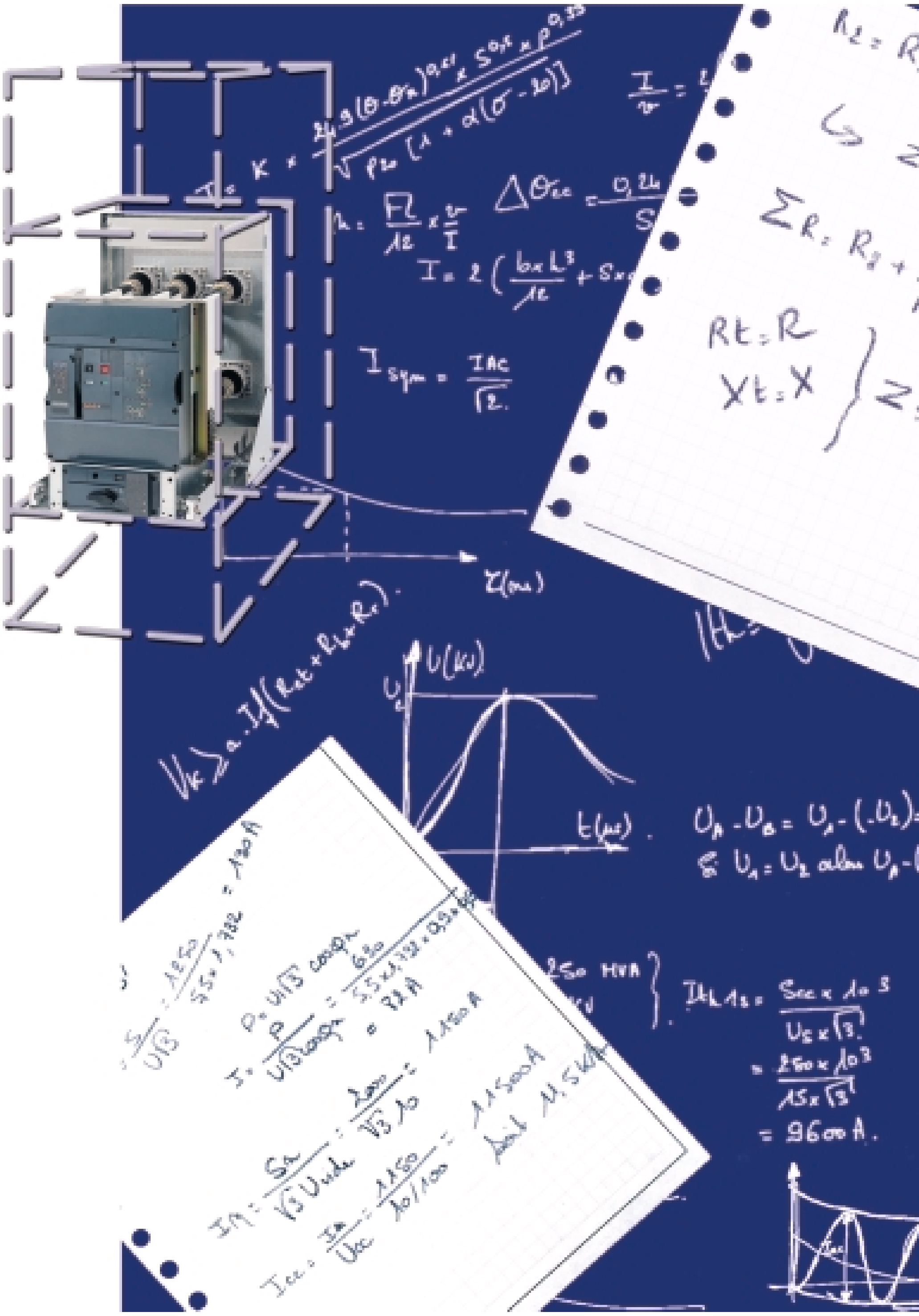
Merlin Gerin technical guide
Medium Voltage

MV design guide



Merlin Gerin
Modicon
Square D
Telemecanique

Schneider Electric
We do more with electricity.

Design Guide

This guide is a catalogue of technical know-how intended for medium voltage equipment designers.

Goal

- Presenting and assisting in the selection of MV equipment in conformity with standards.
- Providing design rules used to calculate the dimensions or ratings of an MV switchboard.

How?

- By proposing simple and clear calculation outlines to guide the designer step by step.
- By showing actual calculation examples.
- By providing information on units of measure and international standards.
- By comparing international standards.

In summary

This guide helps you to carry out the calculations required to define and determine equipment dimensions and provides useful information enabling you to design your MV switchboard.

General contents

MV design guide

Metal-enclosed, factory-built equipment

*To start with,
here is some key
information on MV switchboards!
reference is made to the International
Electrotechnical Commission
(IEC).*

Introduction

In order to design a medium-voltage cubicle, you need to know the following basic magnitudes:

- **Voltage**
- **Current**
- **Frequency**
- **Short-circuit power.**

The voltage, the rated current and the rated frequency are often known or can easily be defined, but how can we calculate the short-circuit power or current at a given point in an installation?

Knowing the short-circuit power of the network allows us to choose the various parts of a switchboard which must withstand significant temperature rises and electrodynamic constraints. Knowing the voltage (kV) will allow us to define the dielectric withstand of the components.
E.g.: circuit breakers, insulators, CT.

Disconnection, control and protection of electrical networks is achieved by using switchgear.

- Metal enclosed switchgear is sub-divided into three types:
  - metal-clad
  - compartmented
  - block.

Metal-enclosed, factory-built equipment

Voltage

Operating voltage U (kV)

This is applied across the equipment terminals.

Rated voltage U_r (kV)

Previously known as nominal voltage, this is the maximum rms. (root mean square) value of the voltage that the equipment can withstand under normal operating conditions.
The rated voltage is always greater than the operating voltage and, is associated with an insulation level.

Insulation level U_d (kV rms. 1 mn) and U_p (kV peak)

This defines the dielectric withstand of equipment to switching operation overvoltages and lightning impulse.

■ **U_d**: overvoltages of internal origin, accompany all changes in the circuit: opening or closing a circuit, breakdown or shorting across an insulator, etc…
It is simulated in a laboratory by the rated power-frequency withstand voltage
for one minute.

■ **U_p**: overvoltages of external origin or atmospheric origin occur when lightning falls on or near a line. The voltage wave that results is simulated in a laboratory and is called the rated lightning impulse withstand voltage.

N.B.: *IEC 694, article 4 sets the various voltage values together with, in article 6, the dielectric testing conditions.*

Example:

- *Operating voltage: 20 kV*
- *Rated voltage: 24 kV*
- *Power frequency withstand voltage 50 Hz 1 mn: 50 kV rms.*
- *Impulse withstand voltage 1.2/50 µs: 125 kV peak.*

Metal-enclosed, factory-built equipment

Standards

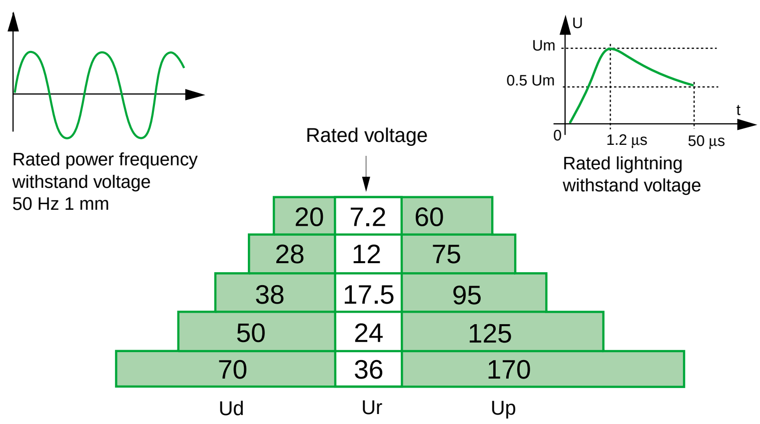
Apart from special cases, MERLIN GERIN equipment is in conformity with list 2 of the series 1 table in IEC 60 071 and 60 298.

Rated voltage kV rms.	**Rated lightning impulse withstand voltage 1.2/50 µs 50 Hz kV peak**		**Rated power-frequency withstand voltage 1 minute kV rms.**	**Normal operating voltage kV rms.**
	list 1	**list 2**		
7.2	40	60	20	3.3 to 6.6
12	60	75	28	10 to 11
17.5	75	95	38	13.8 to 15
24	95	125	50	20 to 22
36	145	170	70	25.8 to 36

Insulation levels apply to metal-enclosed switchgear at altitudes of less than 1 000 metres, 20°C, 11 g/m^3 humidity and a pressure of 1 013 mbar. Above this, derating should be considered.
Each insulation level corresponds to a distance in air which guarantees equipment withstand without a test certificate.

Rated voltage kV rms.	**Rated impulse withstand voltage 1.2/50 µs kV peak**	**Distance/earth in air cm**
7.2	60	10
12	75	12
17.5	95	16
24	125	22
36	170	32

IEC standardised voltages



Metal-enclosed, factory-built equipment

Current

Rated normal current: I_r (A)

This is the rms. value of current that equipment can withstand when closed, without exceeding the temperature rise allowed in standards.
The table below gives the temperature rises authorised by the IEC according to the type of contacts.

Rated normal current:

Type of mechanism of material	Max. values	
	Max. temperature of conductor (°C)	**Max. temp. rise = t°. max. - 40 °C**
contacts in air		
bare copper or copper alloy	75	35
silver or nickel plated	105	65
tin-plated	90	50
bolted connections or equivalent devices		
bare copper, bare copper alloy or aluminium alloy	90	50
silver or nickel plated	115	75
tin-plated	105	65

__N.B.:__ rated currents usually used by Merlin Gerin are: 400, 630, 1 250, 2 500 and 3 150 A.

Operating current: I (A)

This is calculated from the consumption of the devices connected to the circuit in question. It is the current that really passes through the equipment.
If we do not have the information to calculate it, the customer has to provide us with its value. The operating current can be calculated when we know the power of the current consumers.

Examples:

■ *For a switchboard with a 630 kW motor feeder and a 1 250 kVA transformer feeder at 5.5 kV operating voltage.*

□ ***calculating the operating current of the transformer feeder:***

Apparent power:

$$S = UI\sqrt{3}$$

$$I = \frac{S}{U\sqrt{3}} = \frac{1\ 250}{5{,}5 \cdot 1{,}732} = 130\ A$$

□ ***calculating the operating current of the motor feeder:***

cosφ = power factor = 0.9

η = motor efficiency = 0.9

$$I = \frac{P}{U\sqrt{3}\cos\varphi\eta} = \frac{630}{5.5 \cdot 1.732 \cdot 0.9 \cdot 0.9} = 82\ A$$

Metal-enclosed, factory-built equipment

Minimal short-circuit current: Isc (kA rms.)

(see explanation in "Short-circuit currents" chapter.)

Rms value of maximal short-circuit current: I_{th} (kA rms. 1 s or 3 s)

(see explanation in "Short-circuit currents" chapter.)

Peak value of maximal short-circuit: I_{dyn} (kA peak)

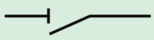
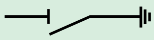
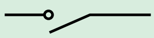
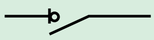
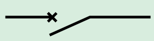
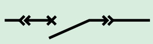
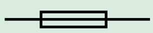
(value of the initial peak in the transient period)

(see explanation in "Short-circuit currents" chapter.)

Frequency fr (Hz)

■ Two frequencies are usually used throughout the world:
□ 50 Hz in Europe
□ 60 Hz in America.
Several countries use both frequencies indiscriminately.

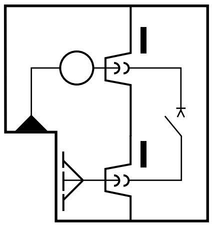
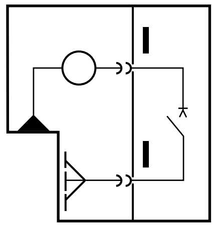
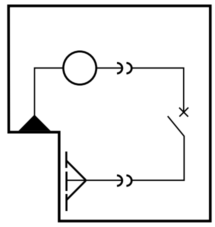
Switchgear functions

Designation and symbol	function	Current switching	
		operating	fault
Disconnecter 	isolates		
Earthing disconnecter 	isolates		(short-circuit closing capacity)
Switch 	switches, does not isolate	✔	
Disconnecter switch 	switches isolates	✔	
Fixed circuit breaker 	switches protects does not isolate	✔	✔
Withdrawable circuit breaker 	switches protects isolates if withdrawn	✔	✔
Fixed contactor 	switches does not isolate	✔	
Withdrawable contactor 	switches isolates if withdrawn	✔	
Fuse 	protects does not isolate		✔ (once)

✔ = YES

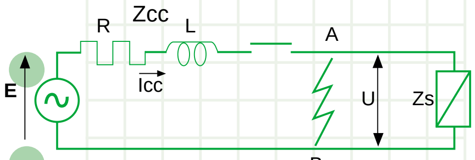
Metal-enclosed, factory-built equipment

Different enclosure types

Characteristics	Metal-clad	Compartment	Block-type
Cubicles			
External walls	metal and always earthed		
Number of MV compartments	≥ 3	3	≤ 2
Internal partitions	metal and always earthed	indifferent metal or not	indifferent metal or not
Presence of bushings	✔	possible	
Shutters to prevent access to live compartments	✔	✔	
Ease of operations when live	✔	✔	
Arcing movement within the cubicle	difficult, but always possible	✔	✔

✔ = YES

Example 1:
25 kA at an operating voltage of 11 kV



$S_{sc} = \sqrt{3} \cdot U \cdot I_{sc}$

Introduction

■ The short-circuit power depends directly on the network configuration and the impedance of its components:
lines, cables, transformers, motors... through which the short-circuit current passes.

■ It is the maximum power that the network can provide to an installation during a fault, expressed in MVA or in kA rms for a given operating voltage.

U	:	operating voltage (kV)
Isc	:	short-circuit current (kA rms.) Ref: following pages

The short-circuit power can be assimilated to an apparent power.

■ The customer generally imposes the value of short-circuit power on us because we rarely have the information required to calculate it.
Determination of the short-circuit power requires analysis of the power flows feeding the short-circuit in the worst possible case.

Possible sources are:

■ Network incomer via power transformers.

■ Generator incomer.

■ Power feedback due to rotary sets (motors, etc); or via MV/LV transformaters.

Example 2:

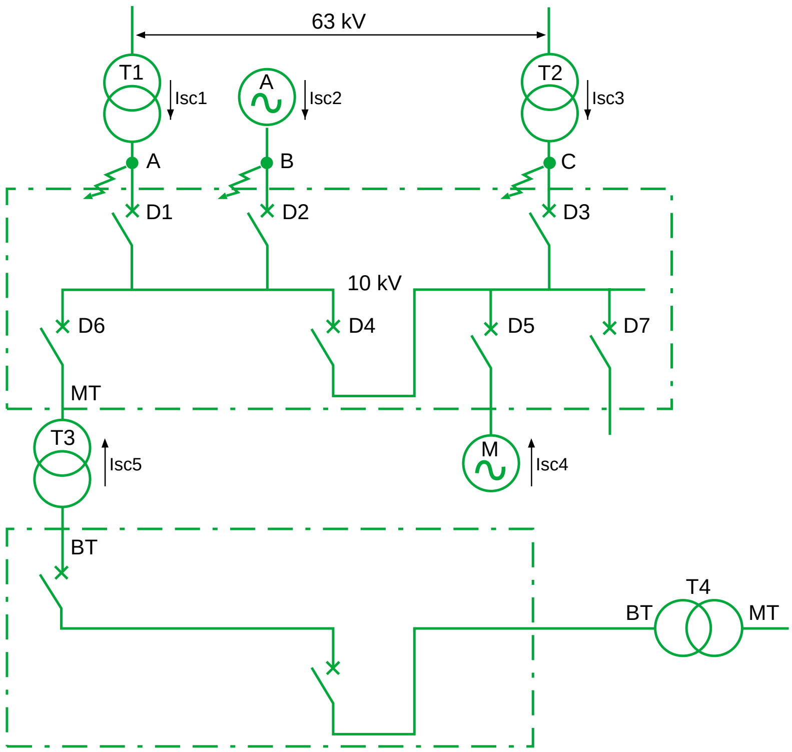
■ *Feedback via LV Isc5 is only possible if the transformer (T4) is powered by another source.*

■ *Three sources are flowing in the switchboard (T1-A-T2)*

□ ***circuit breaker D1*** *(s/c at A)*
Isc1 + Isc2 + Isc3 + Isc4 + Isc5

□ ***circuit breaker D2*** *(c/c at B)*
Isc1 + Isc2 + Isc3 + Isc4 + Isc5

□ ***circuit breaker D3*** *(c/c at C)*
Isc1 + Isc2 + Isc3 + Isc4 + Isc5



We have to calculate each of the Isc currents.

