Electrical installations contain receivers, the power supply to which must be controlled by switchgear.

Medium voltage switchgear application guide

This guide is based on the analysis of phenomena arising from the behaviour of electrical equipment (transformers, motors, etc.), during normal or faulty running. Its aim is to help you choose the type and characteristics of the device best adapted to your needs.

Switchgear provides circuit electrical protection, disconnection and control.
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</table>
1 - TRANSFORMER

1 - 1 Switchgear to be used

A fused switch-disconnector, fused contactor and circuit breaker are usually used for operating and protecting high power transformers.

<table>
<thead>
<tr>
<th>type</th>
<th>power</th>
<th>transformer</th>
<th>controlled by</th>
</tr>
</thead>
<tbody>
<tr>
<td>MV/LV transformer</td>
<td>$P \leq 2 \text{ MVA}$</td>
<td>dry or immersed type</td>
<td>fused switch-disconnector or circuit breaker or fused contactor</td>
</tr>
<tr>
<td></td>
<td>$2 \text{ MVA} &lt; P \leq 4 \text{ MVA}$</td>
<td>dry or immersed type</td>
<td>fused switch-disconnector or circuit breaker or fused contactor</td>
</tr>
<tr>
<td>MV/MV transformer</td>
<td>$P \leq 4 \text{ MVA}$</td>
<td>dry type</td>
<td>circuit breaker</td>
</tr>
<tr>
<td></td>
<td></td>
<td>immersed type</td>
<td>circuit breaker</td>
</tr>
<tr>
<td></td>
<td>$P &gt; 4 \text{ MVA}$</td>
<td>immersed type</td>
<td>circuit breaker</td>
</tr>
</tbody>
</table>

The switch and contactor make sure the transformer is switched on and off during normal and overload running.

The fuse limits and breaks short-circuit currents generated by the upstream network short-circuit power.

The circuit breaker can make, withstand and break operating currents as well as short-circuit currents.

The protection system (CT, VT, relay, release...) automatically causes tripping when a fault is detected.

1 - 2 Device characteristics

The device must be able to:

- withstand and operate the continuous operating current and eventual overloads,
- break the fault current at the connection point; on the transformer’s secondary terminals,
- withstand short-circuit switching and no-load transformer switching peaks,
- break the no-load currents without excessive overvoltage (downstream open).

The control and/or protection device must be located upstream of the transformer.

Transformer faults cannot be picked up by downstream protection alone. A downstream control mechanism cannot isolate the fault transformer.
1 - TRANSFORMER
(cont'd)

fig. 1: transformers feeder

MV busbars

MV/LV transformers

MV downstream busbars

MV/MV transformer

fig. 2: transformers incomer

MV upstream busbars

MV/LV transformer tee-off (fig. 1)
630 kVA MV/LV transformer; \( U_{n,\text{primary}} = 20 \text{ kV} \)

\[ I_i = \frac{S}{\sqrt{3} \cdot U} = \frac{630}{\frac{20}{\sqrt{3}}} = 18.18 \text{ A} \]

The control device rating must be higher than or equal to 18.18 A.

The standardised values used by Merlin Gerin are:
400 - 630 - 1250 - 2500 - 3150 A.

If the control device is:
- a fused switch-disconnector: the fuse association limits this current to 200 A and the real rating of the assembly becomes the same as the fuse.
- a fused contactor: it is impossible to use a fused contactor as an control device since the contactor has a maximum rated voltage of 12 kV.
- a circuit breaker: the rating which we approve is 400 A.

MV/MV transformer incomer (fig. 2)
3150 kVA MV/MV transformer; \( U_{n,\text{secondary}} = 5.5 \text{ kV} \) operating with a temporary load of 20% for one hour.

\[ I_{r,\text{secondary}} = \frac{3150}{\frac{5.5}{\sqrt{3}}} = 331 \text{ A} \]

\[ I_{r,\text{overload}} = 331 \times 1.2 = 397 \text{ A} \]

We shall choose a circuit breaker with a rated current of 630 A.

**THE DEVICE MUST BE ABLE TO:**

- **WITHSTAND AND OPERATE THE CONTINUOUS OPERATING CURRENT AND EVENTUAL OVERLOADS**

The device must be dimensioned to be able to withstand the transformer’s rated current and eventual overloads.

The rated current \( I_r \) is given in the following equation:

\[ I_r = \frac{S}{\sqrt{3} \cdot U} \quad \text{U: operating voltage} \]

In specific cases where the transformer must operate in overload, the transformer manufacturer must supply overloads likely to be applied to the device depending on the ambient temperature.

This overload is expressed in time and as a percentage of the rated power.

The current value that should be taken into account is the following:

\[ I_r \text{ overload} = I_r \times X_{\text{overload}} \]

**Examples:**

- MV/LV transformer tee-off (fig. 1)
  - 630 kVA MV/LV transformer; \( U_{n,\text{primary}} = 20 \text{ kV} \)
  - \( I_i \text{ au primaire} = \frac{S}{\sqrt{3} \cdot U} = \frac{630}{\frac{20}{\sqrt{3}}} = 18.18 \text{ A} \)

The control device rating must be higher than or equal to 18.18 A.

The standardised values used by Merlin Gerin are:
400 - 630 - 1250 - 2500 - 3150 A.

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- MV/MV transformer incomer (fig. 2)
  - 3150 kVA MV/MV transformer; \( U_{n,\text{secondary}} = 5.5 \text{ kV} \) operating with a temporary load of 20% for one hour.
  - \( I_{r,\text{secondary}} = \frac{3150}{\frac{5.5}{\sqrt{3}}} = 331 \text{ A} \)

\[ I_{r,\text{overload}} = 331 \times 1.2 = 397 \text{ A} \]

We shall choose a circuit breaker with a rated current of 630 A.

**BREAK THE INSTALLATION’S FAULT CURRENT**

The breaking capacity must be higher than or equal to the maximum short-circuit current at the point of installation.

When a fused contactor is used as a control device, the breaking capacity must be higher than the current limited by the fuse.

The short-circuit current limited by the transformer is equal to:

\[ I_k = \frac{I_{r,\text{transfo.}} \times 100}{U_k,\text{transfo.}} \quad \text{U}_k: \text{transformer short-circuit voltage} \]

You will find in appendix 1 some values of \( U_k \).
1 - TRANSFORMER
(cont’d)

Example:
Transformer: 10 MVA
Secondary voltage: 10 kV, primary voltage: 20 kV
I_{n,\text{secondary}}: 577 A
Short-circuit voltage: 9%

a) the breaking device is upstream of the transformer
The breaking capacity must be equal to or higher than the network I_k
The standardised values are: 8 - 12.5 - 16 - 20 - 25 - 31.5 - 40 - 50 kA.

b) the breaking device is downstream of the transformer
The breaking capacity must be equal to or higher than the short-circuit current limited by the transformer as in the following equation:
\[ I_k = \frac{I_{n,\text{secondary}} \times 100}{U_k} = \frac{577 \times 100}{9} = 6411 \text{ A} \]
We shall choose a device with a breaking capacity equal to 8 kA.

Fuse protection
The fuse makes sure that short-circuit currents generated by the upstream network as a result of a downstream fault are broken.

In order to determine the required fuse rating to ensure transformer protection, you must know:
- the transformer’s characteristics
  - power (S in kVA),
  - short-circuit voltage (U_k in %),
  - rated current with eventual overload (A).
- the characteristics of the fuse family used
  - time/current characteristics (I at 0.1 s),
  - minimum breaking current (I_3 in A).
- the installation and operating conditions
  - in open air,
  - in a cubicle,
  - in fuse chambers.

