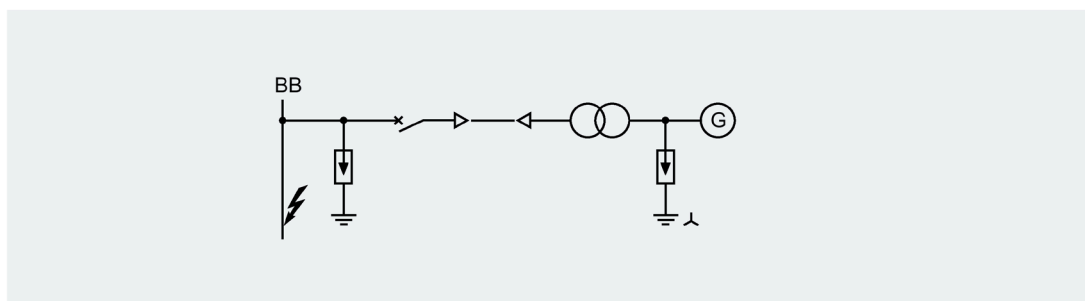
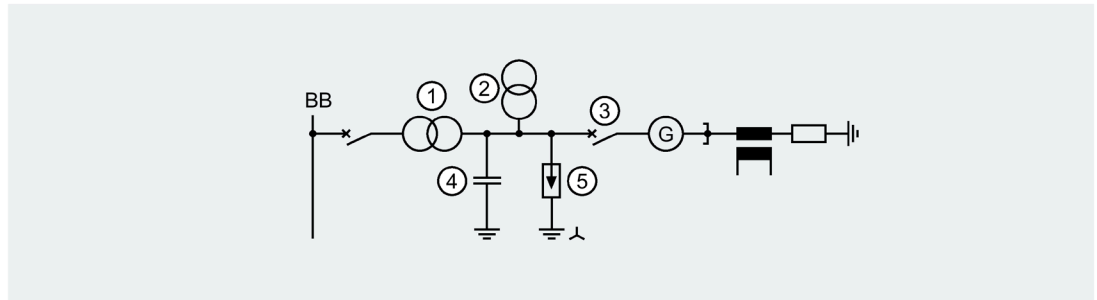


Figure 6-14 Surge arrester in phase-to-earth star connection on the generator

## Generators with $I_k' > 600$ A when fed into an overhead distribution network via a generator transformer

This tends to involve large generators, which feed into high-voltage power systems. The protective measures are planned on a customized basis and are independent of the circuit-breaker.



- ① Generator transformer
- ② Auxiliary power transformer
- ③ Generator circuit-breaker
- ④ Surge capacitor
- ⑤ Machine arrester

Figure 6-15 Overvoltage protection in phase-to-earth star connection on the generator

## 6.4 Making on short circuits

When making on an existing short circuit, the peak short-circuit current  $I_p$  (section Rated values (Page 11)) occurs as the making current, meaning the current amplitude at this point is significantly higher than at the time of making.

According to standard IEC 62 271-100 or comparable regional standards, peak short-circuit current works at a factor of 2.5 (at 50 Hz) or 2.6 (at 60 Hz) to the rated short-circuit breaking current.

The ratio is comprised of two factors:

1. Peak factor  $\kappa = 1.8$ . Here, it is assumed that from the time the short circuit occurs to the time of the DC component, a decay from  $\sqrt{2}$  to  $0.8 \cdot \sqrt{2}$  has taken place.
2. With the  $\sqrt{2}$  factor, the rms value of the AC component of the rated short-circuit breaking current is converted to the peak value. The ratio of  $\kappa \cdot \sqrt{2} = 1.8 \cdot \sqrt{2} = 2.5$  is calculated from this.

As shown in section Breaking of short-circuit currents (Page 50), in the case of short circuits near the generator the ratio of the making current to the AC component of the breaking current can be considerably higher than 2.5.