Short-circuit currents

All electrical installations have to be protected against short-circuits, without exception, whenever there is an electrical discontinuity; which more generally corresponds to a change in conductor cross-section.
The short-circuit current must be calculated at each stage in the installation for the various configurations that are possible within the network; this is in order to determine the characteristics that the equipment has to have withstand or break this fault current.

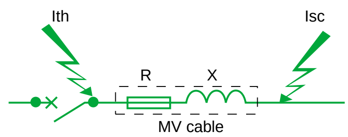


figure 1

■ In order to choose the right switchgear (circuit breakers or fuses) and set the protection functions, three short-circuit values must be known:

□ **minimal short-circuit current:**

I_{sc} = (kA rms) *(example: 25 kA rms)*

This corresponds to a short-circuit at one end of the protected link (fault at the end of a feeder (see fig.1)) and not just behind the breaking mechanism. Its value allows us to choose the setting of thresholds for overcurrent protection devices and fuses; especially when the length of cables is high and/or when the source is relatively impedant (generator, UPS).

□ **rms value of maximal short-circuit current:**

I_{th} = (kA rms. 1 s or 3 s) *(example: 25 kA rms. 1 s)*

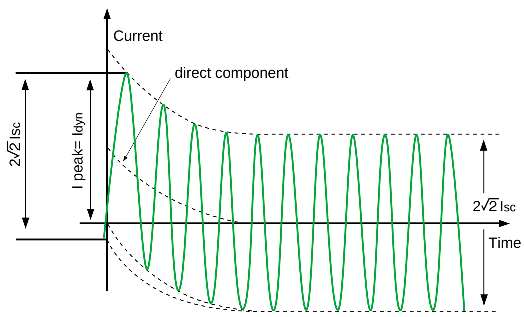
This corresponds to a short-circuit in the immediate vicinity of the upstream terminals of the switching device (see fig.1). It is defined in kA for 1 or 3 second(s) and is used to define the thermal withstand of the equipment.

□ **peak value of the maximum short-circuit current:**
(value of the **initial peak** in the transient period)

I_{dyn} = (kA peak)
(example: 2.5 • 25 kA = 63.75 kA peak IEC 60 056 or 2.7 • 25 kA = 67.5 kA peak ANSI)

- **I_{dyn}** is equal to:

2.5 • Isc at 50 Hz (IEC) or,
2.6 • Isc at 60 Hz (IEC) or,
2.7 • Isc (ANSI) times the **short-circuit current calculated at a given point in the network.**



It determines the breaking capacity and closing capacity of circuit breakers and switches, as well as the electrodynamic withstand of busbars and switchgear.

- **The IEC** uses the following values:
8 - 12.5 - 16 - 20 - 25 - 31.5 - 40 kA rms.
These are generally used in the specifications.

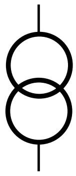
N.B.:
■ *A specification may give one value in kA rms and one value in MVA as below:*
Isc = 19 kA rms or 350 MVA at 10 kV
□ *if we calculate the equivalent current at 350 MVA we find:*

$$I_{sc} = \frac{350}{\sqrt{3} \cdot 10} = 20.2 \text{ kA rms}$$

The difference lies in the way in which we round up the value and in local habits.
The value 19 kA rms is probably the most realistic.
□ *another explanation is possible: in medium and high voltage, IEC 909 applies a coefficient of 1.1 when calculating maximal Isc.*

$$I_{sc} = 1{,}1 \cdot \frac{U}{\sqrt{3} \cdot Z_{cc}} = \frac{E}{Z_{cc}}$$

(Cf: example 1, p 12 Introduction).
This coefficient of 1.1 takes account of a voltage drop of 10 % across the faulty installation (cables, etc).

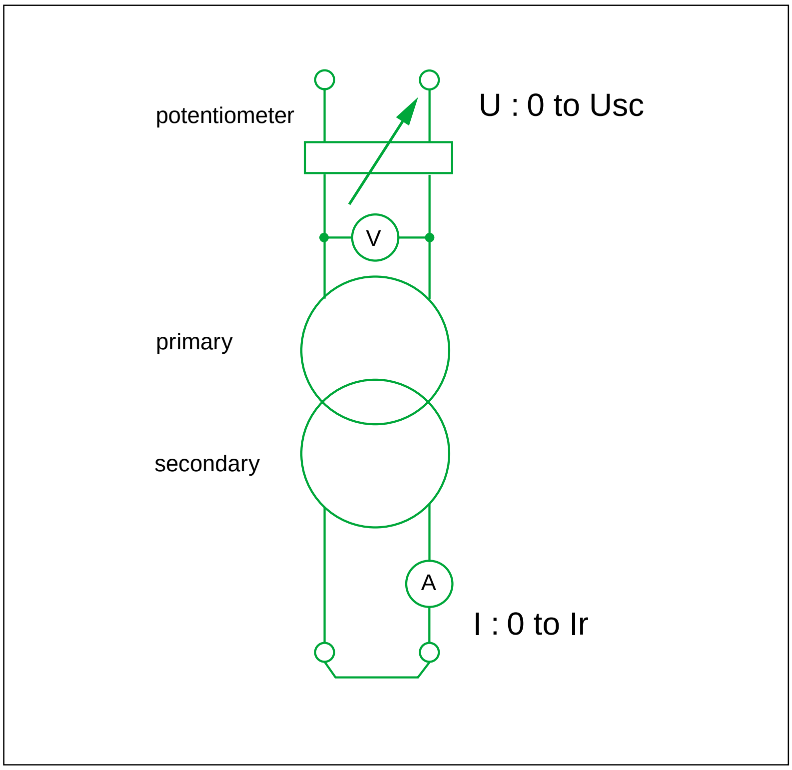


Transformer

In order to determine the short-circuit current across the terminals of a transformer, we need to know the short-circuit voltage (Usc %).

The short-circuit current depends on the type of equipment installed on the network (transformers, generators, motors, lines, etc).

■ U_{sc} % is defined in the following way:



❶ the voltage transformer is not powered: U = 0
❷ **place** the secondary in short-circuit
❸ gradually **increase** voltage U at the primary up to the rated current Ir in the transformer secondary circuit.

The value U read across the primary is then equal to U_{sc}

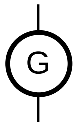
■ The short-circuit current, expressed in kA, is given by the following equation:

$$I_{sc} = \frac{I_r}{U_{sc}}$$

Example:
■ *Transformer 20 MVA*
■ *Voltage 10 kV*
■ *Usc = 10 %*
■ *Upstream power: infinite*

$$Ir = \frac{Sr}{\sqrt{3}\ U\ _{no\text{-}load}} = \frac{20\ 000}{\sqrt{3} \cdot 10} = 1\ 150\ A$$

$$Isc = \frac{Ir}{Usc} = \frac{1\ 150}{10 \div 100} = 11\ 500\ A = 11.5\ kA$$



Synchronous generators (alternators and motors)

Calculating the short-circuit current across the terminals of a synchronous generator is very complicated because the internal impedance of the latter varies according to time.

■ When the power gradually increases, the current reduces passing through three characteristic periods:

□ **sub-transient** (enabling determination of the closing capacity of circuit breakers and electrodynamic contraints), average duration, 10 ms

□ **transient** (sets the equipment's thermal contraints), average duration 250 ms

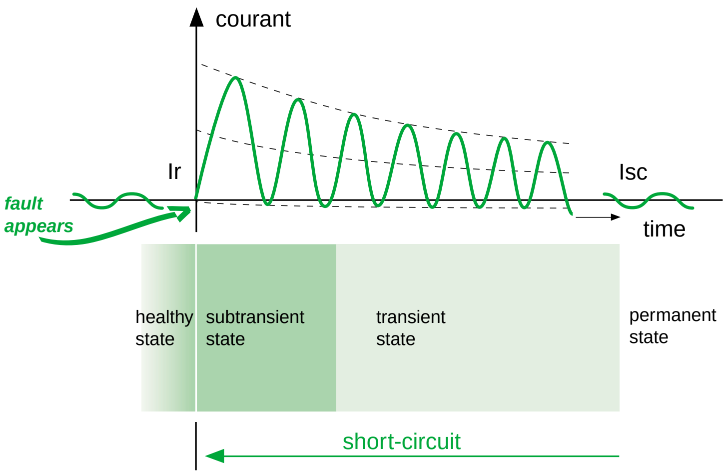
□ **permanent** (this is the value of the short-circuit current in steady state).

■ The short-circuit current is calculated in the same way as for transformers but the different states must be taken account of.

Example:
Calculation method for an alternator or a synchronous motor
■ *Alternator 15 MVA*
■ *Voltage U = 10 kV*
■ *X'd = 20 %*

$$Ir = \frac{Sr}{\sqrt{3} \cdot U} = \frac{15}{\sqrt{3} \cdot 10\,000} = 870\,A$$

$$Isc = \frac{Ir}{Xcc\ trans.} = \frac{870}{20/100} = 4\,350\,A = 4.35\,kA$$



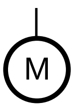
■ The short-circuit current is given by the following equation:

$$I_{sc} = \frac{I_r}{X_{sc}}$$

X_{sc}	:	short-circuit reactance c/c

■ The most common values for a synchronous generator are:

State	Sub-transient X"d	Transient X'd	Permanent Xd
Xsc	10 - 20 %	15 - 25 %	200 - 350 %



Asynchronous motor

■ **For asynchronous motors**

□ the short-circuit current across the terminals equals the start-up current

$$I_{sc} \simeq 5 \text{ at } 8\ I_r$$

□ the contribution of the motors (current feedback) to the short-circuit current is equal to:

$$I \simeq 3 \sum I_r$$

The coefficient of 3, takes account of motors when stopped and the impedance to go right through to the fault.

Reminder concerning the calculation of three-phase short-circuit currents

■ Three-phase short-circuit

$$S_{sc} = 1.1 \cdot U \cdot I_{sc} \cdot \sqrt{3} = \frac{U^2}{Z_{sc}}$$

$$I_{sc} = \frac{1.1 \cdot U}{\sqrt{3} \cdot Z_{sc}} \quad \text{with} \quad Z_{sc} = \sqrt{R^2 + X^2}$$

■ Upstream network

$$Z = \frac{U^2}{S_{sc}} \qquad \frac{R}{X} = \begin{cases} 0.3 \text{ at } 6 \text{ kV} \\ 0.2 \text{ at } 20 \text{ kV} \\ 0.1 \text{ at } 150 \text{ kV} \end{cases}$$

■ Overhead lines

$$R = \rho \cdot \frac{L}{S}$$

X = 0.4 Ω/km	HV
X = 0.3 Ω/km	MV/LV
$\rho = 1.8.10^{-6}$ Ω cm	copper
$\rho = 2.8.10^{-6}$ Ω cm	aluminium
$\rho = 3.3.10^{-6}$ Ω cm	almélec

■ Synchronous generators

$$Z_{(\Omega)} = X_{(\Omega)} = \frac{U^2}{S_r} \cdot \frac{X_{sc\,(\%)}}{100}$$

X_{sc}	sub-transient	transient	permanent
turbo	10 to 20 %	15 to 25 %	200 to 350 %
exposed poles	15 to 25 %	25 to 35 %	70 to 120 %

■ Transformers

(order of magnitude: for real values, refer to data given by manufacturer)

E.g.: 20 kV/410 V; Sr = 630 kVA; U_{sc} = 4 %
63 kV/11 V; Sr = 10 MVA; U_{sc} = 9 %

$$Z_{(\Omega)} = \frac{U^2}{S_r} \cdot \frac{U_{sc(\%)}}{100}$$

Sr (kVA)	100 to 3150	5000 to 5000
U_{sc} (%)	4 to 7.5	8 to 12
	MV/LV	HV/MV

■ Cables

X = 0.10 at 0.15 Ω/km
three-phased or single-phased

■ Busbars

X = 0.15 Ω/km

Short-circuit currents

■ Synchronous motors and compensators

X_{sc}	Sub-transient	transient	permanent
high speed motors	15 %	25 %	80 %
low speed motors	35 %	50 %	100 %
compensators	25 %	40 %	160 %

■ Asynchronous motors only sub-transient

$$Z(\Omega) = \frac{I_r}{I_d} \bullet \frac{U^2}{S_r}$$

$I_{sc} \simeq$ 5 to 8 I_r

$I_{sc} \simeq 3 \sum I_r$,

contribution to I_{sc} by current feedback (with I rated = Ir)

■ Fault arcing

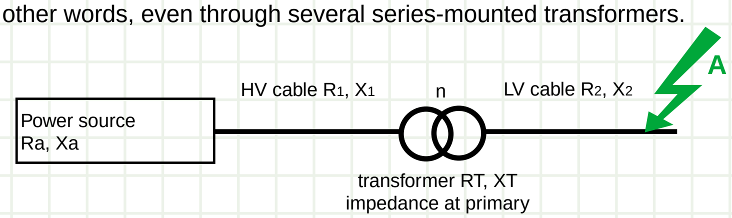
$$I_d = \frac{I_{sc}}{1.3 \text{ to } 2}$$

■ Equivalent impedance of a component through a transformer

□ for example, for a low voltage fault, the contribution of an HV cable upstream of an HV/LV transformer will be:

$$R_2 = R_1\left(\frac{U_2}{U_1}\right)^2 \text{ et } X_2 = X_1\left(\frac{U_2}{U_1}\right)^2 \quad \text{ainsi} \quad Z_2 = Z_1\left(\frac{U_2}{U_1}\right)^2$$

This equation is valid for all voltage levels in the cable, in other words, even through several series-mounted transformers.



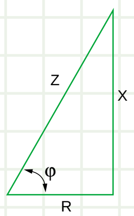
□ Impedance seen from the fault location A:

$$\sum R = R_2 + \frac{R_T}{n^2} + \frac{R_1}{n^2} + \frac{R_a}{n^2} \qquad \sum X = X_2 + \frac{X_T}{n^2} + \frac{X_1}{n^2} + \frac{X_a}{n^2}$$

***n**: transformation ratio*

■ Triangle of impedances

$$Z = \sqrt{(R^2 + X^2)}$$



The complexity in calculating the three-phase short-circuit current basically lies in determining the impedance value in the network upstream of the fault location.

Example of a three-phase calculation

Impedance method

All the components of a network (supply network, transformer, alternator, motors, cables, bars, etc) are characterised by an impedance (Z) comprising a resistive component (R) and an inductive component (X) or so-called reactance. X, R and Z are expressed in ohms.

■ The relation between these different values is given by:

$$Z = \sqrt{(R^2 + X^2)}$$

(cf. example 1 opposite)

■ **The method involves:**
□ breaking down the network into sections
□ calculating the values of R and X for each component
□ calculating for the network:
- the equivalent value of R or X
- the equivalent value of impedance
- the short-circuit current.

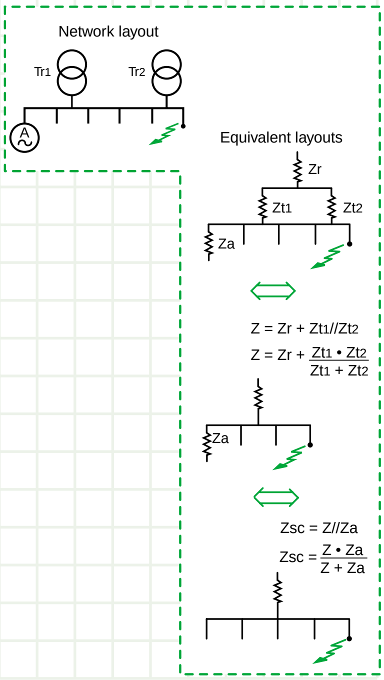
■ **The three-phase short-circuit current is:**

$$I_{sc} = \frac{U}{\sqrt{3} \cdot Z_{sc}}$$

Isc	:	short-circuit current (in kA)
U	:	phase to phase voltage at the point in question before the appearance of the fault, in kV.
Zsc	:	short-circuit impedance (in ohms)

(cf. example 2 below)

Example 1:



Example 2:

■ $Z_{sc} = 0.72$ ohm

■ $U = 10$ kV

$$I_{sc} = \frac{10}{\sqrt{3} \cdot 0{,}27} = 21.38 \text{ kA}$$

Short-circuit currents

Here is a problem
to solve!