In order to determine the fuse rating, you must:
- choose the rated current of the fuse
  - in general: transfo. \( I_r \leq 1.3 \) fuse \( I_r \leq \text{transfo.} \ I_r 1.5 \),
  - if the installation and operating conditions are not fully known, choose a fuse current rating immediately higher than transfo. \( I_r 1.5 \).
- check that transformer switching does not melt the fuse and that the secondary short-circuit current does melt the fuse with the equation:
\[ I_k \times I_3 < I_r \ 	ext{transfo.} < \frac{0.1 \text{ s}}{I_0/ I_r} \]

\( I_3 \): minimum breaking current of the fuse
\( I_0/ I_r \): current which causes the fuse to melt in 0.1 s (see fuse melting curve)
\( I_0/ I_r \): ratio between the current peak due to no-load transformer switching (peak value) and its rated current (root-mean-square value). If no other indication, take \( I_0/ I_r = 14 \).

It is essential to avoid making the fuse operate in the \( I_r \) and \( I_3 \) area.
The network short-circuit current is at the most equal to the \( I_3 \) current of the fuse used.
1 - TRANSFORMER
(cont’d)

**Circuit breaker protection**
Transformer protection is provided mainly by amperimetric relays with two thresholds:
- an immediate high threshold acts on upstream or internal transformer faults.
- a low threshold acts on downstream faults.

Different threshold settings:
- must take transformer switching, load current and fault current peaks into account.
- for the downstream protection device so that selectivity between upstream and downstream protection is ensured.

The following devices are also used:
- thermal image relays: protection against overloads and overheating,
- overvoltage relays: protection against overvoltage,
- earth overcurrent relays,
- tank protection relays,
- restricted earth relays,
- differential relays.

**WITHSTAND THE SHORT-CIRCUIT SWITCHING CURRENT AND THE NO-LOAD TRANSFORMER SWITCHING PEAKS**
The device making capacity must be higher than or equal to the peak value of the short-circuit current ($I_k 2.5$ according to IEC standard).

**BREAK NO-LOAD CURRENTS WITHOUT EXCESSIVE OVERVOLTAGE (DOWNSTREAM OPEN)**
No-load transformer breaking is like small inductive current breaking. The transformer insulation may be damaged by overvoltage. The overvoltage peak value must be limited. The linking circuit between the device and the transformer plays an important role. The presence of cables (thus of capacitances) greatly reduces overvoltage. Insulation co-ordination must be checked.

Such overvoltage must not be higher than $3.5 \text{ pu}$ ($1 \text{ pu} = \frac{U_r}{\sqrt{3}}$), general value accepted by standards.

SF6 breaking devices are particularly well adapted to this utilization.
2 - MOTOR

2 - 1 Switchgear to be used

A fused contactor, contactor and circuit breaker are usually used for operating and protecting motors.

<table>
<thead>
<tr>
<th>type</th>
<th>power or current</th>
<th>controlled by</th>
</tr>
</thead>
<tbody>
<tr>
<td>asynchronous</td>
<td>I &lt; 200 A</td>
<td>fused contactor</td>
</tr>
<tr>
<td></td>
<td>I &lt; 315 A</td>
<td>contactor</td>
</tr>
<tr>
<td></td>
<td>P &lt; 2 MW</td>
<td>circuit breaker</td>
</tr>
<tr>
<td>synchronous</td>
<td>P ≥ 2 MW</td>
<td>circuit breaker</td>
</tr>
</tbody>
</table>

The fused contactor is used to operate the motor when:
- the operating rate is high,
- the power is low (P < 1,500 kW),
- the operating voltage is lower than or equal to 11 kV.

The fuse breaks short-circuit currents generated by the upstream network short-circuit power.

The circuit breaker is used to operate the motor when:
- the operate rate is low,
- the power is high (I > 315 A),
- the operating voltage is higher than 12 kV.

2 - 2 Device characteristics

The control and/or protection device must be able to:
- withstand and operate continuous operating current,
- break the fault current,
- withstand the short-circuit fault current (Iₖ),
- break currents during starting without excessive overvoltage.

**THE DEVICE MUST BE ABLE TO:**

**WITHSTAND AND OPERATE THE OPERATING CURRENT**

The device must be dimensioned to be able to withstand the motor load current.

The rated current Iᵣ is given in the following equation:

\[ Iᵣ (A) = \frac{P \text{ (in kW)}}{\sqrt{3} \times U \times \cos \phi \times \eta} \]

\[ U = \text{phase to phase voltage in kV} \]
\[ \cos \phi = \text{motor power factor} \]
\[ \eta = \text{motor output} \]

**Example:** 1160 kW motor under 6.6 kV; \( \cos \phi = 0.92; \eta = 0.94 \)

\[ Iᵣ (A) = \frac{1160}{\sqrt{3} \times 6.6 \times 0.92 \times 0.94} = 117.35 \text{ A} \]

We shall choose:
- fused contactor: 200 A or 250 A
- circuit breaker: 400 A.
2 - MOTOR (cont’d)

**BREAK FAULT CURRENTS**

When a fused contactor is used as a control device, the contactor breaking capacity must be compatible with the need arising from co-ordination with the fuse and the different protective mechanisms.

The fuse breaking capacity must be higher than or equal to the maximum short-circuit current possible.

When a circuit breaker or a contactor alone is used as a control device, its breaking capacity must be higher than the maximum short-circuit current possible.

**Fuse protection**

The specific type of stress that the fuses must withstand comes from the motor which they must protect and the network on which it is located.

- stress due to the motor
  - rated current ($I_r$)
  - starting current $I_d$ ($I_d = 6$ to $7 I_r$ for direct starting)
  - starting time $t_d$
  - $t_d$ depends on the motor (values between 1 and 30 seconds)
  - the number of consecutive startings.

- stress due to the network
  - rated voltage ($< 11$ kV). Only fuses with $U_r \leq 12$ kV are used
  - prospective short-circuit current.

- choice of fuse characteristics
  - ideal starting current calculation ($I_{d_m}$)
  - The ideal starting current $I_{d_m}$ is equal to:
    - $2.4 I_d$ if the ratio $I_d / I_r$ given by the manufacturer is a design value
    - $2 I_d$ if the ratio $I_d / I_r$ given by the manufacturer is a measured value.
  - This $I_{d_m}$ value guarantees two consecutive start-ups or six start-ups at regular intervals per hour.

- to determine the fuse rating
  - record the $I_{d_m}$ and starting time value on the fuse time-current curve as shown in figure 1
  - choose the value immediately higher than the $I_{d_m}$ and $t_d$ right angle intersection

  On figure 1, the fuse rating to be taken is 250 A.

  When the fused contactor is installed in the cubicle, $I_{d_m}$ must be increased by 20%.

**Circuit breaker protection**

The motors are protected by the following protection devices:

- thermal image against overloads,
- independent time overcurrent for short-circuits,
- earth overcurrent for insulation faults,
- inverse component maximum for unbalance,
- against slow start-ups and rotor-locking.

The motors must be protected against voltage drops by a time-delay undervoltage relay. In general, a single relay is installed on the busbar and carries out load shedding to all the associated devices.
2 - MOTOR (cont’d)

■ **WITHSTAND THE FAULT SWITCHING CURRENT (Iₖ)**

The contactor or circuit breaker making capacity must be higher than or equal to the peak short-circuit current value. It is equal to 2.5 Iₖ according to the IEC.

■ **BREAK CURRENTS DURING STARTING WITHOUT EXCESSIVE OVERVOLTAGE**

The motors are sensitive to overvoltage since, for technological reasons, they are not as well insulated. The switchgear operation creates an overvoltage for each start-up. Repeated overvoltage creates weak points in the turn insulation which cause it to wear down prematurely, if not destroy it.

Devices using the SF6 technique do not generate dangerous overvoltage and do not need motor protection devices.