A similar trend of the short-circuit current as well as for short circuits near the generator can occur in systems with asynchronous motors. Here the ratio of the making current to the AC component of the breaking current can significantly exceed the value of 2.5, as asynchronous motors in the case of short circuit may increase the peak short-circuit current of the system, while they only contribute a negligibly small share of the breaking current.

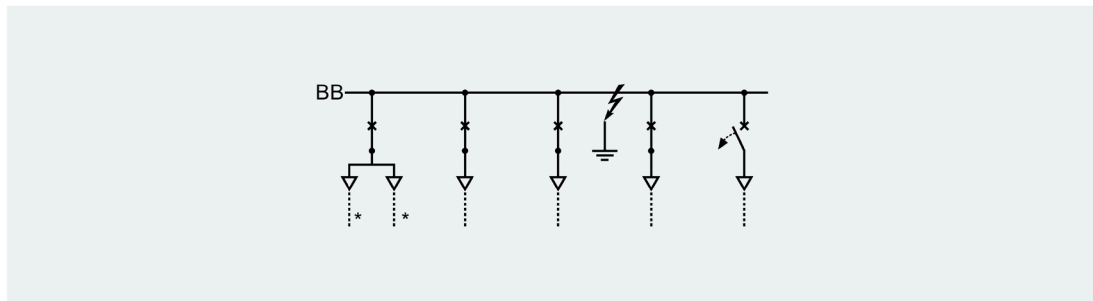
For the short circuit fed simply on several sides, a peak factor with  $\kappa = 1.15 \cdot \kappa_b$  is determined. 1.15 is a safety factor for consideration of inaccuracies, which are a result of the various R/X-ratios in parallel system feeders. The peak factor is however limited to a total of  $1.15 \cdot \kappa_b = 2.0$ . A ratio of the making current to the AC component of the breaking current of  $\max. \kappa \cdot \sqrt{2} = 2.0 \cdot \sqrt{2} = 2.8$  is calculated from this.

## 6.5 Switching duties under earth fault conditions

### 6.5.1 Switching earth faults on the supply side

In a system with a free neutral point or with earth fault compensation, the voltage increases during a phase-to-earth fault (referred to as earth fault) in one of the three phases in the entire system to the phase-to-phase voltage. Disconnecting an earth fault on the supply side then results in a higher voltage load for the switching device.

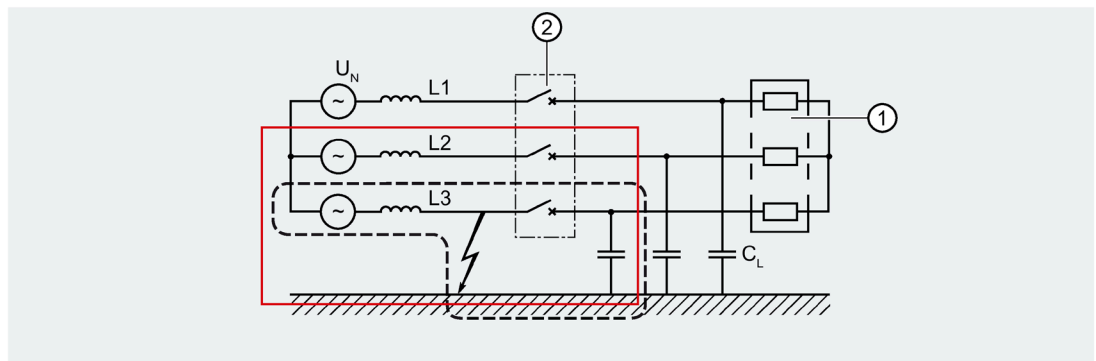
The following figure illustrates the power supply conditions based on the switching device that is about to open.



\* System supply

Figure 6-16 Power supply conditions during an earth fault on the supply side of a system

The critical switch load here is the high transient recovery voltage. If the earth fault is on the supply side (for example, in L3), the fault is not deactivated. The earth fault as well as the offset, higher voltage remain unaffected in fault-free phases. In fault-free poles L1 and L2, the transient recovery voltage is therefore significantly higher than in uninterrupted operation. The switching device must switch off the charging current of the cable or overhead line at increased transient recovery voltage (with unloaded cables or overhead lines) or also the superimposed charging current (with loaded cables or overhead lines).