Exercice data

Supply at 63 kV
Short-circuit power of the source: 2 000 MVA

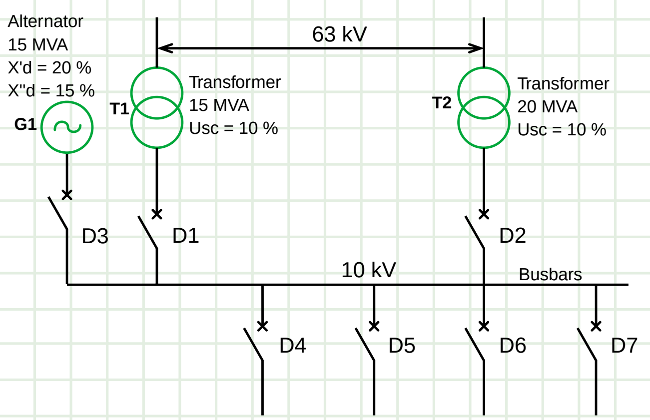
■ ***Network configuration:***
Two parallel mounted transformers and an alternator.

■ ***Equipment characteristics:***
□ *transformers:*
- *voltage 63 kV / 10 kV*
- *apparent power: 1 to 15 MVA, 1 to 20 MVA*
- *short-circuit voltage: U_{sc} = 10 %*

□ *Alternator :*
- *voltage: 10 kV*
- *apparent power: 15 MVA*
- *X'd transient: 20 %*
- *X"d sub-transient: 15 %*

■ ***Question:***
□ *determine the value of short-circuit current at the busbars,*
□ *the breaking and closing capacities of the circuit breakers D1 to D7.*

Single line diagram



Here is the solution to the problem with the calculation method

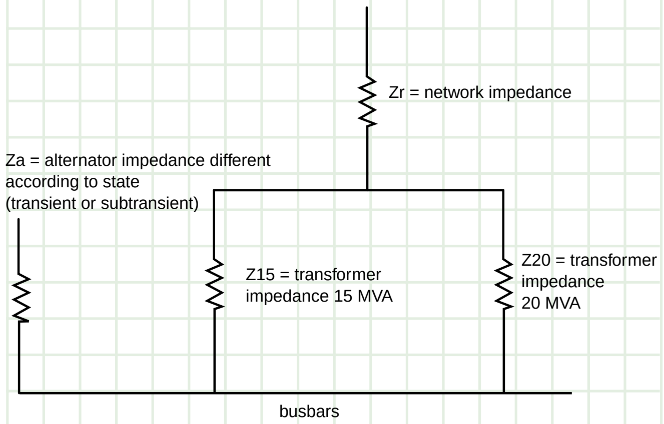
Solving the exercise

■ ***Determining the various short-circuit currents***

The three sources which could supply power to the short-circuit are the two transformers and the alternator.
We are supposing that there can be no feedback of power through D4, D5, D6 and D7.
In the case of a short-circuit upstream of a circuit breaker (D1, D2, D3, D4, D5, D6, D7), this then has the short-circuit current flow through it supplied by T1, T2 and G1.

■ ***Equivalent diagram***

Each component comprises a resistance and an inductance.
We have to calculate the values for each component.
The network can be shown as follows:



Experience shows that the resistance is generally low compared with, reactance, so we can therefore deduce that the reactance is equal to the impedance (X = Z).

■ *To determine the short-circuit power, we have to calculate the various values of resistances and inductances, then separately calculate the arithmetic sum:*

$$Rt = R$$

$$Xt = X$$

■ *Knowing Rt and Xt, we can deduce the value of Zt by applying the equation:*

$$Z = \sqrt{(\Sigma R^2 + \Sigma X^2)}$$

N.B.: *Since R is negligible compared with X, we can say that Z = X.*

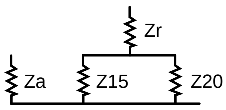
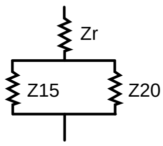
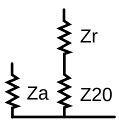
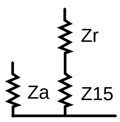
Short-circuit currents

And now here are the results!

Component	Calculation	Z = X (ohms)
Network Ssc = 2 000 MVA U op. = 10 kV	$Zr = \frac{U^2}{Ssc} = \frac{10^2}{2\ 000}$	0.05
15 MVA transformer (Usc = 10 %) U op. = 10 kV	$Z15 = \frac{U^2}{Sr} \cdot Usc = \frac{10^2}{15} \cdot \frac{10}{100}$	0.67
20 MVA transformer (Usc = 10 %) U op. = 10 kV	$Z20 = \frac{U^2}{Sr} \cdot Usc = \frac{10^2}{20} \cdot \frac{10}{100}$	0.5
15 MVA alternator U op. = 10 kV	$Za = \frac{U^2}{Sr} \cdot Xsc$	
Transient state (Xsc = 20 %)	$Zat = \frac{10^2}{15} \cdot \frac{20}{100}$	Zat = 1.33
Sub-transient state (Xsc = 15 %)	$Zas = \frac{10^2}{15} \cdot \frac{15}{100}$	Zas = 1
Busbars Parallel-mounted with the transformers	$Z15//Z20 = \frac{Z15 \cdot Z20}{Z15 + Z20} = \frac{0.67 \cdot 0.5}{0.67 + 0.5}$	Zet = 0.29
Series-mounted with the network and the transformer impedance	$Zr + Zet = 0.05 + 0.29$	Zer = 0.34
Parallel-mounting of the generator set Transient state	$Zer//Zat = \frac{Zer \cdot Zat}{Zer + Zat} = \frac{0.34 \cdot 1.33}{0.34 + 1.33}$	$\simeq$ 0.27
Sub-transient state	$Zer//Zat = \frac{Zer \cdot Zat}{Zer + Zat} = \frac{0.34 \cdot 1}{0.34 + 1}$	$\simeq$ 0.25

N.B.: a circuit breaker is defined for a certain breaking capacity of an rms value in a steady state, and as a percentage of the aperiodic component which depends on the circuit breaker's opening time and on $\frac{R}{X}$ of the network (about 30 %).

For alternators the aperiodic component is very high; the calculations must be validated by laboratory tests.

Circuit breaker	Equivalent circuit Z (ohm)	Breaking capacity in kA rms. $Icc = \frac{U^2}{\sqrt{3} \cdot Zsc} = \frac{10}{\sqrt{3}} \cdot \frac{1}{Zsc}$	Closing capacity 2.5 I_{sc} (in kA peak)
D4 to D7  Zt = [Zr + (Z15//Z20)]//Za	transient state Z = 0.27 sub-transient state Z = 0.25	**21.40**	21.40 • 2.5 = **53.15**
D3 alternator  Zt = Zr + (Z15//Z20)	Z = 0.34	**17**	17 • 2.5 = **42.5**
D1 15 MVA transformer  Zt = (Zr + Z20)//Za	transient state Z = 0.39 sub-transient state Z = 0.35	**17.9**	14.9 • 2.5 = **37.25**
D2 20 MVA transformer  Zt = (Zr + Z15)//Za	transient state Z = 0.47 sub-transient state Z = 0.42	**12.4**	12.4 • 2.5 = **31**

Busbar calculation

In reality, a busbar calculation involves checking that it provides sufficient thermal and electrodynamic withstand and non-resonance.

Introduction

■ The dimensions of busbars are determined taking account of **normal operating conditions**.
The voltage (kV) that the installation operates at determines the phase to phase and phase to earth distance and also determines the height and shape of the supports.
The rated current flowing through the busbars is used to determine the cross-section and type of conductors.

■ We then ensure that the supports (insulators) resist the **mechanical effects** and that the bars resist the **mechanical and thermal effects** due to short-circuit currents.
We also have to check that the period of vibration intrinsic to the bars themselves is not **resonant** with the current period.

■ To carry out a busbar calculation, we have to use the following physical and electrical characteristics assumptions:

Busbar electrical characteristics

Ssc	:	network short-circuit power*		**MVA**
Ur	:	rated voltage		**kV**
U	:	operating voltage		**kV**
I_r	:	rated current		**A**

*** N.B.:** It is is generally provided by the customer in this form or we can calculate it having the short-circuit current Isc and the operating voltage U: ($Ssc = \sqrt{3} \cdot Isc \cdot U$; see chapter on "Short-circuit currents").*

Physical busbar characteristics

S	:	busbar cross section		**cm^2**
d	:	phase to phase distance		**cm**
l	:	distance between insulators for same phase		**cm**
θ_n	:	ambient temperature ($\theta n \leq 40°C$)		**°C**
($\theta - \theta_n$)	:	permissible temperature rise*		**°C**

profile	**:**	flat ☐	
material	**:**	copper ☐	aluminium ☐
arrangement	**:**	flat-mounted ☐	edge-mounted ☐

no. of bar(s) per phase : ______

*** N.B.:** see table V in standard ICE 60 694 on the 2 following pages.*

In summary:
______ bar(s) of ______ x ______ cm per phase

Temperature rise

Taken from table V of standard IEC 60 694

Type of device, of material and of dielectric (Cf: 1, 2 and 3)	Temperature θ (°C)	$(\theta - \theta_n)$ with θ_n = 40°C
Bolt connected or equivalent devices (Cf: 7)		
bare copper, bare copper alloy or aluminium alloy in		
air	90	50
SF6 *	105	65
oil	100	60
silver or nickel plated in		
air	115	75
SF6	115	75
oil	100	60
tin-plated in		
air	105	65
SF6	105	65
oil	100	60

** SF6 (sulphur hexafluoride)*

1 According to its function, the same device may belong to several categories given in table V. In this case, the admissible values of temperature and temperature rise to take into consideration are the lowest for category concerned.

2 For vacuum switchgear, the limit values of temperature and temperature rise do not apply to vacuum devices. Other devices must not exceed the values for temperature and temperature rise given in table V.

3 All the necessary precautions must be taken so that absolutely no damage is caused to surrounding materials.

7 When contact components are protected in different ways, the temperature and temperature rises that are allowed are those for the element for which table V authorises the highest values.

Temperature rise

Extract from table V of standard IEC 60 694

Type of device, of material and of dielectric (Cf: 1, 2 and 3)	**Temperature** θ (°C)	**(θ - θ_n)** with θ_n = 40°C
Contacts (Cf: 4)		
copper or bare copper alloy in		
air	75	35
SF6 *	90	50
oil	80	40
silver or nickel plated (Cf: 5) in		
air	105	65
SF6	105	65
oil	90	50
tin-plated (Cf: 5 and 6) in		
air	90	50
SF6	90	50
oil	90	50

***** SF6 (sulphur hexafluoride)

1 According to its function, the same device may belong to several categories given in table V. In this case, the admissible values of temperature and temperature rise to take into consideration are the lowest for category concerned.

2 For vacuum switchgear, the limit values of temperature and temperature rise do not apply to vacuum devices. Other devices must not exceed the values for temperature and temperature rise given in table V.

3 All the necessary precautions must be taken so that absolutely no damage is caused to surrounding materials.

4 When the contact components are protected in different manners, the temperatures and temperature rises that are allowed are those of the element for which table V authorises the lowest values.

5 The quality of coating must be such that a protective layer remains in the contact zone:
- after the making and breaking test (if it exists),
- after the short time withstand current test,
- after the mechanical endurance test,

according to specifications specific to each piece of equipment. Should this not be true, the contacts must be considered as "bare".

6 For fuse contacts, the temperature rise must be in conformity with publications concerning high voltage fuses.

Let's check if the cross-section that has been chosen:
… bar(s) of … x … cm per phase
satisfies the temperature rises produced by the rated current and by the short-circuit current passing through them for 1 to 3 second(s).

Thermal withstand…

For the rated current (I_r)

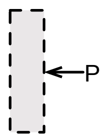
The MELSON & BOTH equation published in the "Copper Development Association" review allows us to define the permissible current in a conductor:

$$I = K \cdot \frac{24.9\,(\theta - \theta_n)^{0.61} \cdot S^{0.5} \cdot p^{0.39}}{\sqrt{\rho_{20}\,[1+ \alpha\,(\theta - 20)]}}$$

with:

I	:	permissible current expressed in amperes (A) *derating in terms of current should be considered:* *- for an ambient temperature greater than 40°C* *- for a protection index greater than IP5*		
θ_n	:	ambient temperature ($\theta_n \le 40°C$)		**°C**
$(\theta - \theta_n)$	:	permissible temperature rise*		**°C**
S	:	busbar cross section		**cm^2**
p	:	busbar perimeter *(opposite diagram)*		**cm**
ρ_{20}	:	conductor resistivity at 20°C		
	:	copper:	1.83 µΩ cm	
	:	aluminium:	2.90 µΩ cm	
α	:	temperature coefficient of the resistivity: 0.004		
K	:	conditions coefficient *product of 6 coefficients (k1, k2, k3, k4, k5, k6), described below*		

(see table V of standard IEC 60 694 in the previous pages)

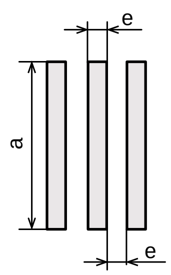


perimeter of a bar

Definition of coefficients k1, 2, 3, 4, 5, 6:

■ **Coefficient k1** is a function of the number of bar strips per phase for:
□ 1 bar (k1 = 1)
□ 2 or 3 bars, see table below:

	e/a								
	0.05	0.06	0.08	0.10	0.12	0.14	0.16	0.18	0.20
no. of bars per phase				k1					
2	1.63	1.73	1.76	1.80	1.83	1.85	1.87	1.89	1.91
3	2.40	2.45	2.50	2.55	2.60	2.63	2.65	2.68	2.70



In our case:

e/a =
the number of bars per phase =
giving k1 =

■ **Coefficient k2** is a function of surface condition of the busbars:

□ bare:	k2 = 1
□ painted:	k2 = 1.15

■ **Coefficient k3** is a function of the position of the bars:

□ edge-mounted bars:	k3 = 1
□ 1 bar base-mounted:	k3 = 0.95
□ several base-mounted bars:	k3 = 0.75

■ **Coefficient k4** is a function of the place where the bars are installed:

□ calm indoor atmosphere :	k4 = 1
□ calm outdoor atmosphere:	k4 = 1.2
□ bars in non-ventilated ducting:	k4 = 0.80

■ **Coefficient k5** is a function of the artificial ventilation:

□ without artificial ventilation: k5 = 1

□ ventilation should be dealt with on a case by case basis and then validated by testing.

■ **Coefficient k6** is a function of the type of current:

□ for a alternatif current of frequency ≤ 60 Hz, k6 is a function of the number of bars **n** per phase and of their spacing.

The value of k6 for a spacing equal to the thickness of the bars:

n	1	2	3
k6	1	1	0.98

In our case:

n = ______ **giving k6 =** ______

In fact we have:

k = ______ • ______ • ______ • ______ • ______ • ______ = ______

$$I = \_\_\_\_ \cdot \frac{24.9\,(\_\_\_\_ - \_\_\_\_)^{0.61} \cdot \_\_\_\_^{0.5} \cdot \_\_\_\_^{0.39}}{\sqrt{\_\_\_\_\,[1+ 0.004\,(\_\_\_\_ - 20)]}}$$

$$I = K \cdot \frac{24.9\,(\theta - \theta_n)^{0.61} \cdot S^{0.5} \cdot p^{0.39}}{\sqrt{\rho_{20}\,[1+ \alpha\,(\theta - 20)]}}$$

I = ______ **A**

The chosen solution ______ bar(s)

of ______ • ______ cm per phase

Is appropriate if I_r of the required busbars ≤ I

For the short-time withstand current (I_{th})

■ We assume that for the whole duration (1 or 3 seconds):
□ all the heat that is given off is used to increase the temperature of the conductor
□ radiation effects are negligible.