Rotating arc techniques should be kept if they work well. Puffer technique devices are likely to provoke higher currents than the rotating arc and therefore more dangerous overvoltage (see "selling points” folder, overvoltage file).
3-1 Switchgear to be used

A fuse-switch combination, fused contactor, circuit-breaker-switch and circuit breaker are usually used for operating and protecting capacitor banks.

<table>
<thead>
<tr>
<th>type</th>
<th>power</th>
<th>( I_{\text{capacitance current}}^{(1)} )</th>
<th>controlled by</th>
</tr>
</thead>
<tbody>
<tr>
<td>delta connection bank</td>
<td>( P \leq 1050 \text{ kvar} ) ( U \leq 11 \text{ kV} )</td>
<td>( I \leq 240 \text{ A} )</td>
<td>fused contactor</td>
</tr>
<tr>
<td></td>
<td>( I \leq 160 \text{ A} )</td>
<td>ISF1 circuit-breaker-switch</td>
<td></td>
</tr>
<tr>
<td></td>
<td>( I \leq 60 \text{ A} )</td>
<td>SM6 fixed fused switch-disconnector</td>
<td></td>
</tr>
<tr>
<td>star connection bank</td>
<td>( 600 \leq P \leq 1050 \text{ kvar} ) ( 11.7 \leq U \leq 21.8 \text{ kV} )</td>
<td>( I \leq 160 \text{ A} )</td>
<td>ISF1 circuit-breaker-switch</td>
</tr>
<tr>
<td></td>
<td>( 1050 \leq P \leq 4200 \text{ kvar} ) ( U \leq 11 \text{ kV} )</td>
<td>( I \leq 240 \text{ A} )</td>
<td>fused contactor</td>
</tr>
<tr>
<td></td>
<td>( I \leq 160 \text{ A} )</td>
<td>ISF1 circuit-breaker-switch</td>
<td></td>
</tr>
<tr>
<td></td>
<td>( 1050 \leq P \leq 4800 \text{ kvar} ) ( U \leq 21.8 \text{ kV} )</td>
<td>( I \leq 160 \text{ A} )</td>
<td>ISF1 circuit-breaker-switch</td>
</tr>
<tr>
<td></td>
<td>( 1050 \leq P \leq 21000 \text{ kvar} ) ( U \leq 21.8 \text{ kV} )</td>
<td>( 440 \text{ A} )</td>
<td>630 A circuit breaker</td>
</tr>
<tr>
<td></td>
<td>( 875 \text{ A} )</td>
<td>1250 A circuit breaker</td>
<td></td>
</tr>
<tr>
<td></td>
<td>( 1750 \text{ A} )</td>
<td>2500 A circuit breaker</td>
<td></td>
</tr>
<tr>
<td></td>
<td>( 2200 \text{ A} )</td>
<td>3150 A circuit breaker</td>
<td></td>
</tr>
</tbody>
</table>

\( (1) \) capacitive current that the breaking device is capable of breaking

The switch and the contactor make sure that the capacitor bank is switched on and off during normal running.

The fuse-switch or fuse-contactor combination make sure that short-circuit currents generated by the upstream network short-circuit power are broken. General protection and breaking device with the required breaking capacity are necessary even if capacitors are designed with an internal fuse.

The circuit breaker is able to make, withstand and break operating currents as well as short-circuit currents. Fault tripping is carried out automatically by the protection system (CT, VT, relay, release, etc.).

The capacitor banks are either mounted in a single bank (fig. 1), or in multi steps bank (fig. 2).

The multi steps capacitor bank with the following arrangement is often used:
- a head circuit breaker ensuring the general protection
- a switch (ISF1) or circuit breaker (if the number of operations is low) control each tap.

fig. 1: single bank

fig. 2: automatic banks
3 - 2 Device characteristics

The control and/or protection device must be able to:
- withstand the continuous operating current,
- break the fault current,
- withstand the network switching current and switching peaks
generated when power to the capacitors is switched on,
- make and break without excessive overvoltage.

THE DEVICE MUST BE ABLE TO:

- WITHSTAND THE CONTINUOUS OPERATING CURRENT

The device must be dimensioned to be able to withstand 1.43 times the
 capacitor bank rated current.

The rated current of the device is given by the following equation:
I_{device} = I_{capacitor} \times 1.1 \times 1.3 = I_{capacitor} \times 1.43

1.3 to take into account overheating due to the presence of harmonic
currents.
1.1 take into account the tolerance over the capacitance value.
The rated capacitive current must be lower than the capacitive current that
the device is able to break (value given by the manufacturer).

Example:
I_{capacitor} = 100 \text{ A}
I_{device} = I_{capacitor} \times 1.43 = 100 \times 1.43 = 143 \text{ A}

The following control devices are the ones we would choose:
- for a switch: ISF1 (I_{broken} capacitor = 160 \text{ A})
- for a contactor: Rollarc (I_{broken} capacitor = 240 \text{ A})
- a circuit breaker with a 630 A rating (I_{broken} capacitor = 440 \text{ A}).

- BREAK THE FAULT CURRENT

The breaking capacity of the device must be higher than or equal to the
maximum short-circuit current possible.
When the device is a fused contactor, the contactor breaking capacity must
be higher than the current limited by the fuse.

Fuse protection
The fuse rating must be between 1.7 and 1.9 times the rated current of the
bank. This coefficient takes into account a downgrading of 1.3 due to the
presence of harmonic currents and the derating due to the inrush currents
I_{capacitor} \times 1.7 \leq I_{fuse} \leq I_{capacitor} \times 1.9

Protection against overloads must also be provided on each phase.

Circuit breaker protection
Protection against short-circuits and overloads must be provided on each
phase.
3 - CAPACITOR (cont’d)

- **WITHSTAND THE SWITCHING CURRENT**

  The making capacity of the device must be equal to or higher than the greatest of the following values:
  - \( I_p \) network (2.5 \( I_k \) according to IEC)
  - bank switching current \( I_e \).

  The bank switching current \( I_e \) must always be less than \( I \) capacitor \times 100. Otherwise it must be limited by installing dumping reactors in order to reduce arcing contact wear.

  This current plays an important role in the mechanical endurance of the device.

  **Example:** Rollarc contactor, \( I_r = 400 \text{ A} \); \( I_{\text{broken capacitor}} = 240 \text{ A} \);
  maximum number of operations: 300,000 in mechanical latching.
  \( I_{ \text{max. switching current} } = 8 \text{ kA peak} \);
  number of operations at \( I_{ \text{max. switching current} } = 10,000 \).
  The determination of switching current values is given in appendix 3.

- **MAKE AND BREAK WITHOUT EXCESSIVE OVERVOLTAGE**

  If \( 1 \text{ pu} = \frac{U_r \sqrt{3}}{3} \)

  the overvoltage must not be higher than:
  - for a single bank: 2 pu
  - for a automatic bank (\( n \) identical taps):
    \[ \frac{2n}{2n + 1} = \text{ pu} \]

  SF6 devices are especially well adapted to this application.
4 - GENERATOR

4 - 1 Switchgear to be used

The control device usually used for operating and protecting generators is a circuit breaker.

The two most current uses for the generator circuit breaker are:

- low power station generator protection
- protection of auxiliary generators providing a power supply to priority circuits in the event of a distribution network failure.

In practical cases, power station generators are built as self-contained units (generator/transformer set). A VHV circuit breaker is used to operate and protect them.

In this case, the circuit breaker is used as a transformer protection incomer. Its characteristics are those described in chapter 1 (transformer).

4 - 2 Device characteristics

When in use, the generator circuit breaker comes up against very different operating conditions. It must:

- withstand high load currents (overheating),
- break strong and highly asymmetrical fault currents which may be higher than 100% (generator terminal fault),
- close on very high currents generated by the asymmetry,
- withstand transient recovery voltage with highly increasing speeds,
- withstand phase displacement.