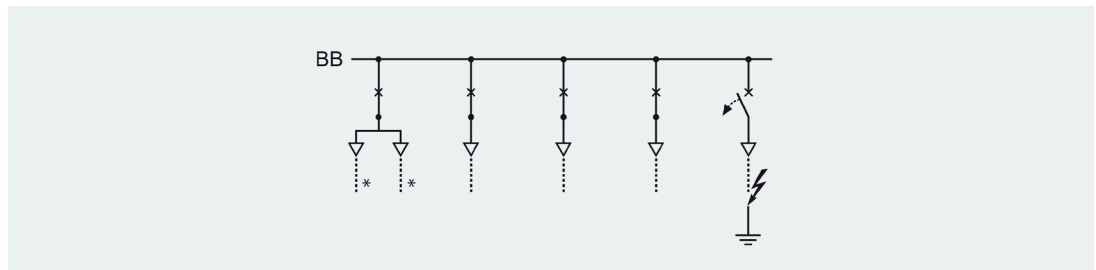


- ① Three-phase load
- ② Circuit-breakers
- Route of the capacitive charging current, for example, through the earth fault point and in the fault-free phase L2, which the switching device must open

Figure 6-17 Earth fault phase L3 - earth on supply side of the system

## 6.5.2 Switching earth faults on the load side

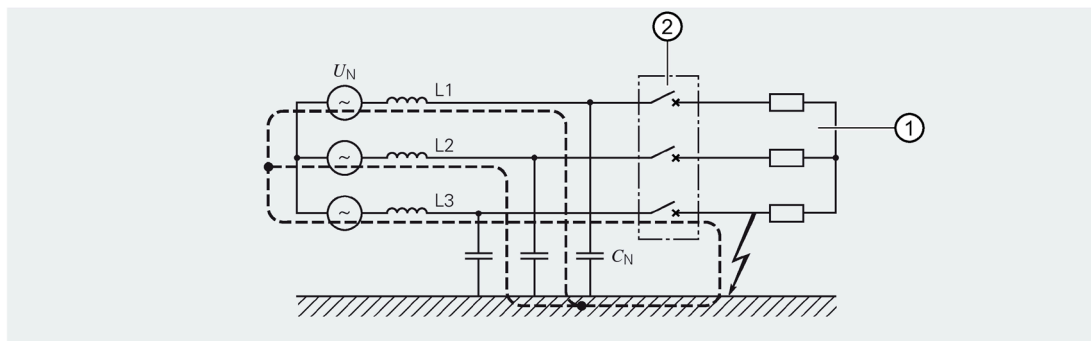
When switching an earth fault on the load side, this results in a lower voltage load for the switching device than when switching an earth fault on the supply side. The following figure illustrates the power supply conditions based on the switching device that is about to open.



- \* System supply

Figure 6-18 Power supply conditions during an earth fault on the load side of a system

If the earth fault, as shown in the following illustration, is on the load side of the switch, the L3 pole must switch off the capacitive charging current of the entire system (case of unloaded cables/overhead lines with fault on the load side). The charging current can reach very high values, depending on the expansion of the galvanically connected cable or overhead distribution system. A charging current is potentially superimposed (for loaded cables or overhead lines). The transient recovery voltage is normal here as the fault has been disconnected.



- ① Three-phase load
- ② Circuit-breakers
- Route of the capacitive charging current

Figure 6-19 Earth fault phase L3 - earth on load side of the system

The load side capacitances have not been included, as they are not decisive for this earth fault case.

## 6.6 Rapid load transfer

Particularly sensitive loads and industrial systems tend to be supplied via two or more infeeds. If only one supply is usually active, in the event of failure of this supply, a swift switchover must be made to an alternative supply. In most cases, this switchover must take place within 100 ms. Such applications can be implemented with conventional vacuum circuit-breakers and a suitable control system.