The equation below can be used to calculate the short-circuit temperature rise:

$$\Delta\theta_{cc} = \frac{0.24 \bullet \rho_{20} \bullet I_{th}^2 \bullet t_k}{(n \bullet S)^2 \bullet c \bullet \delta}$$

with:

$\Delta\theta_{sc}$	:	short-circuit temperature rise		
c	:	specific heat of the metal copper: aluminium:	 0.091 kcal/daN°C 0.23 kcal/daN °C	
S	:	busbar cross section		cm^2
n	:	number of busbar(s) per phase		
I_{th}	:	is the short-time withstand current: (maximum short-circuit current, rms value)		A rms
t_k	:	short-time withstand current duration (1 to 3 s)		in s
δ	:	density of the metal copper: aluminium:	 8.9 g/cm^3 2.7 g/cm^3	
ρ_{20}	:	resistivity of the conductor at 20°C copper: aluminium:	 1.83 μΩ cm 2.90 μΩ cm	
$(\theta - \theta_n)$	:	permissible temperature rise		°C

$$\Delta\theta_{sc} = \frac{0.24 \bullet \square\ 10^{-6} \bullet (\square)^2 \bullet \square}{(\square)^2 \bullet \square \bullet \square}$$

$\Delta\theta_{sc}$ = ☐ °C

The temperature, θ_t of the conductor after the short-circuit will be:

$$\theta_t = \theta_n + (\theta - \theta_n) + \Delta\theta_{sc}$$

θ_t = ☐ °C

Example:
How can we find the value of Ith for a different duration?
Knowing: $(Ith)^2 \bullet t$ = constant

■ ***If Ith_2 = 26.16 kA rms. 2 s, what does Ith_1 correspond to for t = 1 s?***

$(Ith_2)^2 \bullet t$ = constant
$(26.16 \bullet 10^3)^2 \bullet 2 = 137 \bullet 10^7$

so $Ith_1 = \sqrt{\left(\frac{constant}{t}\right)} = \sqrt{\left(\frac{137 \bullet 10^7}{1}\right)}$

Ith_1 = 37 kA rms. for 1 s

■ ***In summary:***

□ *at 26.16 kA rms. 2 s, it corresponds to 37 kA rms. 1 s*

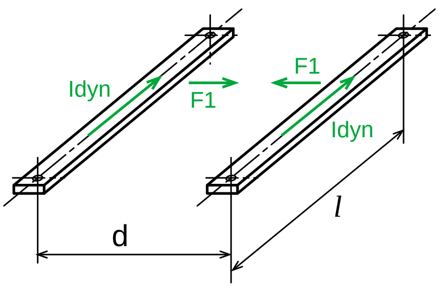
□ *at 37 kA rms. 1 s, it corresponds to 26.16 kA rms. 2 s*

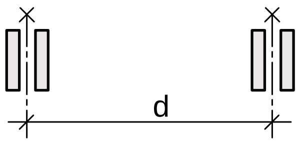
Check:

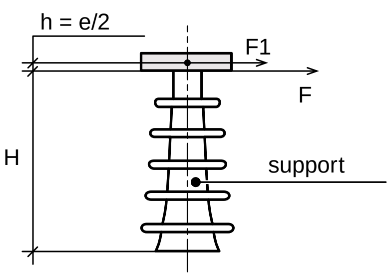
$\theta_t \leq$ maximum admissible temperature by the parts in contact with the busbars.

Check that this temperature θ_t is compatible with the maximum temperature of the parts in contact with the busbars (especially the insulator).

We have to check if the bars chosen withstand the electrodynamic forces.







Electrodynamic withstand

Forces between parallel-mounted conductors

The electrodynamic forces following a short-circuit current are given by the equation:

$$F_1 = 2\frac{l}{d} \bullet I_{dyn}^2 \bullet 10^{-8}$$

with

F_1	:	force expressed in daN
I_{dyn}	:	is the peak value of short-circuit expressed in A, to be calculated with the equation below:

$$I_{dyn} = k \bullet \frac{S_{sc}}{U\sqrt{3}} = k \bullet I_{th}$$

S_{sc}	:	short-circuit power		kVA
I_{th}	:	short-time withstand current		A rms
U	:	operating voltage		kV
l	:	distance between insulators on the same phase		cm
d	:	phase to phase distance		cm
k	:	2.5 for 50 Hz ; 2.6 for 60 Hz for IEC and 2.7 according to ANSI		

Giving : I_{dyn} = ______ A and F_1 = ______ daN

Forces at the head of supports or busducts

Equation to calculate the forces on a support:

$$F = F_1 \bullet \frac{H + h}{H}$$

with

F	:	force expressed		daN
H	:	insulator height		cm
h	:	distance from insulator head to busbar centre of gravity		cm

Calculation of forces if there are N supports

■ The force **F** absorbed by each support is at most equal to the calculated force **F_1** (see previous chapter) multiplied by a coefficient **k_n** which varies according to the total number **N** of equidistant supports that are installed.

□ number of supports ______ **= N**

□ we know **N**, let us define **k_n** with the help of the table below:

giving F = ______ (F1)• ______ (k_n) = ______ **daN**

N	2	3	4	≥ 5
k_n	0.5	1.25	1.10	1.14

■ The force found after applying a coefficient **k** should be compared with the mechanical strength of the support to which we will apply a safety coefficient:

□ the supports used have a bending resistance

F' = ______ **daN**

check if F' > F

□ we have a safety coefficient of

$\frac{F'}{F}$ = ______

Busbar calculation

Mechanical busbar strength

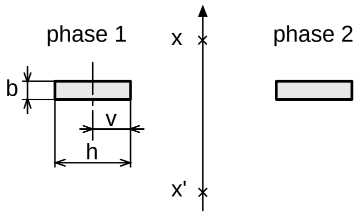
■ By making the assumption that the ends of the bars are sealed, they are subjected to a bending moment whose resultant strain is:

$$\eta = \frac{F_1 \cdot l}{12} \cdot \frac{v}{I}$$

with

η	:	is the resultant strain, it must be **less than** the **permissible strain** for the bars this is: copper 1/4 hard: 1 200 daN/cm^2 copper 1/2 hard: 2 300 daN/cm^2 copper 4/4 hard: 3 000 daN/cm^2 tin-plated alu: 1 200 daN/cm^2		
F_1	:	force between conductors		**daN**
l	:	distance between insulators in the same phase		**cm**
I/v	:	is the modulus of inertia between a bar or a set of bars *(choose the value in the table on the following page)*		**cm^3**
v	:	distance between the fibre that is neutral and the fibre with the highest strain (the furthest)		

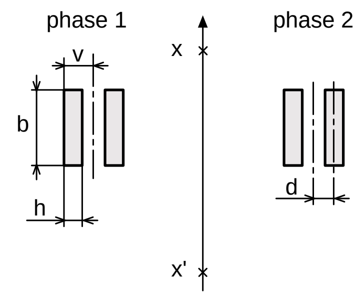
■ **One bar per phase:**



$$I = \frac{b \cdot h^3}{12}$$

$$\frac{I}{v} = \frac{b \cdot h^2}{6}$$

■ **Two bars per phase:**



xx': perpendicular to the plane of vibration

$$I = 2\left(\frac{b \cdot h^3}{12} + S \cdot d^2\right)$$

$$\frac{I}{v} = \frac{2\left(\frac{b \cdot h^3}{12} + S \cdot d^2\right)}{1.5 \cdot h}$$

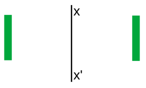
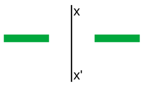
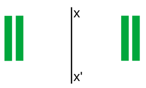
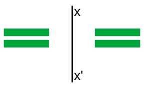
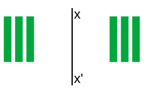
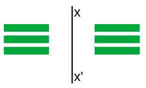
S	**:**	busbar cross section (in cm^2)

Check:

η ______ < η Bars Cu or Al ______ (in daN/cm^2)

Busbar calculation

Choose your cross-section **S**, linear mass **m**, modulus of inertia **I/v**, moment of inertia **I** for the bars defined below:

Arrangement*			Busbar dimensions (mm)								
			100 x 10	**80 x 10**	**80 x 6**	**80 x 5**	**80 x 3**	**50 x 10**	**50 x 8**	**50 x 6**	**50 x 5**
	S	cm^2	10	8	4.8	4	2,4	5	4	3	2.5
	m	Cu	0.089	0.071	0.043	0.036	0.021	0.044	0.036	0.027	0.022
	daN/cm	A5/L	0.027	0.022	0.013	0.011	0.006	0.014	0.011	0.008	0.007
	I	cm^4	0.83	0.66	0.144	0.083	0.018	0.416	0.213	0.09	0.05
	I/v	cm^3	1.66	1.33	0.48	0.33	0.12	0.83	0.53	0.3	0.2
	I	cm^4	83.33	42.66	25.6	21.33	12.8	10.41	8.33	6.25	5.2
	I/v	cm^3	16.66	10.66	6.4	5.33	3.2	4.16	3.33	2.5	2.08
	I	cm^4	21.66	17.33	3.74	2.16	0.47	10.83	5.54	2.34	1.35
	I/v	cm^3	14.45	11.55	4.16	2.88	1.04	7.22	4.62	2.6	1.8
	I	cm^4	166.66	85.33	51.2	42.66	25.6	20.83	16.66	12.5	10.41
	I/v	cm^3	33.33	21.33	12.8	10.66	6.4	8.33	6.66	5	4.16
	I	cm^4	82.5	66	14.25	8.25	1.78	41.25	21.12	8.91	5.16
	I/v	cm^3	33	26.4	9.5	6.6	2.38	16.5	10.56	5.94	4.13
	I	cm^4	250	128	76.8	64	38.4	31.25	25	18.75	15.62
	I/v	cm^3	50	32	19.2	16	9.6	12.5	10	7.5	6.25

***arrangement:** cross-section in a perpendicular plane to the busbars (2 phases are shown)*

Intrinsic resonant frequency

The intrinsic frequencies **to avoid** for the busbars subjected to a 50 Hz current are frequencies of around 50 and 100 Hz.
This intrinsic frequency is given by the equation:

$$f = 112 \sqrt{\frac{E \cdot I}{m \cdot l^4}}$$

Check that the chosen busbars will not resonate.

f	:	resonant frequency in Hz
E	:	modulus of elasticity: for copper = $1.3 \cdot 10^6$ daN/cm^2 for aluminium A5/L = $0.67 \cdot 10^6$ daN/cm^2
m	:	linear mass of the busbar (choose the value on the table above) .... **daN/cm**
l	:	length between 2 supports or busducts .... **cm**
I	:	moment of inertia of the busbar cross-section relative to the axis x'x, perpendicular to the vibrating plane .... **cm^4**

(see formula previously explained or choose the value in the table above)

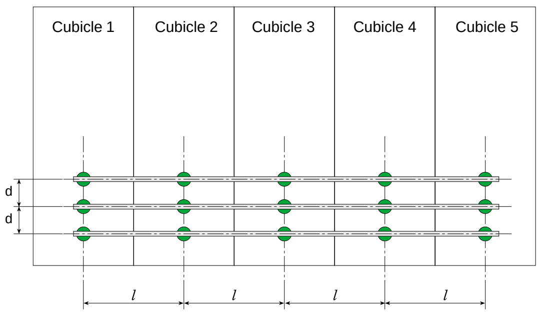
giving **f =** .... **Hz**

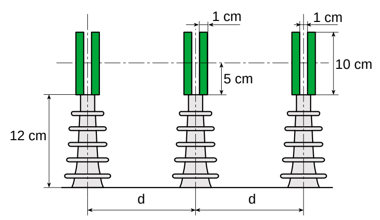
We **must check** that this frequency is outside of the values that must be avoided, in other words between 42 and 58 and 80 and 115 Hz.

Busbar calculation example

Here is a busbar calculation to check.

Top view





Exercise data

■ *Consider a switchboard comprised of at least 5 MV cubicles. Each cubicle has 3 insulators (1 per phase). Busbars comprising 2 bars per phase, inter-connect the cubicles electrically.*

Busbar characteristics to check:

S	:	busbar cross-section (10 •1)	*10*	**cm²**
d	:	phase to phase distance	*18*	**cm**
l	:	distance between insulators on the same phase	*70*	**cm**
θ_n	:	ambient temperature	*40*	**°C**
(θ - θ_n)	:	permissible **temperature rise** (90-40=50)	*50*	**°C**
profile	:	flat		
material	:	busbars in copper 1/4 hard, with a permissible strain η = 1 200 daN/cm²		
arrangement	:	edge-mounted		
number of busbar(s) per phase:			*2*	

■ *The busbars must be able to withstand a rated current* ***I_r = 2,500 A*** *on a permanent basis and a short-time withstand current* ***I_{th} = 31,500 A rms.*** *for a time of* ***t_k = 3 seconds.***

■ *Rated frequency* ***f_r = 50 Hz***

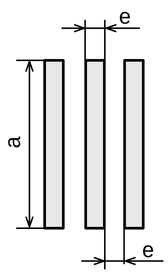
■ *Other characteristics:*

❑ *parts in contact with the busbars can withstand a maximum temperature of* ***θ_{max} = 100°C***

❑ *the supports used have a bending resistance of* ***F' = 1 000 daN***

Busbar calculation

Let's check the thermal withstand of the busbars!



For the rated current (I_r)

The MELSON & BOTH equation allows us to define the permissible current in the conductor:

$$I = K \cdot \frac{24.9\,(\theta - \theta_n)^{0.61} \cdot S^{0.5} \cdot p^{0.39}}{\sqrt{\rho_{20}\,[1 + \alpha\,(\theta - 20)]}}$$

with:

I	:	permissible current expressed in amperes (A)		
θ_n	:	ambient temperature	*40*	°C
($\theta - \theta_n$)	:	permissible temperature rise*	*50*	°C
S	:	busbar cross-section	*10*	cm²
p	:	busbar perimeter	*22*	cm
ρ_{20}	:	resistivity of the conductor at 20°C		
		copper:	*1.83 μΩcm*	
α	:	temperature coefficient for the resistivity:	*0.004*	
K	:	condition coefficient *product of 6 coefficients (k1, k2, k3, k4, k5, k6), described below*		

**(see table V in standard CEI 60 694 pages 22 and 23)*

Definition of coefficients k1, 2, 3, 4, 5, 6:

■ **Coefficient k1** is a function of the number of bar strips per phase for:
- □ 1 bar (k1 = 1)
- □ 2 or 3 bars, see table below:

	e / a								
	0.05	0.06	0.08	0.10	0.12	0.14	0.16	0.18	0.20
number of bars per phase	**k1**								
2	1.63	1.73	1.76	1.80	1.83	1.85	1.87	1.89	1.91
3	2.40	2.45	2.50	2.55	2.60	2.63	2.65	2.68	2.70

In our case:

e/a =	*0.1*
number of bars per phase =	*2*
giving k1 =	*1.80*

■ **Coefficient k2** is a function of the surface condition of the bars:
- bare: k2 = *1*
- painted: k2 = 1.15

■ **Coefficient k3** is a function of the busbar position:
- edge-mounted busbars: k3 = *1*
- 1 bar flat-mounted: k3 = 0.95
- several flat-mounted bars: k3 = 0.75

■ **Coefficient k4** is a function of where the bars are installed:
- calm indoor atmosphere: k4 = 1
- calm outdoor atmosphere: k4 = 1.2
- bars in non-ventilated ducting: k4 = *0.80*

■ **Coefficient k5** is a function of the artificial ventilation:
- without artificial ventilation: k5 = *1*
- cases with ventilation must be treated on a case by case basis and then validated by testing.

■ **Coefficient k6** is a function of the type of current:
- for alternatif current at a frequency of 60 Hz, k6 is a function of the number of busbars **n** per phase and of their spacing.