**IN OPERATION, THE GENERATOR CIRCUIT BREAKER MEETS VERY DIFFERENT CONDITIONS OF RUNNING. IT MUST BE ABLE TO:**

- **WITHSTAND HIGH LOAD CURRENTS**

The rated current is given by the following equation: \( I \geq \frac{S}{\sqrt{3} \cdot U} \)
4 - GENERATOR (cont’d)

**BREAK HIGHLY ASYMMETRICAL FAULT CURRENTS**

When a short-circuit occurs on a network close to a generator the fault current speed is the one represented in figure 1. It is essential to know the evolution of the short-circuit current and the values at the moment the circuit breaker arcing contacts separate: aperiodic ($I_{dc}$) and periodic ($I_{ac}$) component value.

Current asymmetry can reach very high values, sometimes higher than 100%, which delays the natural passages of the current through zero that are necessary for breaking.

In highly asymmetrical breaking, the SF6 technique is limited to 100% asymmetry for a total asymmetrical current equal to 2 times the peak symmetrical short-circuit current.

$$I_{asym} = I_{sym} \sqrt{1 + 2A^2} \quad \text{with} \quad A = \% \text{ asymmetry} = \frac{I_{dc} \cdot 100}{I_{ac \text{ peak}}}$$

The breaking capacity of the generator circuit breaker must be higher than or equal to the maximum short-circuit current possible.

The value to be taken into account is the greatest of:

- the short-circuit current supplied by the network,
- the asymmetrical current of the generator at the moment the contacts open.

**Example:** when the contacts separate, the periodic short-circuit current is 29 kA with 80% asymmetry at $t_0$.

Asymmetrical current = $I_{sym} \sqrt{1 + 2A^2} = 29 \cdot \sqrt{1 + 2 \times (80\%)}$

$$= 29 \cdot 1.35 = 39.15 \text{ kA}$$

The short-circuit current supplied by the network is 25 kA.

We shall choose a circuit breaker with a breaking capacity equal to 40 kA.

If the breaking capacity required is higher than the breaking capacity of the device, one solution consists in delaying circuit breaker switching in order to avoid an overly high asymmetry when the circuit breaker has to open due to a fault.

**SWITCHING WITH VERY HIGH CURRENTS**

The making capacity must be higher than or equal to the peak value of the short-circuit current made.

The value to be taken into account is the greatest of the following:

- 2.5 times the breaking capacity of the circuit breaker,
- the peak value of the short-circuit current, taking into account the asymmetry of the generator current (figure 1).

**INVERSION OPERATION**

The short-circuit current value in phase inversion must be lower than the breaking capacity given by the manufacturer of the circuit breaker.

**TRANSIENT RECOVERY VOLTAGE VALUES (TRV)**

The TRV values as well as the TRV increase time must be compatible with the circuit breaker in all types of situations (see circuit breaker technical guide § 5.11).
4 - GENERATOR (cont’d) 4 - 3 Characteristics required for the determination of a generator circuit breaker

To be able to select a generator circuit breaker, the following characteristics must be satisfied:

- the rated current in continuous operation
- generator power in MVA or kVA,
- operating voltage in kV,
- generator rated current.
- the short-circuit symmetrical current in rms kA
- the asymmetrical current and the continuous component value
- the closing current in peak kA
- the rated withstand current (rms kA/1 s)
- the peak value of the TRV (in peak kA) as well as the increase time in µs
- the rated operating cycle (O - 3 mn - CO - 3 mn - CO advised).

The generator circuit breaker can operate in phase inversion which implies the following values are known:

- the short-circuit current,
- the peak value TRV and increase time.
5 - CABLES OR CABLES/LINES

5 - 1 Switchgear to be used

A switch, fused switch-disconnector and circuit breaker are usually used to operate and protect lines and cables.

![Diagram of switchgear]

<table>
<thead>
<tr>
<th>type</th>
<th>current</th>
<th>controlled by</th>
</tr>
</thead>
<tbody>
<tr>
<td>cables</td>
<td></td>
<td></td>
</tr>
<tr>
<td>I ≤ 630 A</td>
<td>switch</td>
<td></td>
</tr>
<tr>
<td>I ≤ 200 A</td>
<td>fused switch-disconnector</td>
<td></td>
</tr>
<tr>
<td>I ≤ 3150 A</td>
<td>circuit breaker</td>
<td></td>
</tr>
</tbody>
</table>

5 - 2 Device characteristics

The operating and/or protection device must be able to:
- carry the load current,
- withstand the short-circuit current,
- break the fault current if the device is an incomer,
- operate weak currents (no-load cables or lines) without excessive overvoltage.

**THE DEVICE MUST BE ABLE TO:**

- **CARRY THE LOAD CURRENT**

  The rated current depends directly on the supply power and voltage of the receivers installed on the outlet feeder.

  \[ I = \frac{S}{U \sqrt{3}} \]
5 - CABLES OR CABLES/LINES (cont’d)

**BREAK THE INSTALLATION’S FAULT CURRENTS**

The breaking capacity must be higher than or equal to the maximum short-circuit current possible at the installation point.

**If the device is used as an incomer**

The breaking capacity must be higher than or equal to the maximum short-circuit current possible at the installation point.

The short-circuit current limited by the overhead or underground link depends on the type and section of the conductors.

\[ I_k = \frac{U}{\sqrt{3} \cdot Z_k} = \frac{U}{\sqrt{3} \cdot \sqrt{R^2 + X^2}} \]

- for an overhead link
  \( X = 0.4 \text{ ohm/km} \)
  \( R = \frac{\rho L}{S} \) with \( \rho = 3.3 \times 10^{-6} \text{ ohm cm}^2/\text{cm} \)

- for an underground link
  Three-phase cables: \( X = 0.1 \) to \( 0.15 \) ohm/km
  Single-phase cables: \( X = 0.1 \) to \( 0.20 \) ohm/km
  \( R = \frac{\rho L}{S} \) with \( \rho = 1.81 \times 10^{-6} \text{ ohm cm}^2/\text{cm} \) for copper
  \( \rho = 2.81 \times 10^{-6} \text{ ohm cm}^2/\text{cm} \) for aluminium

**If the device is used as an outlet**

The switch does not have a short-circuit current breaking capacity. It is the protection device located upstream which provides protection against short-circuits.

It must however be able to withstand the short-circuit current induced for the time needed to eliminate it.

If protection against short-circuits is required the fused switch-disconnector or the fuse-switch combination must be used.

The circuit breaker must have a breaking capacity higher than or equal to the short-circuit current at the connection point.

**OPERATE WEAK CURRENTS WITHOUT EXCESSIVE OVERVOLTAGE**

Applying voltage to a no-load line can be compared to capacitor switching.
6 - ARC FURNACES

6 - 1 Switchgear to be used

The ISF2 switch-circuit breaker was designed for arc furnace application. The maximum characteristics of the ISF2 are given in the table below.

<table>
<thead>
<tr>
<th>max. power</th>
<th>voltage</th>
<th>max. load current</th>
<th>breaking capacity</th>
<th>no. of daily operations</th>
</tr>
</thead>
<tbody>
<tr>
<td>180 MVA</td>
<td>40.5 kV</td>
<td></td>
<td>2500 A</td>
<td>20 kA</td>
</tr>
<tr>
<td>156 MVA</td>
<td>36 kV</td>
<td></td>
<td></td>
<td>200</td>
</tr>
<tr>
<td>104 MVA</td>
<td>24 kV</td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

6 - 2 Device characteristics

The switch must be able to:
- operate the load current,
- break the installation’s short-circuit currents,
- operate weak currents (no-load transformer) without excessive overvoltage,
- carry out a large number of operations.