For applications with higher requirements with changeover times of 20 to 30 ms, the circuit-breakers must be used with a very easily reproduced make/break time. Conventional stored-energy mechanisms can also be used for this purpose, the use of magnetic operating mechanisms is not required.

These cases involve load-breaking operations. The switches are not loaded with short-circuit currents.

For rapid load transfer, circuit-breakers with short make/break times as well as with switching times of reproducibly the same length are needed, in order to be able to reliably switch over important loads to another supply without an extended current-free pause ( $\leq 150$  ms).



# List of abbreviations

## A.1 List of abbreviations

### Overview

Table A- 1 Meaning of abbreviations used in this document

Abbreviation	Meaning
AC	alternating current
AWE	Automatic reclosing
C	Capacity
DC	DC current
DIN	Deutsches Institut für Normierung e. V. (German Institute for Standardization)
EN	European Standard
EVU	Power supply companies
G	Generator
IEC	International Electrotechnical Commission
IEEE	Institute of Electrical and Electronics Engineers
KU	Auto-reclosing
L	Inductance
M	Motor
R	Resistance
RC	Resistor-capacitor circuit
SS	Busbar
SVC	Static VAR Compensator
TRV	Transient Recovery Voltage
VDE	Verein Deutscher Ingenieure (Association of German Engineers)
X	Reactance

Table A- 2 Meaning of symbols and abbreviations

Sym- bol/abbreviatio n	Meaning
$C_L$	Load-side capacitance
$C_N$	Grid capacitance
$f_F$	Natural frequency of the filter
$f_N$	Power frequency
$\hat{i}$	Peak value of current
$I, i$	Current

Sym- bol/abbreviatio n	Meaning
$i_a$	Chopping current
$I_{an}$	Motor starting current
$I_c, i_c$	Capacitor current, rated cable-charging breaking current
$I_e$	Making current
$\hat{I}_e$	Peak value of the making current
$I_F$	Filter current
$I_k$	Uninterrupted short-circuit current
$I_k'$	Transient short-circuit current
$I_k''$	Initial balanced short-circuit current
$I_l$	Rated power charge breaking current
$i_{L1}, i_{L2}, i_{L3} \dots$	Phase currents in L1, L2, L3
$I_{ma}$	Rated short-circuit making current
$I_p$	Impulse short-circuit current
$I_r$	Rated operational current
$I_{rG}$	Rated operational current of the generator
$I_{rMot}$	Rated operational current of the motor
$I_{sb}$	Rated capacitor bank breaking current
$I_{sc}$	Rated short-circuit breaking current
$k$	Peak factor
$k_b$	Peak factor reference value
$L_N$	Supply system inductance
$L_s$	Busbar inductance
$N', N''$	Power subsystem
$Q_C$	Reactive power of the capacitor unit or capacitor bank (capacitance)
$R$	Ohmic resistance
$S_k''$	Short-circuit power of the system
$S_{Motor}$	Apparent power of the motor
$t$	Time
$t_1$ to $t_n$	Times (for example, for current zero crossing, restrike)
$\hat{u}$	Peak value of the voltage
$U, u$	Voltage
$U_c, u_c$	Capacitor voltage
$U_{co-}$	Capacitor voltage just before switching off
$U_F$	Voltage at the filter
$U_{F0+}$	Filter voltage after switching off
$U_L$	Voltage across the reactor
$U_{max}$	Maximum overvoltage
$U_N, u_N$	Line voltage
$U_r$	Rated voltage of the switching device
$u_s$	Recovery voltage across the contact gap
$u_w$	Recovery voltage
$u_{WL1}, u_{WL2}, u_{WL3} \dots$	Recovery voltage in conductors L1, L2, L3 etc.
$X$	Positive reactance of the system impedance

---

Symbol/abbreviation	Meaning
$Z', Z''$	System impedances
$v$	Number of harmonics (ordinal number)
$\tau$	Damping time constant, decay time constant
$\omega t$	Phase angle





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