The value of k6 for a spacing equal to the thickness of the busbars:

n	1	*2*	3
k6	1	*1*	0.98

In our case:

n = *2* **giving k6 =** *1*

In fact, we have:

k = *1.80* • *1* • *1* • *0.8* • *1* • *1* = *1.44*

$$I = 1.44 \bullet \frac{24.9\,(90 - 40)^{0.61} \bullet 10^{0.5} \bullet 22^{0.39}}{\sqrt{1.83\,[1 + 0.004\,(90 - 20)]}}$$

$$I = K \bullet \frac{24.9\,(\theta - \theta_n)^{0.61} \bullet S^{0.5} \bullet p^{0.39}}{\sqrt{\rho_{20}\,[1 + \alpha\,(\theta - 20)]}}$$

I = *2 689* **A**

The chosen solution: *2* *busbars of* *10 • 1* *cm per phase is appropriate:*

I_r < I *either* ***2 500 A < 2 689 A***

For the short-time withstand current (I_{th})

■ we assume that, for the whole duration (3 seconds) :
□ all the heat given off is used to increase the temperature of the conductor
□ the effect of radiation is negligible.

The equation below can be used to calculate the temperature rise due to short-circuit:

$$\Delta\theta_{cc} = \frac{0.24 \cdot \rho_{20} \cdot I_{th}^2 \cdot t_k}{(n \cdot S)^2 \cdot c \cdot \delta}$$

with:

c	:	specific heat of the metal *copper:*	*0.091 kcal/daN°C*	
S	:	is the cross section expressed in cm^2	*10*	**cm^2**
n	:	number of bars per phase	*2*	
I_{th}	:	is the short-time withstand current *(rms. value of the maximum short-circuit current)*	*31 500*	**A rms.**
t_k	:	short-time withstand current duration (1 to 3 secs)	*3*	**in secs**
δ	:	density of the metal *copper:*	*8.9 g/cm³*	
ρ_{20}	:	resistivity of the conductor at 20°C *copper:*	*1.83 µΩ cm*	
(θ - θ_n)	:	permissible temperature rise	*50*	**°C**

□ The temperature rise due to the short circuit is:

$$\Delta\theta_{cc} = \frac{0.24 \cdot 1.83 \; 10^{-6} \cdot (31\,500)^2 \cdot 3}{(2 \cdot 10)^2 \cdot 0.091 \cdot 8.9}$$

$\Delta\theta_{cc}$ = *4* °C

The temperature θ_t of the conductor after short-circuit will be:

$$\theta_t = \theta_n + (\theta - \theta_n) + \Delta\theta_{cc}$$
$$= 40 + 50 + 4$$
$$= 94 \text{ °C}$$

for I = *2 689* A *(see calculation in the previous pages)*

Calculation of θ_t must be looked at in more detail because the required busbars have to withstand Ir = 2 500 A at most and not 2 689 A.

■ ***Let us fine tune the calculation for θ_t for Ir = 2 500 A***
(rated current for the busbars)

□ *the MELSON & BOTH equation (cf: page 31), allows us to deduce the following:*

$$I = constant \cdot (\theta - \theta n)^{0.61} \text{ et}$$

$$Ir = constant \cdot (\Delta\theta)^{0.61}$$

$$\text{therefore } \frac{I}{Ir} = \left(\frac{(\theta - \theta n)}{(\Delta\theta)}\right)^{0.61}$$

$$\frac{2\,689}{2\,500} = \left(\frac{50}{(\Delta\theta)}\right)^{0.61}$$

$$\frac{50}{\Delta\theta} = \left(\frac{2\,689}{2\,500}\right)^{\frac{1}{0.61}}$$

$$\frac{50}{\Delta\theta} = 1.126$$

$$\boxed{\Delta\theta = 44.3\ °C}$$

□ *temperature θ_t of the conductor after short-circuit, for a rated current Ir = 2 500 A is:*

$$\theta_t = \theta_n + \Delta\theta + \Delta\theta_{cc}$$

$$= \boxed{40} + \boxed{44.3} + \boxed{4}$$

$$= \boxed{88.3}\ °C \text{ for } Ir = 2\,500\ A$$

The busbars chosen are suitable because:

$$\boxed{\theta_t = 88.3\ °C \text{ is less than } \theta max = 100\ °C}$$

(θmax = maximum temperature that can be withstood by the parts in contact with the busbars).

Let's check the electrodynamic withstand of the busbars.

Forces between parallel-mounted conductors

Electrodynamc forces due to the short-circuit current are given by the equation:

$$F_1 = 2 \frac{l}{d} \cdot I_{dyn}^2 \cdot 10^{-8}$$

(see drawing 1 at the start of the calculation example)

l	:	distance between insulators in the same phase	70	cm
d	:	phase to phase distance	18	cm
k	:	2.5 for 50 Hz according to IEC		
I_{dyn}	:	peak value of short-circuit current = k • I_{th} = 2.5 • 31 500 = 78 750 A		

F1 = 2 • (70/18) • 78 750^2 • 10^{-8} = 482.3 daN

Forces at the head of the supports or busducts

Equation to calculate forces on a support :

$$F = F_1 \cdot \frac{H + h}{H}$$

with

F	:	force expressed in daN		
H	:	insulator height	12	cm
h	:	distance from the head of the insulator to the busbar centre of gravity	5	cm

Calculating a force if there are N supports

■ The force **F** absorbed by each support is at most equal to the force **F1** that is calulated multiplied by a coefficient **kn** which varies according to the total number **N** of equi-distant supports that are installed.

□ number of supports ≥ 5 = **N**

□ we know **N**, let us define **kn** using the table below:

N	2	3	4	≥ 5
kn	0.5	1.25	1.10	1.14

giving F = 683 (F1)• 1.14 (kn) = 778 daN

The supports used have a bending resistance
F' = 1 000 daN calculated force F = 778 daN.

The solution is OK

Busbar calculation

Mechanical strength of the busbars

Assuming that the ends of the bars are sealed, they are subjected to a bending moment whose resultant strain is:

$$\eta = \frac{F_1 \cdot l}{12} \cdot \frac{v}{I}$$

with

η	:	is the **resultant strain in daN/cm²**	
l	:	distance between insulators in the same phase	*70* cm
I/v	:	is the modulus of inertia of a busbar or of a set of busbars *(value chosen in the table below)*	*14.45* cm³

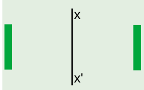
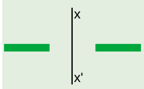
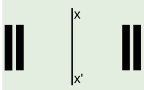
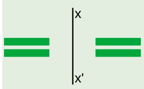
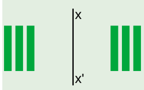
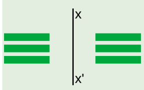
$$\eta = \frac{482.3 \cdot 70}{12} \cdot \frac{1}{14.45}$$

$$\eta = 195 \ daN/cm^2$$

*The calculated resultant strain (**η = 195 daN / cm²**) is less than the permissible strain for the copper busbars 1/4 hard (**1200 daN / cm²**) :*

The solution is OK

Busbar dimensions (mm)

Arrangement			100 x 10
	S	cm²	***10***
	m	Cu	***0.089***
	daN/cm	A5/L	0.027
	I	cm⁴	0,83
	I/v	cm³	1.66
	I	cm⁴	83.33
	I/v	cm³	16.66
	***I***	cm⁴	***21.66***
	I/v	cm³	***14.45***
	I	cm⁴	166.66
	I/v	cm³	33.33
	I	cm⁴	82.5
	I/v	cm³	33
	I	cm⁴	250
	I/v	cm³	50

Let us check that the chosen busbars do not resonate.

Inherent resonant frequency

The inherent resonant frequencies to avoid for busbars subjected to a current at 50 Hz are frequencies of around 50 and 100 Hz. This inherent resonant frequency is given by the equation:

$$f = 112 \sqrt{\frac{E \cdot I}{m \cdot l^4}}$$

f	:	frequency of resonance in Hz		
E	:	modulus of elasticity for copper =	$1.3 \cdot 10^6$ daN/cm²	
m	:	linear mass of the bar	0.089	daN/cm
l	:	length between 2 supports or busducts	70	cm
I	:	moment of inertia of the busbar section relative to the axis x'x perpendicular to the vibrating plane	21.66	cm⁴

(choose m and I on the table on the previous page)

$$f = 112 \sqrt{\left(\frac{1.3 \cdot 10^6 \cdot 21.66}{0.089 \cdot 70^4}\right)}$$

$$f = 406 \text{ Hz}$$

f is outside of the values that have to be avoided, in other words 42 to 58 Hz and 80 to 115 Hz:

The solution is OK

In conclusion

The busbars chosen, i.e. 2 bars of 10 • 1 cm per phase, are suitable for an Ir = 2 500 A and Ith = 31.5 kA 3 sec.

Dielectric withstand

A few orders of magnitude
Dielectric strength
(20°C, 1 bar absolute): 2.9 to 3 kV/mm
Ionization limit
(20°C, 1 bar absolute): 2.6 kV/mm

■ The dielectric withstand depends on the following 3 main parameters:
□ the dielectric strength of the medium
□ the shape of the parts
□ the distance:
- ambient air between the live parts
- insulating air interface between the live parts.

The dielectric strength of the medium

This is a characteristic of the fluid (gas or liquid) making up the medium. For ambient air this characteristic depends on atmospheric conditions and pollution.

The dielectric strength of air depends on the following ambient conditions

■ **Pollution**
Conductive dust can be present in a gas, in a liquid, or be deposited on the surface of an insulator.
Its effect is always the same: reducing the insulation performances by a factor of anything up to 10!

■ **Condensation**
Phenomena involving the depositing of droplets of water on the surface of insulators which has the effect of locally reducing the insulating performance by a factor of 3.

■ **Pressure**
The performance level of gas insulation, is related to pressure.
For a device insulated in ambient air, altitude can cause a drop in insulating performance due to the drop in pressure.
We are often obliged to derate the device.

■ **Humidity**
In gases and liquids, the presence of humidity can cause a change in insulating performances.
In the case of liquids, it always leads to a drop in performance.
In the case of gases, it generally leads to a drop (SF_6, N_2 etc.) apart from air where a low concentration (humidity < 70%) gives a slight improvement in the overall performance level, or so called "full gas performance"*.

■ **Temperature**
The performance levels of gaseous, liquid or solid insulation decrease as the temperature increases. For solid insulators, thermal shocks can be the cause of **micro-fissuration** which can lead very quickly to insulator breakdown. Great care must therefore be paid to expansion phenomena: a solid insulator expands by between 5 and 15 times more than a conductor.

** We talk about "full gas" insulation.*

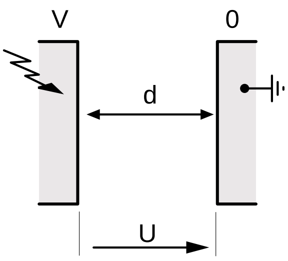
Pollution level

Pollution may originate: from the external gaseous medium (dust), initial lack of cleanliness, possibly the breaking down of an internal surface, pollution combined with humidity causes electrochemical conduction which will worsen discharge phenomena.
Its scope can be a constraint of the external medium (exposure to external elements).

The shape of parts

This plays a key role in switchgear dielectric withstand.
It is essential to eliminate any "peak" effect which would have a disastrous effect on the impulse wave withstand in particular and on the surface ageing of insulators:

Distance between parts



Ambient air between live parts

■ For installations in which, for various reasons, we cannot test under impulse conditions, the table in publication IEC 71-2 gives, according to the rated lightning impulse withstand voltage, the minimum distances to comply with in air either phase to earth or phase to phase.

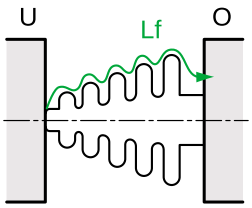
■ These distances guarantee correct withstand for unfavourable configurations: altitude < 1 000 m.

■ Distances in air* between conductive parts that are live and structures which are earthed giving a specified impulse withstand voltage under dry conditions:

Rated lightning impulse withstand voltage	Minimum distance in air phase to earth and phase to phase
Up (kV)	**d (mm)**
40	60
60	90
75	120
95	160
125	220

The values for distances in air given in the table above are minimum values determined by considering dielectric properties, they do not include any increase which could be required to take account of design tolerances, short circuit effects, wind effects, operator safety, etc.

**These indications are relative to a distance through a single air gap, without taking account of the breakdown voltage by tracking across the surfaces, related to pollution problems.*



Lf : tracking path

Insulating air interface between live parts

■ There are 4 severity levels of pollution, given in the table below, according to IEC 60 815*:

Pollution level	Example of characteristic environments
I-low	□ industry free zone with very low density of housing equipped with heating installations □ zones with low density of industry or housing but frequently subjected to wind and/or rain □ agricultural regions [1] □ mountain regions □ all these zones can be located at distances of at least 10 km from the sea and must not be exposed to wind blowing in from the sea [2]
II-medium	□ zones with industries producing particularly polluting smoke and/or with an average density of housing equipped with heating installations □ zones with a high density of housing and/or industries but subjected frequently to winds and/or to rainfall □ zones exposed to a sea wind, but not too close to the coast (at a distance of at least several kilometres) [2]
III-high	□ zones with a high density of industries and suburbs of major cities with a high density of polluting heating installations □ zones situated near to the sea, or at least exposed to quite high winds coming in from the sea [2]
IIII-very high	□ generally fairly small areas, subjected to conductive dust and to industrial smoke producing conductive deposits that are particularly thick □ generally fairly small areas, very close to the coast and exposed to mist or to very high winds and to pollutants coming from the sea [2] □ desert zones characterise by long periods without rain, exposed to high winds carrying sand and salt and subjected to regular condensation.

**IEC 60 815 guides you in choosing insulators for polluted environments*

[1] The use of sprayed fertilisers or the burning of harvested land can lead to a higher level of pollution due to dispersion by the winds

[2] The distances to the waters edge depends on the topography of the coast region and the extreme conditions of wind.

Temperature derating must be considered.

The IP code

Introduction

Protection of people against direct contact and protection of equipment against certain external influences is required by international standards for electrical installations and products (IEC 60 529).
Knowing the protection index is essential for the specification, installation, operation and quality control of equipment.

Definitions

The protection index is the level of protection provided by an enclosure against access to hazardous parts, the penetration of solid foreign bodies and of water. The IP code is a coding system to indicate the protection index.

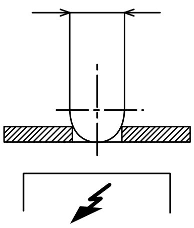
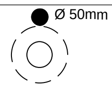
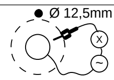
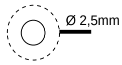
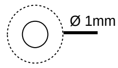
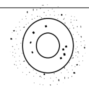
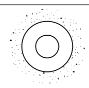
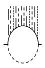
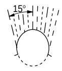
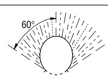
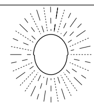
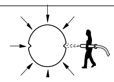
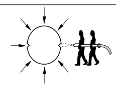
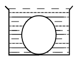
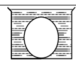
Applicational scope

It applies to enclosures for electrical equipment with a rated voltage of less than or equal to 72.5 kV. It does not concern the circuit breaker on its own but the front panel must be adapted when the latter is installed within a cubicle (e.g. finer ventilation grills).

The various IP codes and their meaning

A brief description of items in the IP code is given in the table on the following page.

Protection index

Item	Figures or letters	Meaning for protection of equipment	of people	Representation
Code letter	**IP**			
first characteristic figure		**against penetration of solid foreign bodies**	**against access to hazardous parts with**	
	0	(not protected)	(not protected)	
	1	diameter ≥ 50 mm	back of the hand	
	2	diameter ≥ 12.5 mm	finger	
	3	diameter ≥ 2.5 mm	tool	
	4	diameter ≥ 1 mm	wire	
	5	protected against dust	wire	
	6	sealed against dust	wire	
second characteristic figure		**against penetration of water with detrimental effects**		
	0	(not protected)		
	1	vertical water drops		
	2	water drops (15° inclination)		
	3	rain		
	4	water projection		
	5	spray projection		
	6	high power spray projection		
	7	temporary immersion		
	8	prolonged immersion		
additional letter (optional)			**against access to hazardous parts with:**	
	A		back of the hand	
	B		finger	
	C		tool	
	D		wire	
additional letter (optional)		**additional information specific to:**		
	H	high voltage equipment		
	M	movement during the water testing		
	S	stationary during the water testing		
	W	bad weather		

Protection Index

IK code

Introduction

■ Certain countries felt the need also to code the protection provided by enclosures against mechanical impact.
To do this they added a third characteristic figure to the IP code (the case in Belgium, Spain, France and Portugal). But since the adoption of IEC 60 529 as the European standard, no European country can have a different IP code.