**THE DEVICE MUST BE ABLE TO:**

- **OPERATE THE LOAD CURRENT**

  The rated current depends directly on the furnace supply voltage and power.

  Furnace power:  
  \[ S = U I \sqrt[3]{3} \Rightarrow I = \frac{S}{U \sqrt[3]{3}} \]

  S: apparent power of furnace
  U: primary voltage of furnace transformer

  **Example:**
  
  Furnace power: 100 MVA
  Supply voltage: 30 kV
  
  \[ I = \frac{S}{U \sqrt[3]{3}} = \frac{100}{30 \cdot \sqrt[3]{3}} \approx 1924 \text{ A} \]

- **BREAK THE SHORT-CIRCUIT CURRENTS**

  The furnace switch must be able to break the electrode short-circuit current. The short-circuit current may be calculated in a perfectly general way. The short-circuit impedance is essentially due to the LV links.

  \( Z_{k, LV} = 2.5 \cdot 10^{-3} \Omega \) whatever the furnace size is

  The primary short-circuit power is:

  \( S_{k, MV} = U_{MV} \cdot I_{k, MV} \cdot \sqrt[3]{3} \) and \( U_{MV} = Z_{k} \cdot I_{k} \)

  The primary short-circuit current is:

  \[
  I_{k, MV} = \frac{U_{MV}}{\sqrt[3]{3} \cdot Z_{k, MV}} \quad \text{with} \quad Z_{k, MV} = \left( \frac{U_{MV}}{U_{LV}} \right)^2 \cdot Z_{k, LV} \]

  \[
  I_{k, LV} = \frac{U_{MV} \cdot (U_{LV})^2}{\sqrt[3]{3} \cdot (U_{MV})^2} \cdot \frac{1}{Z_{k, LV}}
  \]
6 - ARC FURNACES (cont’d)

**OPERATE TRANSFORMER NO-LOAD CURRENTS WITHOUT EXCESSIVE OVERVOLTAGE**

In the melting process (see appendix 6) a switch operates with the no-load transformer: 50% of the case upon opening and 90% of the case upon closing.

Operating overvoltage must be limited when the arc furnace is installed. This overvoltage arises during furnace transformer operation. It contributes to the progressive destruction of the transformer’s internal insulation and reduces its lifespan.

The network must be adapted to the breaking device’s characteristics (installation of overvoltage protection capacitors for example).

With SF6 technology operating overvoltage is low. The means of limiting overvoltage are simple.

A simple RC circuit placed upstream of the furnace transformer is sufficient.

**MECHANICAL AND ELECTRICAL ENDURANCE**

In the melting process a switch operates: 50% of the case upon opening with currents between 0.8 I_{load} and 2.6 I_{load} and 90% of the case upon closing with load currents of 2.5 I_{load}.

The mechanical endurance of the ISF2 is 50,000 operations.

The electrical endurance depends on the average value of the current supplying the furnace transformer during the process and the number of operations carried out under this current.

The expected lifespan of the poles (number of CO cycles) depending on the load current is given by the curve below.

![Graph](image)

- Curve 1: without replacement of the poles
- Curve 2: with 1 replacement of the poles
- Curve 3: with 2 replacements of the poles

**Example:** for an arc furnace supplied by a 52 MVA transformer under 30 kV with a load current of 1000 A, the expected lifespan of an ISF2 is 25,000 CO cycles (or 50,000 CO cycles if the pole set is replaced).
7 - APPENDICES

Appendix 1: transformer
Appendix 2: motor
Appendix 3: capacitor
Appendix 4: generator
Appendix 5: cables
Appendix 6: alternating current melting arc furnaces
Appendix 7: diode and thyristor applications
Appendix 8: fused switch-disconnector or fused contactor
Appendix 1: transformer

A transformer is defined by its rated power, its rated primary and secondary currents, its rated primary and secondary voltages, its insulation level, its short-circuit voltage and its coupling. The peak-switching current is also a parameter that should not be forgotten in the determination of protective switchgear.

1 - RATED POWER
The rated power (S in kVA or MVA) of a transformer is equal to:
\[ S = U \sqrt{3} \cdot I_r \]

2 - RATED CURRENT OF ONE WINDING
The rated current \( I_n \) is equal to:
\[ I_r = \frac{S}{\sqrt{3} \cdot U} \]

3 - RATED VOLTAGE AND INSULATION LEVEL OF ONE WINDING
This is the specified voltage to be applied (primary) or developed (secondary) in “no-load” operating between the terminals of one transformer winding. The rated primary voltage must be higher than or equal to that of the network.

<table>
<thead>
<tr>
<th>rated voltage ( U_r ) (kV)</th>
<th>insulation level rms kV (50 Hz - 1 mn)</th>
<th>kV impulse (1.2/50 µs)</th>
</tr>
</thead>
<tbody>
<tr>
<td>7.2</td>
<td>20</td>
<td>60</td>
</tr>
<tr>
<td>12</td>
<td>28</td>
<td>75</td>
</tr>
<tr>
<td>17.5</td>
<td>38</td>
<td>95</td>
</tr>
<tr>
<td>24</td>
<td>50</td>
<td>125</td>
</tr>
<tr>
<td>36</td>
<td>70</td>
<td>170</td>
</tr>
</tbody>
</table>

4 - SHORT-CIRCUIT VOLTAGE
The short-circuit voltage (expressed in %) allows the transformer’s secondary short-circuit current to be calculated. The short-circuit current is given in the following equation:
\[ I_k = \frac{I_n \cdot 100}{U_k} \quad \text{and} \quad P_k = U_r \cdot I_k \cdot \sqrt{3} \]

\( I_n \): rated current in Amps
\( U_k \): short-circuit voltage in %

The usual \( U_k \) values depending on transformer voltage and power are given in the tables on the following page. The real values must be requested from the manufacturer.
Appendix 1: transformer (cont’d)

For a MV/LV transformer

<table>
<thead>
<tr>
<th>power (kVA)</th>
<th>( U_k(%) )</th>
<th>( U_k(%) )</th>
</tr>
</thead>
<tbody>
<tr>
<td>50 to 630</td>
<td>4</td>
<td>4</td>
</tr>
<tr>
<td>800</td>
<td>4.5</td>
<td>5</td>
</tr>
<tr>
<td>1000</td>
<td>5</td>
<td>5.5</td>
</tr>
<tr>
<td>1250</td>
<td>5.5</td>
<td>6</td>
</tr>
<tr>
<td>1600</td>
<td>6</td>
<td>6.5</td>
</tr>
<tr>
<td>2000</td>
<td>6.5</td>
<td>7</td>
</tr>
<tr>
<td>2500</td>
<td>7</td>
<td>7.5</td>
</tr>
<tr>
<td>3150</td>
<td>7</td>
<td>7.5</td>
</tr>
</tbody>
</table>

For a MV/MV transformer

<table>
<thead>
<tr>
<th>power (MVA)</th>
<th>( U_k(%) )</th>
<th>primary voltage (kV)</th>
<th>secondary voltage (kV)</th>
</tr>
</thead>
<tbody>
<tr>
<td>5</td>
<td>8</td>
<td>24 or 36</td>
<td>7.2 or 12 or 17.5 or 24</td>
</tr>
<tr>
<td>10</td>
<td>9</td>
<td></td>
<td></td>
</tr>
<tr>
<td>20</td>
<td>11</td>
<td></td>
<td></td>
</tr>
<tr>
<td>25</td>
<td>12</td>
<td></td>
<td></td>
</tr>
<tr>
<td>5</td>
<td>9</td>
<td>72.5</td>
<td>7.2 or 12 or 17.5 or 24</td>
</tr>
<tr>
<td>10</td>
<td>9</td>
<td></td>
<td></td>
</tr>
<tr>
<td>20</td>
<td>9.5</td>
<td></td>
<td></td>
</tr>
<tr>
<td>25</td>
<td>9.5</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

5 - COUPLING

The coupling is a conventional symbol indicating:
- the respective connection modes of the high and low voltage windings,
- The angular gap between the two vectors representing the voltage values between the neutral point (real or ideal) and the corresponding high and low voltage terminals. This phase displacement is expressed by a time index.

<table>
<thead>
<tr>
<th>connection mode</th>
<th>HV symbol</th>
<th>LV symbol</th>
</tr>
</thead>
<tbody>
<tr>
<td>delta</td>
<td>D</td>
<td>d</td>
</tr>
<tr>
<td>star</td>
<td>Y</td>
<td>y</td>
</tr>
<tr>
<td>zig-zag</td>
<td>Z</td>
<td>z</td>
</tr>
<tr>
<td>neutral out</td>
<td>N</td>
<td>n</td>
</tr>
</tbody>
</table>

To give you an example, the most widely used couplings are the following:
- for low powers (25 to 160 kVA): Yzn11 or Dyn11;
- for medium powers (250 kVA to 3150 kVA): Dyn11;
- for high powers: Yyn11, Ydn11 or Dyn11.
Appendix 1: transformer (cont’d)

6 - SWITCHING CURRENT PEAK

When the power is switched on, very high signals or switching peaks are produced.

![Diagram of transient state of the current during no-load transformer switching]

They may be 14 times greater than the rated current. This switching current is very quickly absorbed. The time constant of the damp down depends on the winding resistance and the secondary load. The real values must be requested from the manufacturer.

<table>
<thead>
<tr>
<th>transformer power (kVA)</th>
<th>$n_e$</th>
<th>$I_{e\text{ peak}}/I_{r\text{ rms}}$</th>
<th>time constant (s)</th>
</tr>
</thead>
<tbody>
<tr>
<td>100</td>
<td>14</td>
<td>0.15</td>
<td></td>
</tr>
<tr>
<td>160</td>
<td>12</td>
<td>0.20</td>
<td></td>
</tr>
<tr>
<td>250</td>
<td>12</td>
<td>0.22</td>
<td></td>
</tr>
<tr>
<td>400</td>
<td>12</td>
<td>0.25</td>
<td></td>
</tr>
<tr>
<td>630</td>
<td>11</td>
<td>0.30</td>
<td></td>
</tr>
<tr>
<td>800</td>
<td>10</td>
<td>0.30</td>
<td></td>
</tr>
<tr>
<td>1000</td>
<td>10</td>
<td>0.35</td>
<td></td>
</tr>
<tr>
<td>1250</td>
<td>9</td>
<td>0.35</td>
<td></td>
</tr>
<tr>
<td>1600</td>
<td>9</td>
<td>0.40</td>
<td></td>
</tr>
<tr>
<td>2000</td>
<td>8</td>
<td>0.45</td>
<td></td>
</tr>
<tr>
<td>5000</td>
<td>8</td>
<td>0.50</td>
<td></td>
</tr>
<tr>
<td>10000</td>
<td>8</td>
<td>0.50</td>
<td></td>
</tr>
<tr>
<td>15000</td>
<td>8</td>
<td>0.50</td>
<td></td>
</tr>
<tr>
<td>20000</td>
<td>8</td>
<td>0.50</td>
<td></td>
</tr>
</tbody>
</table>

In the event of low voltage switching, the ratio $n_e$ should be multiplied by 2 and the time constant divided by 1.5 in relation to the values given in the table above.

These switching peaks must be taken into account when the type of protection is defined.

The transformer may have its own optional protective devices.

Depending on the type, the transformer's own protective devices are the following:

- the waterproof protection unit for complete filling transformer: gas leak, pressure and temperature detector.
- Buchholz protection relay for transformer fitted with a conservator: gaz leak and pressure detector.
- thermostat, thermometer for immersed-type transformers: temperature monitoring.
- thermostatic probes for dry-type transformers: temperature control.
Appendix 2: motor

A motor is defined by its mechanical power, its voltage, its insulation level, its starting type (torque, current, time) as well as

1 - RATED POWER

A motor's power is the mechanical power which it develops. We may calculate the rated power by taking the output into account.

The rated power (P in kW) of a motor is equal to:

\[ P = U \cdot \sqrt{3} \cdot I_r \cdot \cos \varphi \cdot \eta \]

- \( U \): phase to phase voltage in V;
- \( I_r \): rated current in Amps;
- \( \cos \varphi \): power factor (generally \( \cos \varphi = 0.92 \));
- \( \eta \): efficiency (generally \( \eta = 0.94 \) is used)

2 - RATED CURRENT

The rated current \( I_r \) is equal to:

\[ I_r = \frac{P}{\sqrt{3} \cdot U \cdot \cos \varphi \cdot \eta} \]

3 - RATED VOLTAGE AND INSULATION LEVEL

The rated voltage must be higher than that of the network as well as its insulation level.

<table>
<thead>
<tr>
<th>rated voltage ( U_r ) (kV)</th>
<th>insulation level</th>
<th>rms kV (50 Hz - 1 mn)</th>
<th>impulse kV (1.2/50 ( \mu )s)</th>
</tr>
</thead>
<tbody>
<tr>
<td>3</td>
<td>2 ( U_r + 1 ) kV *</td>
<td>4 ( U_r + 5 ) kV *</td>
<td></td>
</tr>
<tr>
<td>3.3</td>
<td>2 ( U_r + 1 ) kV *</td>
<td>4 ( U_r + 5 ) kV *</td>
<td></td>
</tr>
<tr>
<td>5</td>
<td>2 ( U_r + 1 ) kV *</td>
<td>4 ( U_r + 5 ) kV *</td>
<td></td>
</tr>
<tr>
<td>6.6</td>
<td>2 ( U_r + 1 ) kV *</td>
<td>4 ( U_r + 5 ) kV *</td>
<td></td>
</tr>
<tr>
<td>10</td>
<td>2 ( U_r + 1 ) kV *</td>
<td>4 ( U_r + 5 ) kV *</td>
<td></td>
</tr>
<tr>
<td>11</td>
<td>2 ( U_r + 1 ) kV *</td>
<td>4 ( U_r + 5 ) kV *</td>
<td></td>
</tr>
</tbody>
</table>

* for modern motors

\( \Rightarrow \) note: the real values should be requested from the manufacturer.
## 4 - DIFFERENT MEDIUM VOLTAGE MOTORS

Alternating current medium voltage motors are situated in the 2 kV to 14 kV and 100 kW to 40 MW ranges. The motors can be classed in 4 families whose main characteristics and applications are given in the table below.

<table>
<thead>
<tr>
<th>Motor Type</th>
<th>Characteristics, Advantages</th>
<th>Drawbacks</th>
<th>Applications</th>
</tr>
</thead>
<tbody>
<tr>
<td>Asynchronous motors with single cage, double cage, or deep slots</td>
<td>Highly robust due to their simple construction</td>
<td>Hardly any on-load speed variation</td>
<td>High quantity of reactive power absorbed with weak load</td>
</tr>
<tr>
<td>Asynchronous motors with widening rotor</td>
<td>Easy optimisation of starting torque or signal</td>
<td>Rotor resistances and rings needing adjustment and maintenance</td>
<td>Power factor usually lower than 0.9</td>
</tr>
<tr>
<td>Synchronous motors</td>
<td>Same technology as alternators</td>
<td>High transient state</td>
<td>Good output and good power factor</td>
</tr>
<tr>
<td>Synchronised asynchronous motors</td>
<td>Mixture of two previous ones: good starting torque and good power factor</td>
<td>Complex starting co-ordination</td>
<td>Tending to disappear</td>
</tr>
</tbody>
</table>

## 5 - DIFFERENT MV ASYNCHRONOUS MOTOR STARTING TYPES

<table>
<thead>
<tr>
<th>Starting Type</th>
<th>Diagram</th>
</tr>
</thead>
<tbody>
<tr>
<td>Direct</td>
<td>![Direct Start Diagram]</td>
</tr>
<tr>
<td>Auto-transformer</td>
<td>![Auto-transformer Diagram]</td>
</tr>
<tr>
<td>Reactance</td>
<td>![Reactance Diagram]</td>
</tr>
<tr>
<td>Rotors</td>
<td>![Rotors Diagram]</td>
</tr>
</tbody>
</table>

## 6 - ASYNCHRONOUS MOTOR CHARACTERISTICS

Direct starting asynchronous motors are the most widely used. The main characteristics influencing motor operation are given in the table opposite.