■ Since the IEC has up to now refused to add this third figure to the IP code, the only solution to maintain a classification in this field was to create a different code. This is a subject of a draft European standard EN 50102: code IK.

■ Since the third figure in various countries could have different meanings and we had to introduce additional levels to cover the main requirements of product standards, the IK indices have a different meaning to those of the previous third figures (cf. table below).

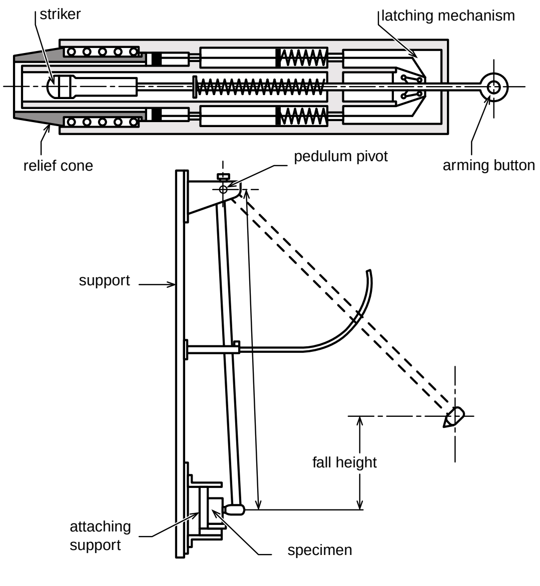
Previous 3rd figures of the IP code in NF C 20-010 (1986)	IK code
IP XX1	IK 02
IP XX3	IK 04
IP XX5	IK 07
IP XX7	IK 08
IP XX9	IK 10

NB: *to limit confusion, each new index is given by a two figure number.*

Definitions

■ The protection indices correspond to impact energy levels expressed in joules
□ hammer blow applied directly to the equipment
□ impact transmitted by the supports, expressed in terms of vibrations therefore in terms of frequency and acceleration

■ The protection indices against mechanical impact can be checked by different types of hammer: pendulum hammer, spring-loaded hammer or vertical free-fall hammer (diagram below).



Protection index

The various IK codes and their meaning

IK code	IK 01	IK 02	IK 03	IK 04	IK 05	IK 06	IK 07	IK 08	IK 09	IK 10
energies in joules	0.15	0.2	0.35	0.5	0.7	1	2	5	10	20
radius mm [1]	10	10	10	10	10	10	25	25	50	50
material [1]	P	P	P	P	P	P	A	A	A	A
steel = A [2]										
polyamide = P [3]										
hammer										
pendulum	✔	✔	✔	✔	✔	✔	✔	✔	✔	✔
spring loaded 4	✔	✔	✔	✔	✔	✔				
vertical							✔	✔	✔	✔

✔ = yes

N.B.:

[1] of the hammer head
[2] Fe 490-2 according to ISO 1052, hardness 50 HR to 58 HR according to ISO 6508
[3] hardness HR 100 according to ISO 2039-2

IEC 60 056 and ANSI C37-06
define on one hand the operating conditions, the rated characteristics, the design and the manufacture; and on the other hand the testing, the selection of controls and installation.

Introduction

■ The circuit breaker is a device that ensures the control and protection on a network. It is capable of making, withstanding and interrupting operating currents as well as short-circuit currents.

■ The main circuit must be able to withstand without damage:
□ the thermal current = short-circuit current during 1 or 3 s
□ the electrodynamic current:
2.5 • I_{sc} for 50 Hz (IEC)
2.6 • I_{sc} for 60 Hz (IEC)
2.7 • I_{sc} (ANSI), for a particular time constant (IEC)
□ the constant load current.

■ Since a circuit breaker is mostly in the "closed" position, the load current must pass through it without the temperature running away throughout the equipment's life.

Characteristics

Compulsory rated characteristics

■ Rated voltage
■ Rated insulation level
■ Rated normal current
■ Rated short-time withstand current
■ Rated peak withstand current
■ Rated short-circuit duration
■ Rated supply voltage for opening and closing devices and auxiliary circuits
■ Rated frequency
■ Rated short-circuit breaking current
■ Rated transient recovery voltage
■ Rated short-circuit making current
■ Rated operating sequence
■ Rated time quantities.

Special rated characteristics

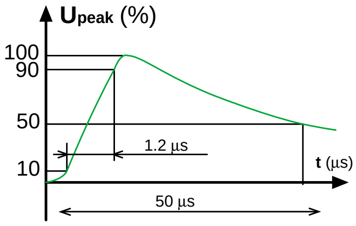
■ These characteristics are not compulsory but can be requested for specific applications:
□ rated out-of-phase breaking current,
□ rated cable-charging breaking current,
□ rated line-charging breaking current,
□ rated capacitor bank breaking current,
□ rated back-to-back capacitor bank breaking current,
□ rated capacitor bank inrush making current,
□ rated small inductive breaking current.

Rated voltage (cf. § 4.1 IEC 60 694)

The rated voltage is the maximum rms. value of the voltage that the equipment can withstand in normal service. It is always greater than the operating voltage.

■ Standardised values for Ur (kV) : **3.6 - 7.2 -12 - 17.5 - 24 - 36 kV**.

Medium voltage circuit breaker



Standardised wave 1.2/50 µs

Rated insulation level (cf. § 4.2 IEC 60 056 and 60 694)

■ The insulation level is characterised by two values:
□ the impulse wave withstand (1.2/50 µs)
□ the power frequency withstand voltage for 1 minute.

Rated voltage	Impulse withstand voltage	Power frequency withstand voltage
(Ur in kV)	(Up in kV)	(Ud in kV)
7.2	60	20
12	75	28
17.5	95	38
24	125	50
36	170	70

Rated normal current (cf. § 4.4 IEC 60 694)

With the circuit breaker always closed, the load current must pass through it in compliance with a maximum temperature value as a function of the materials and the type of connections.
IEC sets the maximum permissible temperature rise of various materials used for an ambient air temperature of no greater than 40°C (cf. § 4.4.2 table 3 IEC 60 694).

Rated short-time withstand current (cf. § 4.5 IEC 60 694)

$$I_{sc} = \frac{S_{sc}}{\sqrt{3} \cdot U}$$

S_{sc}	:	short-circuit power	(in MVA)
U	:	operating voltage	(in kV)
I_{sc}	:	short-circuit current	(in kA)

This is the standardised rms. value of the maximum permissible short-circuit current on a network for 1 or 3 seconds.
■ Values of rated breaking current under maximum short-circuit (kA):
6.3 - 8 - 10 - 12.5 - 16 - 20 - 25 - 31.5 - 40 - 50 kA.

Rated peak withstand current (cf. § 4.6 IEC 60 694) and making current (cf. § 4.103 IEC 60 056)

The making current is the maximum value that a circuit breaker is capable of making and maintaining on an installation in short-circuit.
It must be greater than or equal to the rated short-time withstand peak current.
I_{sc} is the maximum value of the rated short-circuit current for the circuit breakers' rated voltage. The peak value of the short-time withstand current is equal to:

2.5 • I_{sc} for 50 Hz
2.6 • I_{sc} for 60 Hz
2.7 • I_{sc} for special applications.

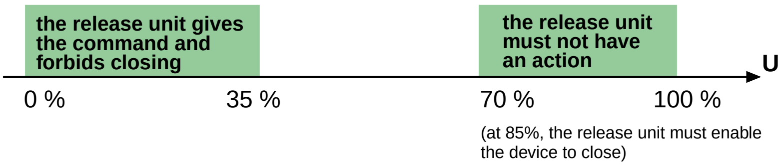
Rated short-circuit duration (cf. § 4.7 IEC 60 694)

The rated short-circuit is equal to 1 or 3 seconds.

Rated supply voltage for closing and opening devices and auxiliary circuits (cf. § 4.8 IEC 60 694)

■ Values of supply voltage for auxiliary circuits:
□ for direct current (dc): **24 - 48 - 60 - 110** or **125 - 220 or 250** volts,
□ for alternating current (ac): **120 - 220 - 230 - 240** volts.

■ The operating voltages must lie within the following ranges:
□ motor and closing release units:
-15% to +10% of U_r in dc and ac
□ opening release units:
-30% to +10% of U_r in dc
-15% to +10% of U_r in ac
□ undervoltage opening release unit:

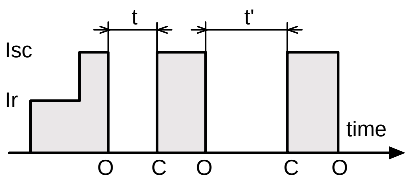


Rated frequency (cf. § 4.9 IEC 60 694)

Two frequencies are currently used throughout the world:
50 Hz in Europe and 60 Hz in America, a few countries use both frequencies. The rated frequency is either 50 Hz or 60 Hz.

Rated operating sequence (cf. § 4.104 IEC 60 056)

■ Rated switching sequence according to IEC, O - t - CO - t' - CO.
(cf: opposite diagram)

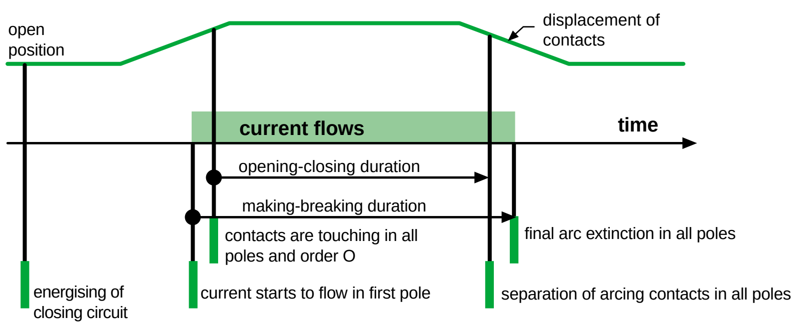


O	:	represents opening operation
CO	:	represents closing operation followed immediately by an opening operation

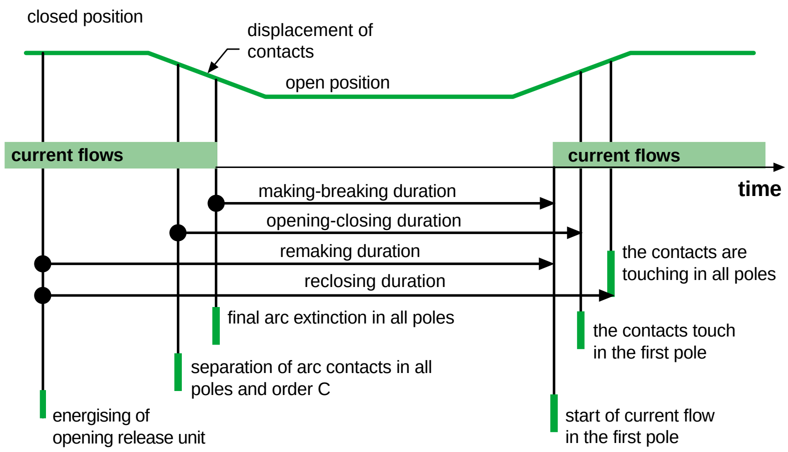
■ Three rated operating sequences exist:
□ slow: 0 - 3 mn - CO - 3 mn - CO
□ quick 1: O - 0.3 s - CO - 3 mn - CO
□ quick 2: O - 0.3 s - CO - 15 s - CO

N.B.: *other sequences can be requested.*

■ **Opening/closing cycle**
Assumption: O order as soon as the circuit breaker is closed.



■ **Automatic reclosing cycle**
Assumption: C order as soon as the circuit breaker is open, (with time delay to achieve 0.3 sec or 15 secs or 3 min).



Example 1:
■ *For a circuit breaker with a minimum opening duration of 45 ms (Top) to which we add 10 ms (Tr) due to relaying, the graph gives a percentage of the aperiodic component of around 30 % for a time constant τ1 = 45 ms:*

$$\%_{DC} = e^{\frac{-(45+10)}{45}} = 29.5\ \%$$

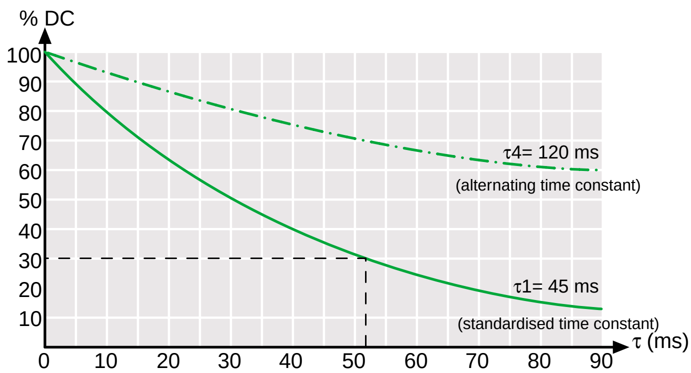
Rated short-circuit breaking current (cf. § 4.101 IEC 60 056)

The rated short-circuit breaking current is the highest value of current that the circuit breaker must be capable of breaking at its rated voltage.

■ **It is characterised by two values:**
□ the rms. value of its periodic component, given by the term: "rated short-circuit breaking current"
□ the percentage of the aperiodic component corresponding to the circuit breaker's opening duration, to which we add a half-period of the rated frequency. The half-period corresponds to the minimum activation time of an overcurrent protection device, this being 10 ms at 50 Hz.

■ According to IEC, the circuit breaker must break the rms. value of the periodic component of the short-circuit (= its rated breaking current) with the percentage of asymmetry defined by the graphs below.

Percentage of the aperiodic component (% DC) as a function of the time interval (τ)



t : circuit breaker opening duration (Top), increased by half a period at the power frequency (τr)

Example 2:
■ *Supposing that % DC of a MV circuit breaker is equal to 65% and that the symmetric short-circuit current that is calculated (Isym) is equal to 27 kA.*
What does Iasym equal?

$$I_{asym} = I_{sym} \sqrt{1 + 2\left(\frac{\%DC}{100}\right)^2} \quad [A]$$

$$= 27\ kA \sqrt{1 + 2\ (0.65)^2}$$

$$= 36.7\ kA$$

■ *Using the equation [A], this is equivalent to a symmetric short-circuit current at a rating of:*

$$\frac{36.7\ kA}{1.086} = 33.8\ kA \quad \text{for a \%DC of 30\%.}$$

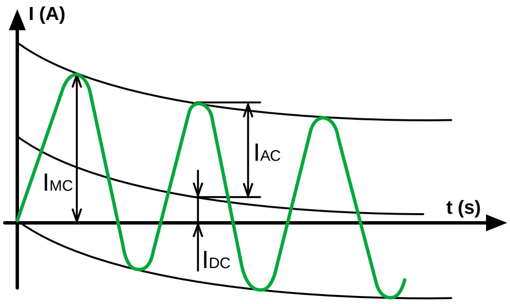
■ *The circuit breaker rating is greater than 33.8 kA. According to the IEC, the nearest standard rating is 40 kA.*

■ As standard the IEC defines MV equipment for a %DC of 30%, for a peak value of maximum current equal to 2.5 • Isc at 50 Hz or 2.6 • Isc at 60 Hz. In this case use the τ1 graph.

■ For low resistive circuits such as generator incomers, $\%_{DC}$ can be higher, with a peak value of maximum current equal to 2.7 • Isc.
In this case use the τ_4 graph.
For all constants of between τ_1 and τ_4, use the equation:

$$\%_{DC} = 100 \cdot e^{\frac{-(T_{op} + T_r)}{\tau_{1, \ldots, 4}}}$$

■ Values of rated short-circuit breaking current:
6.3 - 8 - 10 - 12.5 - 16 20 - 25 - 31.5 - 40 - 50 - 100 kA.