<table>
<thead>
<tr>
<th>Characteristics</th>
<th>Asynchronous Motor</th>
</tr>
</thead>
<tbody>
<tr>
<td>Voltage</td>
<td>2 kV to 14 kV</td>
</tr>
<tr>
<td>Power</td>
<td>100 kW to 40 MW</td>
</tr>
<tr>
<td>Starting Current</td>
<td>6 to 7 times motor I_n</td>
</tr>
<tr>
<td>No-load Current</td>
<td>= 0.3 times motor I_n</td>
</tr>
<tr>
<td>Starting Current cos φ</td>
<td>0.1 to 0.2</td>
</tr>
<tr>
<td>No-load Current cos φ</td>
<td>= 0.1</td>
</tr>
<tr>
<td>Load Current cos φ</td>
<td>0.7 to 0.9</td>
</tr>
</tbody>
</table>
Appendix 3: capacitor

A capacitor bank is defined by the power, the voltage, the insulation level and the rated current. Depending on the connection mode (single or multi-steps bank), the switching current is an important parameter which must be taken into account.

1 - REACTIVE POWER

The reactive power (Q in kvar or Mvar) of a capacitor bank is equal to:

\[ Q = U_r \cdot 3 \cdot I_c \]  
\[ Q = U_r^2 \cdot C \cdot \omega \]

- \( U_r \): rated voltage of the bank or network voltage of the network (kV)
- \( I_c \): rated current or current absorbed by the capacitor
- \( C \): capacitance
- \( \omega = 2 \cdot \pi \cdot f_{\text{network}} = \text{network pulsation} \)

2 - RATED CURRENT

The rated current \( I_c \) is equal to:

\[ I_c = \frac{Q_c}{\sqrt{3} \cdot U_n} \]

3 - RATED VOLTAGE

The rated voltage must be the same as that of the network as well as its insulation level.

<table>
<thead>
<tr>
<th>rated voltage ( U_r ) (kV)</th>
<th>insulation level</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>rms kV (50 Hz - 1 mn)</td>
</tr>
<tr>
<td>7.2</td>
<td>20</td>
</tr>
<tr>
<td>12</td>
<td>28</td>
</tr>
<tr>
<td>17.5</td>
<td>38</td>
</tr>
<tr>
<td>24</td>
<td>50</td>
</tr>
<tr>
<td>36</td>
<td>70</td>
</tr>
</tbody>
</table>
Appendix 3: capacitor
(cont’d)

4 - SWITCHING CURRENT

The switching current must always be lower than 100 times the rated current of the capacitance. It is generally limited to 10 kA peak by impulse reactors.

The switching current value depends on the type of bank used. It is equal to:

1) for a single bank:

\[
I_e = \frac{1}{\gamma L_0 \cdot C} \cdot \frac{1}{\omega} \cdot \frac{l_c}{\sqrt{2}}
\]

\[
I_e = l_c \cdot \sqrt{2} \cdot \sqrt{S_k \over Q_c}
\]

Where:
- \(I_e\): peak-switching current
- \(C\): capacitance of one tap
- \(L_0\): network short-circuit reactor
- \(S_k\): supply short-circuit power in MVA

\[
S_k = \sqrt{3} \cdot U \cdot I_{sc} \quad \text{with} \quad \frac{U}{\sqrt{3}} = L_0 \cdot \omega \cdot I_{sc} = \frac{U^2}{L_0} \cdot \omega
\]

- \(Q_c\): capacitor bank power in Mvar
- \(\omega = 2 \cdot \pi \cdot f_{network} = \text{network pulsation}\n
2) for a multi-steps bank with \(n\) identical steps:

\[
I_e = l_c \cdot \sqrt{2} \cdot \frac{n + 1}{f_{inherent}} \cdot f_{network}
\]

\[
I_e = \sqrt{2 \over 3} \cdot U \cdot \frac{n}{n + 1} \cdot \sqrt{e_1}
\]

Where:
- \(I_e\): peak-switching current
- \(U\): network phase to phase voltage
- \(n\): number of energized taps
- \(C\): capacitance of one tap
- \(l\): link reactor
- \(\omega = 2 \cdot \pi \cdot f_{network} = \text{network pulsation}\n
\[
f_{inherent} = \frac{1}{2 \cdot \pi \cdot \sqrt{E/C}}
\]
Appendix 4: generator

A generator is defined by its power, its voltage and its internal impedance.

1 - RATED POWER

The rated power ($S$ in kVA or MVA) of a generator is equal to:

$$S_r = U \cdot \sqrt[3]{3} \cdot l_g$$

In large power stations, the power ranges between 500 and 1500 MVA.

2 - RATED CURRENT

The rated current is equal to $I_g = \frac{S_r}{\sqrt[3]{3} \cdot U}$

3 - RATED VOLTAGE

Generator voltage — contrary to distribution network voltage — is not standardised.

There is a variety of rated voltage values for generators.

<table>
<thead>
<tr>
<th>generator power (MVA)</th>
<th>generator rated voltage (kV)</th>
</tr>
</thead>
<tbody>
<tr>
<td>$S_r &lt; 200$</td>
<td>10 and 16</td>
</tr>
<tr>
<td>200 - 400</td>
<td>14 and 21</td>
</tr>
<tr>
<td>400 - 600</td>
<td>16 and 23</td>
</tr>
<tr>
<td>600 - 1000</td>
<td>18 and 26</td>
</tr>
<tr>
<td>$S_r &gt; 1000$</td>
<td>20 and 27</td>
</tr>
</tbody>
</table>

4 - INTERNAL IMPEDANCE

Manufacturers generally specify generator impedance expressed in %.

- the subtransient reactance ($X''_d = 20\%$),
- the transient reactance ($X'_d = 30\%$),
- the earth reactance ($X'_o = 6\%$).

These values will allow us to determine the circuit breaker breaking and making capacities as well as protection setting.

$I_k$: short-circuit current (three-phase) kA  
$S_r$: generator rated power (MVA)  
$U_r$: generator rated voltage (kV)  
$X'_{cc}$: transient reactance expressed in % by the manufacturer.

$$I_k = \frac{S_r}{\sqrt[3]{3} \cdot U_r} \cdot \frac{1}{X'_{cc}} = \frac{45}{\sqrt[3]{3} \cdot 10} \cdot \frac{100}{30} = 8.66 \text{ kA}$$
Appendix 5: cables

The purpose of all cable systems is to allow the transit of electrical energy which implies that in order to determine the system layout, it is necessary to know the following basic data:

- rated voltage,
- laying procedure,
- operating and short-circuit currents,
- conductor type.

1 - RATED VOLTAGE

The rated voltage is defined by three values.

- $U_o$: rms rated power frequency voltage between the phase conductor and the earth or the metal screen.
- $U$: rms rated power frequency voltage between two phase conductors.
- $U_m$: rms maximum power frequency voltage between two phase conductors.

Belted cables have the same phase to phase and phase to earth insulation.

These cables are only used for voltages of 10 kV or less.

These three values are written: $U_o/U (U_m)$ kV

Example:

- individually screened cable: 12/20 (24) kV
- belted cable: 6/6 (7.2) kV

2 - OPERATING AND SHORT-CIRCUIT CURRENT

When calculating the allowable current for a cable, the maximum allowable temperature at the surface of the conductor and screens must be taken into account:

- allowable permanent operating temperature: this depends on the type of cable, its section and how it is laid.
- allowable short-circuit current: the conductor sections (phase fault) and screens (phase-earth fault) must be dimensioned so that the maximum temperatures reached during the fault remain below the allowable short-circuit temperatures.

3 - CABLE-LAYING PROCEDURE

The characteristics of allowable steady operating currents indicated by the manufacturer correspond to specific ambient temperatures and cable-laying conditions which are taken as a reference.

The ambient temperatures are sometimes higher and the links are often laid so that they heat each other or cool down with greater difficulty.

So that the allowable temperatures of the cable constituents are respected, the currents must be adjusted in accordance with the installation conditions.
Appendix 5: cables
(cont'd)

**4 - TYPE OF CONDUCTOR**

A cable is comprised of either one conductor, or several electrically distinct and mechanically united conductors.

The different types of cables insulated by extruded solid dielectrics are:
- single-pole individually screened cables,
- individually screened three-pole cables,
- belted three-pole cables.

The metal part of the conductor is defined by:
- the type of metal: annealed electrolytic copper or 3/4 hard or sometimes annealed aluminium,
- electric resistance per unit of length (R in ohm/km),
- self-induction coefficient (L in H/km) which depends essentially on the geometrical size and the relative disposition of the conductors,
- the rated section (mm$^2$),
- the cables capacitance.

**5 - MV CABLES CAPACITANCE**

The capacitance of a cable depends on the construction type:
- **single-pole cables**: the conductor is surrounded by a screen and the cable capacitance $C$ is that measured between the conductor and the screen which is earthed.
- **individually screened three-pole cables**: each conductor is surrounded by a screen and the cable capacitance is that measured between each conductor and its individual screen which is earthed.
- **belted three-pole cables**: a screen surrounds the three conductors and there is a capacitance $K$ between conductors and a capacitance $C$ between a conductor and the screen which is earthed.

The capacitive current $I_c$ of a network in the event of an earth fault is:

$$I_c = 3 C \cdot V$$

which causes capacitance $C$ only to intervene whatever the cable type.

In practice, for a star-connected capacitance, the cable makers indicate:
- the value $C$ for individually screened cables.
- the value $3 K + C$ for belted cables.

Upon request, the cable maker will tell you the capacitance $C_2$ ($C_2 = 3 C$) measured between the three inter-connected conductors and the metal sleeve.
Appendix 6: alternating current melting arc furnaces

1 - MELTING PROCESS

Arc furnace operating principle
The standard processing cycle of an arc furnace comprises a series of operations including scrap metal loading, melting, liquid steel refining and casting.

- scrap metal loading and intermediary loading is carried out when the furnace is stopped. For a single processing cycle, two or three basket loads are required.
- scrap metal melting during which the solid load is liquefied and the main part of the energy is consumed.
- liquid bath refining which only requires thermal loss compensation.
- liquid steel casting in ladles involves the furnace tipping so that the liquid metal is poured from the furnace into the ladles and the time needed for the furnace to return to its original position.

The scrap metal melting period is characterised by:
- frequent arcing and arc suppression at the beginning of each basket,
- strong current variations caused by arc displacement during the melting period,
- short-circuits, generated by the metal as it collapses.

2 - OPERATING FREQUENCY

The number of casts per day depends on the type of furnace.
- furnace with refining in the furnace: 13 casts per day.
- furnace with refining in the ladle furnace: 22 casts per day.
Appendix 6: alternating current melting arc furnaces (cont’d)

3 - ELECTRICAL POWER SUPPLY

The power supply must be channelled from the HV (with step-down transformer) or on the factory distribution network. The power available varies from 10 to 100 MVA with voltage values ranging from 15 to 40 kV.

The furnace switch controls all devices downstream of the transformer.

For an average of 13 casts per day the switchgear carries out:
- ≈ 8 operations per cast.
- ≈ 100 operations per day.
- ≈ 30,000 operations per year.

The furnace transformer, located next to the furnace, allows intermediate voltage (15 to 40 kV) to pass to the low voltage used by the furnace (800 to 1000 V).
Appendix 7: diode and thyristor applications

The transformer’s type coupling determines the choice of the breaking device.

In a diode or thyristor application, the shape of the load current which goes through the contactor or the circuit breaker located upstream of the MV/LV transformer is greatly deformed. It depends on the transformer’s type of rectifier bridge and coupling.

1 - SWITCHGEAR TO BE USED

We have to consider two types of feeding:

- **the feeding transformer has the same primary and secondary coupling.**
  The primary and secondary currents have the same shape.

![Diagram of current shapes](image)

All our devices can interrupt this type of current because the current passes through zero during long periods owing to the switching cycle.

- **no specific recommendations**

- **the feeding transformer has a different coupling on the primary and the secondary.**
The primary current is shaped as a stair with a high value of the \( \frac{d}{dt} \) when the current reaches the zero

![Diagram of current shapes](image)

- **if the rectifier bridge is with diodes and if the number of operations is acceptable, the vaccum technology or the SF6 auto-expansion (LF) are OK.**

- **if the rectifier bridge is with thyristors:**
  - the puffer technology (SF) can be used without any particular precautions.
  - the rotating arc technology (LF or Rollarc) can be used if any tripping commands are accompanied by a thyristor locking command.
Appendix 7: diode and thyristor applications (cont’d)

The corresponding relay must be positively safe and the device’s opening information should be taken directly from its auxiliary contacts (opening contact) and relayed as directly as possible to the thyristor trigger operating device.

In this case, the arc is maintained in the device as long as the $\frac{d}{d_1}$ is higher than the given values.

The vacuum technology allows the breaking in every cases.
Appendix 8: fused switch-disconnector or fused contactor

This is a good association if the switchgear breaking capacity is higher than the rated breaking current of the fuse \( I_3 \) and if the fuse is able to withstand the load current

\[ I_{load} < \frac{I_{fuse}}{2} \]

1 - SWITCHGEAR CHARACTERISTICS

The fused contactor co-ordination imposes two parameters on the contactor which are:

- the maximum fault current that it is likely to break, taking into account the presence of the fuses.
- the electrodynamic withstands of the contactor without fuses and with fuses which depend on the prospective short-circuit current value and the fuse rating.

The figure below illustrates the fused contactor association.

Example of characteristics required of contactor when protection is provided by an interior Fusarc type fuse (250 A/7.2 kV) installed on a 6.6 kV network with a prospective short-circuit current of 50 rms kA.

- A device that withstands 25 peak kA without a fuse could, if it had a fuse, withstand a fuse peak current of over 35 peak kA without being destroyed. In fact, contact repulsion takes place above 25 peak kA but the destructive effect is linked to the thermal constraint which is relatively weak in the case of fuses intervening in less than 10 ms.

The fuse must not be required to intervene in \( I_r \) to \( I_3 \) range. The network short-circuit current is at the most equal to the \( I_1 \) of the fuse used. Rated voltage fuses matching the network voltage must be used.
Appendix 8: fused switch-disconnector or fused contactor (cont’d)

2 - DEVICE FUNCTIONS

Each associated element ensures different and complementary functions.

The role of the switch or contactor is to:
- make or break the load current,
- break fault currents which are not high enough to melt the fuse,
- cause three-phase tripping as a result of fuse breaking.

The role of the fuse is to:
- break short-circuit currents,
- limit switching currents (in the event of a fault circuit being produced),
- steadily withstand the load current without excessive overheating depending on the installation and/or operating conditions.