■ Short-circuit breaking tests must meet the five following test sequences:

Sequence	% Isym.	% aperiodic component $\%_{DC}$
1	10	≤ 20
2	20	≤ 20
3	60	≤ 20
4	100	≤ 20
5*	100	according to equation

** for circuit breakers opening in less than 80 ms*

I_{MC} : making current
I_{AC} : periodic component peak value ($I_{sc\ peak}$)
I_{dc} : aperiodic component value
$\%_{DC}$: % asymmetry or aperiodic component:

$$\frac{I_{DC}}{I_{AC}} \cdot 100 = 100 \cdot e^{\frac{-(T_{op} + T_r)}{\tau (1, \ldots, 4)}}$$

■ Symmetric short-circuit current (in kA):

$$I_{sym} = \frac{I_{AC}}{\sqrt{2}}$$

■ Asymmetric short-circuit current (in kA):

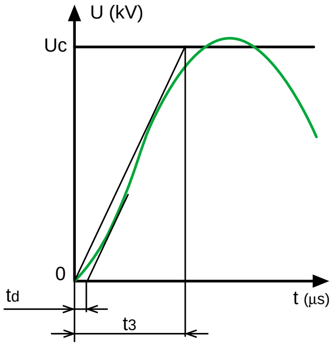
$$I_{asym}^2 = I^2_{AC} + I^2_{DC}$$

$$I_{asym} = I_{sym} \sqrt{1 + 2\left(\frac{\%_{DC}}{100}\right)^2}$$

Rated Transient Recovery Voltage (TRV) (cf. § 4.102 IEC 60 056)

This is the voltage that appears across the terminals of a circuit breaker pole after the current has been interrupted. The recovery voltage wave form varies according to the real circuit configuration.
A circuit breaker must be able to break a given current for all recovery voltages whose value remains less than the rated TRV.

■ **First pole factor**
For three-phase circuits, the TRV refers to the pole that breaks the circuit initially, in other words the voltage across the terminals of the open pole. The ratio of this voltage to a simple voltage is called the first pole factor, it is equal to 1.5 for voltages up to 72.5 kV.



■ **Value of rated TRV**

□ the TRV is a function of the asymmetry, it is given for an asymmetry of 0%.

Rated voltage (U_r in kV)	TRV value (U_c in kV)	Time (t_3 in µs)	Delay (t_d in µs)	Increase rate (U_c/t_d in kV/µs)
7.2	12.3	52	8	0.24
12	20.6	60	9	0.34
17.5	30	72	11	0.42
24	41	88	13	0.47
36	62	108	16	0.57

$$U_c = 1.4 \cdot 1.5 \cdot \frac{\sqrt{2}}{\sqrt{3}} \cdot U_r = 1.715\ U_r$$

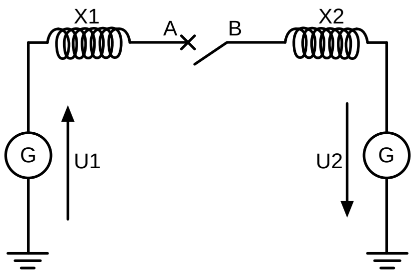
$$t_d = 0.15\ t_3$$

□ a specified TRV is represented by a reference plot with two parameters and by a segment of straight line defining a time delay.

T_d	:	time delay
t_3	:	time defined to reach U_c
U_c	:	peak TRV voltage in kV
TRV increase rate:		U_c/t_3 in kV/µs

Rated out-of-phase breaking current (cf. § 4.106 IEC 60 056)

When a circuit breaker is open and the conductors are not synchronous, the voltage across the terminals can increase up the sum of voltages in the conductors (phase opposition).



$U_A - U_B = U_1 - (-U_2) = U_1 + U_2$
si $U_1 = U_2$ so $U_A - U_B = 2U$

■ In practice, standards require the circuit breaker to break **a current equal to 25% of the fault current across the terminals**, at a voltage equal to twice the voltage relative to earth.

■ If U_r is the rated circuit breaker voltage, the recovery voltage (TRV) at power frequency is equal to:

□ $2\sqrt{3}\ U_r$ for networks with a neutral earthing arrangement

□ $2.5\sqrt{3}\ U_r$ for other networks.

■ Peak values for TRV for networks other than those with neutral earthing:

$$U_c = 1.25 \cdot 2.5 \cdot \frac{\sqrt{3}}{\sqrt{2}} \cdot U_r$$

Rated voltage (U_r in kV)	TRV value (U_c in kV)	Time (t_3 in µs)	Rate of increase (U_c/t_d in kV/µs)
7.2	18.4	104	0.18
12	30.6	120	0.26
17.5	45	144	0.31
24	61	176	0.35
36	92	216	0.43

Rated cable-charging breaking current (cf. § 4 .108 IEC 60 056)

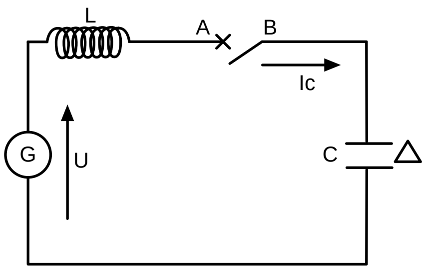
The specification of a rated breaking current for a circuit breaker located at the head of no-load cables is not compulsory and is considered as not being necessary for voltages less than 24 kV.

■ Normal rated breaking current values for a circuit breaker located at the head of no-load cables:

Rated voltage (U_r in kV)	Rated breaking current for no-load cables (I_c in kA)
7.2	10
12	25
17.5	31.5
24	31.5
36	50

Rated line-charging breaking current (cf. § 4.107 IEC 60 056)

The specification of a rated breaking current for a circuit breaker switch situated at the head of no-load lines is limited to overhead, three-phased lines and to a rated voltage ≥ 72 kV.



Rated single capacitor bank breaking current (cf. § 4.109 IEC 60 056)

The specification of a breaking current for a circuit breaker switch located upstream of capacitors is not compulsory. Due to the presence of harmonics, the breaking current for capacitors is equal to 0.7 times the device's rated current.

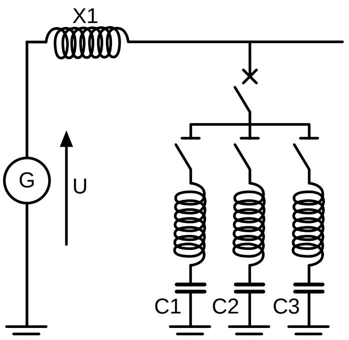
Rated current (A)	Breaking current for capacitors (A)
400	280
630	440
1250	875
2500	1750
3150	2200

By definition

$$pu = U_r \frac{\sqrt{2}}{\sqrt{3}}$$

■ The normal value of over-voltage obtained is equal to 2.5 pu, this being:

$$2.5 \cdot U_r \frac{\sqrt{2}}{\sqrt{3}}$$



Rated back-to-back capacitor bank breaking current (cf. § 4.110 IEC 60 056)

The specification of a breaking current for multi-stage capacitor banks is not compulsory.

■ If **n** is equal to the number of stages, then the over-voltage is equal to:

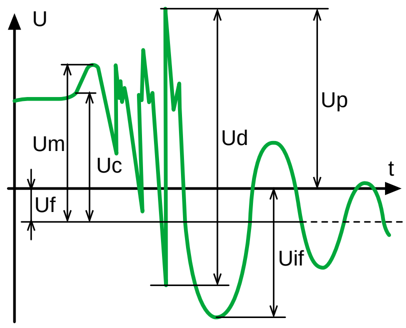
$$\frac{2n}{2n + 1} \cdot pu \text{ with } pu = U_r \frac{\sqrt{2}}{\sqrt{3}}$$

Rated capacitor bank inrush making current (cf. § 4.111 IEC 60 056)

The rated closing current for capacitor banks is the peak current value that the circuit breaker must be capable of making at the rated voltage. The value of the circuit breaker's rated closing current must be greater than the making current for the capacitor bank. In service, the frequency of the pick-up current is normally in the region of 2 - 5 kHz.

Rated small inductive breaking current (cf. § 4.112 IEC 60 056)

The breaking of a low inductive current (several amperes to several tens of amperes) causes overvoltages. The type of circuit breaker will be chosen so that the overvoltages that appear do not damage the insulation of the current consumers (transformer, motors).



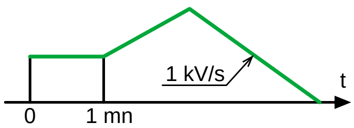
■ The figure opposite shows the various voltages on the load side

Uf	:	instantaneous network voltage value
Uc	:	network voltage at the moment of breaking
Um	:	extinction point
Uif	:	overvoltage relative to earth
Up	:	maximum overvoltage relative to earth
Ud	:	maximum peak-to-peak amplitude of the overvoltage due to restrike.

■ **Insulation level of motors**

IEC 60 034 stipulates the insulation level of motors.
Power frequency and impulse withstand testing is given in the table below (rated insulation levels for rotary sets).

Insulation	Test at 50 (60) Hz rms. value	Impulse test
Between turns		(4 U_r + 5) kV 4.9 pu + 5 = 31 kV at 6.6 kV (50% on the sample) increase time 0.5 µs
Relative to earth	(2 U_r + 5) kV 2U_r + 1 ⇒ 2(2U_r + 1) ⇒ 0 14 kV ⇒ 28 kV ⇒ 0	(4 U_r + 5) kV 4.9 pu + 5 = 31 kV at 6.6 kV increase time 1.2 µs



Normal operating conditions (cf. IEC 60 694)

For all equipment functioning under other conditions than those described below, derating should be carried out (see derating chapter). Equipment is designed for normal operation under the following conditions:

■ **Temperature**

0°C	Installation	
Instantaneous ambient	**Indoor**	**Outdoor**
minimal	-5°C	-25°C
maximal	+40°C	+40°C
average daily maximum value	35°C	35°C

Medium voltage circuit breaker

■ **Humidity**

Average relative humidity for a period	**Indoor equipment**
24 hours	95%
1 month	90%

■ **Altitude**

The altitude must not exceed 1 000 metres.

Electrical endurance

The electrical endurance requested by the recommendation is three breaking operations at I_{sc}.
Merlin Gerin circuit breakers are capable of breaking I_{sc} at least 15 times.

Mechanical endurance

The mechanical endurance requested by the recommendation is 2 000 switching operations.
Merlin Gerin circuit breakers guarantee 10 000 switching operations.

Co-ordination of rated values (cf. § IEC 60 056)

Rated voltage	**Rated short-circuit breaking current**	**Rated current in continuous service**					
U_r (kV)	**Isc (kV)**	**Ir (A)**					
3.6	10	400					
	16		630	1250			
	25			1250	1600	2500	
	40			1250	1600	2500	3150
7.2	8	400					
	12.5	400	630	1250			
	16		630	1250	1600		
	25		630	1250	1600	2500	
	40			1250	1600	2500	3150
12	8	400					
	12.5	400	630	1250			
	16		630	1250	1600		
	25		630	1250	1600	2500	
	40			1250	1600	2500	3150
	50			1250	1600	2500	3150
17.5	8	400	630	1250			
	12.5		630	1250			
	16		630	1250			
	25			1250			
	40			1250	1600	2500	3150
24	8	400	630	1250			
	12.5		630	1250			
	16		630	1250			
	25			1250	1600	2500	
	40			1250	1600	2500	3150
36	8		630				
	12.5		630	1250			
	16		630	1250	1600		
	25			1250	1600	2500	
	40			1250	1600	2500	3150

Current transformer

Please note!
Never leave a CT in an open circuit.

This is intended to provide a secondary circuit with a current proportional to the primary current.

Transformation ratio (Kn)

$$Kn = \frac{I_{pr}}{I_{sr}} = \frac{N_2}{N_1}$$

N.B.: current transformers must be in conformity with standard IEC 185 but can also be defined by standards BS 3938 and ANSI.

■ It comprises one or several primary windings around one or several secondary windings each having their own magnetic circuit, and all being encapsulated in an insulating resin.

■ It is dangerous to leave a CT in an open circuit because dangerous voltages for both people and equipment may appear across its terminals.

Primary circuit characteristics according to IEC standards

Rated frequency (fr)

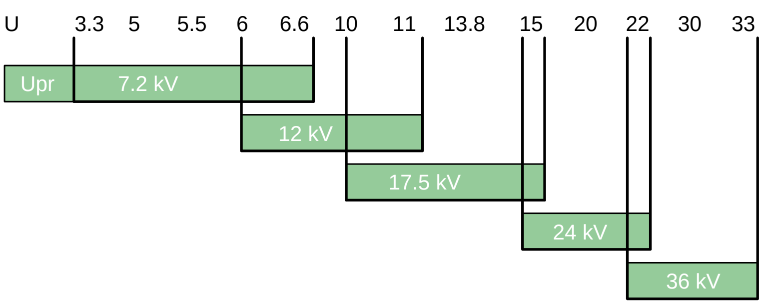
A CT defined at 50 Hz can be installed on a 60 Hz network.
Its precision is retained. **The opposite is not true**.

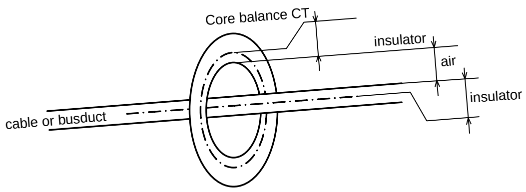
Rated primary circuit voltage (Upr)

■ **General case:**

Rated CT voltage ≥ rated installation voltage

The rated voltage sets the equipment insulation level (see "Introduction" chapter of this guide). Generally, we would choose the rated CT voltage based on the installation operating voltage U, according to the chart:





(sheathed or not sheathed busduct)

■ **Special case:**

If the CT is a **core balance CT** installed on a busduct or on a cable.
The dielectric insulation is provided by the cable or busducting insulation and the air located between them. The core balance CT is itself insulated.

Current transformer

Primary operating current (I_{ps})

An installation's primary operating current I (kA) (for a transformer feeder for example) **is equal to the CT primary operating current (I_{ps}) taking account of any possible derating.**

■ **If:**

S	:	apparent power in kVA
U	:	primary operating voltage in kV
P	:	active power of the motor in kW
Q	:	reactive power of capacitors in kvars
I_{ps}	:	primary operating current in A

■ **We will have:**

□ incomer cubicle

$$I_{ps} = \frac{S}{\sqrt{3} \cdot U}$$

□ generator set incomer

$$I_{ps} = \frac{S}{\sqrt{3} \cdot U}$$

□ transformer feeder

$$I_{ps} = \frac{S}{\sqrt{3} \cdot U}$$

□ motor feeder

$$I_{ps} = \frac{P}{\sqrt{3} \cdot U \cdot \cos\varphi \cdot \eta}$$

η	:	motor efficiency

If you do not know the exact values of φ and η, you can take as an initial approximation: cos φ = 0.8 ; η = 0.8.

□ capacitor feeder
1.3 is a derating coefficient of 30% to take account of temperature rise due to capacitor harmonics.

$$I_{ps} = \frac{1.3 \cdot Q}{\sqrt{3} \cdot U}$$

□ bus sectioning
The current I_{ps} of the CT is the greatest value of current that can flow in the bus sectioning on a permanent basis.

Example:

A thermal protection device for a motor has a setting range of between 0.6 and 1.2 • I_{rTC}. In order to protect this motor, the required setting must correspond to the motor's rated current.

■ *If we suppose that Ir for the motor = 45 A, the required setting is therefore 45 A;*

□ *if we use a 100/5 CT, the relay will never see 45 A because: 100 • 0.6 = 60 > 45 A.*

□ *if on the other hand, we choose a CT 75/5, we will have:*

$$0.6 < \frac{45}{75} < 1.2$$

and therefore we will be able to set our relay. This CT is therefore suitable.

Rated primary current (I_{pr})

The rated current (Ipr) will always be greater than or equal to the operating current (I) for the installation.

■ Standardised values:

10 -12.5 - 15 - 20 - 25 - 30 - 40 - 50 - 60 - 75 and their multiples and factors.

■ For metering and usual current-based protection devices, the rated primary current must not exceed 1.5 times the operating current.
In the case of protection, we have to check that the chosen rated current enables the relay setting threshold to be reached in the case of a fault.

N.B.: *current transformers must be able to withstand 1.2 times the rated current on a constant basis and this as well must be in conformity with the standards.*

Current transformer

In the case of an ambient temperature greater than 40°C for the CT, the CT's nominal current (I_{pn}) must be greater than I_{ps} multiplied by the derating factor corresponding to the cubicle.
As a general rule, the derating is of 1% I_{pn} per degree above 40°C.
(See "Derating" chapter in this guide).

Rated thermal short-circuit current (I_{th})

The rated thermal short-circuit current is generally the rms. value of the installation's maximum short-circuit current and the duration of this is generally taken to be equal to 1 s.

■ Each CT must be able to withstand the short-circuit current which can flow through its primary circuit both thermally and dynamically until the fault is effectively broken.

■ If S_{sc} is the network short-circuit power expressed in MVA, then:

$$I_{th} = \frac{S_{sc}}{U \cdot \sqrt{3}}$$

Example:

■ $Ssc = 250\ MVA$
■ $U = 15\ kV$

$$I_{th\ 1\ s} = \frac{Ssc \cdot 10^3}{U \cdot \sqrt{3}} = \frac{250 \cdot 10^3}{15 \cdot \sqrt{3}} = 9\ 600\ A$$

■ **When the CT is installed in a fuse protected cubicle, the I_{th} to use is equal to 80 I_r.**

■ **If 80 I_r > I_{th} 1 s for the disconnecting device, then I_{th} 1 s for the CT = I_{th} 1 s for the device.**

Overcurrent coefficient (K_{si})

Knowing this allows us to know whether a CT will be easy to manufacture or otherwise.

■ It is equal to:

$$K_{si} = \frac{I_{th\ 1\ s}}{I_{pr}}$$

■ **The lower K_{si} is, the easier the CT will be to manufacture.**
A high K_{si} leads to over-dimensioning of the primary winding's section. The number of primary turns will therefore be limited together with the induced electromotive force; the CT will be even more difficult to produce.

Order of magnitude k_{si}	Manufacture
K_{si} < 100	standard
100 < K_{si} < 300	sometimes difficult for certain secondary characteristics
100 < K_{si} < 400	difficult
400 < K_{si} < 500	limited to certain secondary characteristics
Ksi > 500	very often impossible

A CT's secondary circuit must be adapted to constraints related to its use, either in metering or in protection applications.

Current transformer

Secondary circuit's characteristics according to IEC standards

Rated secondary current (I_{sr}) 5 or 1 A?

■ **General case:**
□ for **local** use **I_{sr} = 5 A**
□ for **remote** use **I_{sr} = 1 A**

■ **Special case:**
□ for **local** use **I_{sr} = 1 A**
N.B.: *Using 5 A for a remote application is not forbidden but leads to an increase in transformer dimensions and cable section, (line loss: $P = R I^2$).*

Accuracy class (cl)

■ Metering: class 0.5
■ Switchboard metering: class 1
■ Overcurrent protection: class 10P sometimes 5P
■ Differential protection: class X
■ Zero-sequence protection: class 5P.

Real power that the TC must provide in VA

This is the sum of the consumption of the cabling and that of each device connected to the TC secondary circuit.

■ **Consumption of copper cabling** (line losses of the cabling), knowing that: $P = R.I^2$ and $R = \rho.L/S$ then:

$$(VA) = k \cdot \frac{L}{S}$$

k = 0.44	:	if I_{sr} = 5 A
k = 0.0176	:	if I_{sr} = 1 A
L	:	length in metres of link conductors (feed/return)
S	:	cabling section in mm²

Example:

■ *Cable section:*	*2.5 mm²*
■ *Cable length (feed/return):*	*5.8 m*
■ *Consumed power by the cabling:*	*1 VA*

■ **Consumption of metering or protection devices.**
Consumption of various devices are given in the manufacturer's technical data sheet.

Rated output

Take the standardised value immediately above the real power that the CT must provide.

■ The standardised values of rated output are:
2.5 - 5 - 10 - 15 - 30 VA.

Safety factor (SF)

■ Protection of metering devices in the case of a fault is defined by the safety factor **SF**. The value of **SF** will be chosen according to the current consumer's short-time withstand current: $5 \leq SF \leq 10$. **SF** is the ratio between the limit of rated primary current (I_{pl}) and the rated primary current (I_{pr}).

$$SF = \frac{I_{pl}}{I_{pr}}$$

■ I_{pl} is the value of primary current for which the error in secondary current = 10 %.

Current transformer

■ An ammeter is generally guaranteed to withstand a short-time current of 10 I_r, i.e. 50 A for a 5 A device.
To be sure that this device will not be destoyed in the case of a primary fault, the current transformer must be saturated before 10 I_r in the secondary. A safety factory of 5 is suitable.

■ In accordance with the standards, Schneider Electric CT's have a safety factor of 10. However, according to the current consumer characteristic a lower safety factor can be requested.

Accuracy limit factor (ALF)

In protection applications, we have two constraints: having an accuracy limit factor and an accuracy class suited to the application.
We will determine the required ALF in the following manner:

Definite time overcurrent protection.

■ The relay will function perfectly if:

$$ALF_{\text{real of CT}} > 2 \cdot \frac{I_{re}}{I_{sr}}$$

I_{re}	:	relay threshold setting
I_{sr}	:	rated secondary current of the CT

■ For a relay with two setting thresholds, we will use the highest threshold,
□ For a transformer feeder, we will generally have an instantaneous high threshold set at 14 I_r max., giving the real ALF required **> 28**
□ for a motor feeder, we will generally have a high threshold set to 8 I_r max., giving a real ALF required **> 16.**

Inverse definite time overcurrent protection

■ In all cases, refer to the relay manufacturer's technical datasheet.
For these protection devices, the CT must guarantee accuracy across the whole trip curve for the relay up to 10 times the setting current.

$$ALF_{\text{real}} > 20 \cdot I_{re}$$

■ **Special cases:**
□ if the maximum short-circuit current is greater than or equal to 10 Ire:

$$ALF_{\text{real}} > 20 \cdot \frac{I_{re}}{I_{sr}}$$

I_{re}	:	relay setting threshold

□ if the maximum short-circuit current is less than 10 Ire:

$$ALF_{\text{real}} > 2 \cdot \frac{I_{sc\ secondary}}{I_{sr}}$$

□ if the protection device has an instantaneous high threshold that is used, (never true for feeders to other switchboards or for incomers):

$$ALF_{\text{real}} > 2 \cdot \frac{I_{r2}}{I_{sr}}$$

I_{r2}	:	instantaneous high setting threshold for the module

Differential protection

Many manufacturers of differential protection relays recommend class X CT's.

■ Class X is often requested in the form of:

$$V_k \leq a \,.\, I_f \,(R_{ct} + R_b + R_r)$$

The exact equation is given by the relay manufacturer.

Values characterising the CT

V_k	:	Knee-point voltage in volts
a	:	asymmetry coefficient
R_{ct}	:	max. resistance in the secondary winding in Ohms
R_b	:	loop resistance (feed/return line) in Ohms
R_r	:	resistance of relays not located in the differential part of the circuit in Ohms
I_f	:	maximum fault current seen by the CT in the secondary circuit for a fault outside of the zone to be protected $I_f = \frac{I_{sc}}{K_n}$
I_{sc}	:	primary short-circuit current
K_n	:	CT transformation ratio

What values should I_f be given to determine Vk?

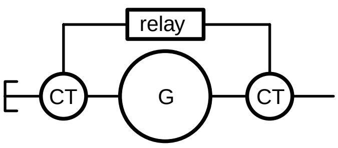
■ The short-circuit current is chosen as a function of the application:

□ generator set differential
□ motor differential
□ transformer differential
□ busbar differential.

■ **For a generator set differential:**

□ if I_{sc} is known: I_{sc} short-circuit current for the generator set on its own

$$I_f = \frac{I_{sc}}{K_n}$$



□ if the $I_{r\,gen}$ is known: we will take

$$I_f = \frac{7 \cdot I_{r\,gen}}{K_n}$$

□ if the $I_{r\,gen}$ is unknown: we will take

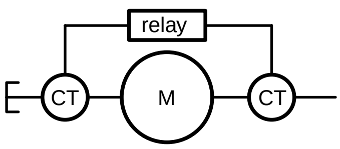
$$I_f = 7 \cdot I_{sr\,(CT)}$$
$$I_{sr(CT)} = 1 \text{ or } 5 \text{ A}$$

■ **For motor differential:**

□ if the start-up current is known: we will take

$$I_{sc} = I_{\text{start-up}}$$

$$I_f = \frac{I_{sc}}{K_n}$$



□ if the $I_{r\,motor}$ is known: we will take

$$I_f = \frac{7 \cdot I_r}{K_n}$$

□ if the $I_{r\,motor}$ is not known: we will take

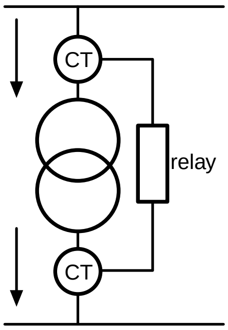
$$I_f = 7 \cdot I_{sr\,(CT)}$$

$$I_{sr(TC)} = 1 \text{ or } 5 \text{ A}$$

Reminder

I_r **:** rated current

Current transformer



■ **For a transformer differential**

The I_{sc} to take is that flowing through the CT's for a current consumer side fault. In all cases, the fault current value I_f is less than 20 $I_{sr(CT)}$.

□ if we do not know the exact value, we will take:

$$I_f = 20\ I_{sr(CT)}$$

■ **For busbar differential**

□ the I_{sc} to take is the switchboard Ith

$$I_f = \frac{I_{th}}{K_n}$$

■ **For a line differential**

The I_{sc} to take is the I_{sc} calculated at the other end of the line, therefore limited by the cable impedance. If the impedance of the cable is not known, we will take the switchboard I_{th}.

Voltage transformer

We can leave a voltage transformer in an open circuit without any danger ***but it must never be short-circuited.***

The voltage transformer is intended to provide the secondary circuit with a secondary voltage that is proportional to that applied to the primary circuit.
N.B.: *IEC standard 60 186 defines the conditions which voltage transformers must meet.*

It comprises a primary winding, a magnetic core, one or several secondary windings, all of which is encapsulated in an insulating resin.

Characteristics

The rated voltage factor (KT)

The rated voltage factor is the factor by which the rated primary voltage has to be multiplied in order to determine the maximum voltage for which the transformer must comply with the specified temperature rise and accuracy recommendations. According to the network's earthing arrangement, the voltage transformer must be able to withstand this maximum voltage for the time that is required to eliminate the fault.

Normal values of the rated voltage factor

Rated voltage factor	Rated duration	Primary winding connection mode and network earthing arrangement
1.2	continuous	phase to phase on any network neutral point to earth for star connected transformers in any network
1.2 1.5	continuous 30 s	phase to earth in an earthed neutral network
1.2 1.9	continuous 30 s	phase to earth in a network without an earthed neutral with automatic elimination of earthing faults
1.2 1.9	continuous 8 h	phase to earth in an isolated neutral network without automatic elimination of earthing faults, or in a compensated network with an extinction coil without automatic elimination of the earthing fault

N.B.: *lower rated durations are possible when agreed to by the manufacturer and the user.*

Generally, voltage transformer manufacturers comply with the following values: VT phase/earth 1.9 for 8 h and VT phase/phase 1.2 continuous.

Rated primary voltage (U_{pr})

■ According to their design, voltage transformers will be connected:

□ **either phase to earth**

$$\frac{3000\ V}{\sqrt{3}} \,/\, \frac{100\ V}{\sqrt{3}} \qquad U_{pr} = \frac{U}{\sqrt{3}}$$

□ **or phase to phase**

$$3000\ V \,/\, 100\ V \qquad U_{pr} = U$$

Voltage transformer

Rated secondary voltage (Usr)

■ For phase to phase VT the rated secondary voltage is 100 or 110 V.

■ For single phase transformers intended to be connected in a phase to earth arrangement, the rated secondary voltage must be divided by $\sqrt{3}$.

$$E.g.: \frac{100\,V}{\sqrt{3}}$$

Rated output

Expressed in VA, this is the apparent power that a voltage transformer can provide the secondary circuit when connected at its rated primary voltage and connected to the nominal load.
It must not introduce any error exceeding the values guaranteed by the accuracy class. ($S = \sqrt{3}$ UI in three-phase circuits)

■ Standardised values are:
10 - 15 - 25 - 30 - 50 - 75 - 100 - 150 - 200 - 300 - 400 - 500 VA.

Accuracy class

This defines the limits of errors guaranteed in terms of transformation ratio and phase under the specified conditions of both power and voltage.

Measurement according to IEC 60 186

Classes 0.5 and 1 are suitable for most cases, class 3 is very little used.

Application	Accuracy class
not used industrially	0.1
precise metering	0.2
everyday metering	0.5
statistical and/or instrument metering	1
metering not requiring great accuracy	3

Protection according to IEC 60 186

Classes 3P and 6P exist but **in practice only class 3P is used.**

■ The accuracy class is guaranteed for values:
□ of voltage of between 5% of the primary voltage and the maximum value of this voltage which is the product of the primary voltage and the rated voltage factor (kT x U_{pr})
□ for a secondary load of between 25% and 100% of the rated output with a power factor of 0.8 inductive.

Accuracy class	Voltage error as ± %		Phase shift in minutes	
	between 5% U_{pr} and kT • U_{pr}	between 2% and 5% U_{pr}	between 5% U_{pr} and kT • U_{pr}	between 2% and 5% U_{pr}
3P	3	6	120	240
6P	6	12	24	480

U_{pr} = rated primary voltage
kT = voltage factor
phase shift = see explanation next page

Voltage transformer

Transformation ratio (K_n)

$$K_n = \frac{U_{pr}}{U_{sr}} = \frac{N_1}{N_2}$$ for a TT

Voltage ratio error

This is the error that the transformer introduces into the voltage measurement.

$$\text{voltage error (\%)} = \frac{(k_n\ U_{sr} - U_{pr}) \cdot 100}{U_{pr}}$$

K_n = transformation ratio

Phase error or phase-shift error

This is the phase difference between the primary voltage U_{pr} and the secondary voltage U_{sr}. IT is expressed in minutes of angle.

The thermal power limit or rated continuous power

This is the apparent power that the transformer can supply in steady state at its rated secondary voltage without exceeding the temperature rise limits set by the standards.

Derating

Introduction

The various standards or recommendations impose validity limits on device characteristics.
Normal conditions of use are described in the "Medium voltage circuit breaker" chapter.
Beyond these limits, it is necessary to reduce certain values, in other words to derate the device.

■ **Derating must be considered:**
□ in terms of the insulation level, for altitudes of over 1 000 metres
□ in terms of the rated current, when the ambient temperature exceeds 40°C and for a protection index of over IP3X,
(see chapter on "Protection indices").
These different types of derating can be accumulated if necessary.

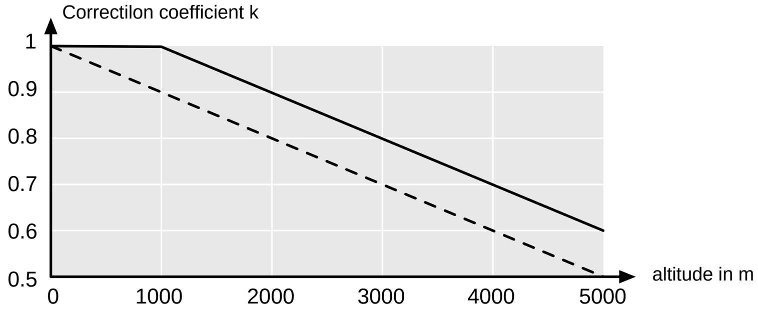
__N.B.:__ there are no standards specifically dealing with derating.
However, table V § 442 of IEC 60 694 deals with temperature rises and gives limit temperature values not to be exceeded according to the type of device, the materials and the dielectric used.

Insulation derating according to altitude

Standards give a derating for all equipment installed at an altitude greater than 1 000 metres.
As a general rule, we have to derate by 1.25 % U peak every 100 metres above 1 000 metres.
This applies for the lightning impulse withstand voltage and the power frequency withstand voltage 50 Hz - 1 mn. Altitude has no effect on the dielectric withstand of circuit breakers in SF6 or vacuum, because they are within a sealed enclosure. Derating, however, must be taken account of when the circuit breaker is installed in cubicles. In this case, insulation is in air.

■ **Merlin Gerin uses correction coefficients:**
□ for circuit breakers outside of a cubicle, use the graph below
□ for circuit breakers in a cubicle, refer to the cubicle selection guide (derating depends on the cubicle design).

Exception of the Mexican market: derating starts from zero metres (cf. dotted line on the graph below).



Example of application:

Can equipment with a rated voltage of 24 kV be installed at 2500 metres?
The impulse withstand voltage required is 125 kV.
The power frequency withstand 50 Hz is 50 kV. 1 mn.

■ *For 2500 m:*
□ *k is equal to 0.85*
□ *the impulse withstand must be 125/0.85 = 147.05 kV*
□ *the power frequency withstand 50 Hz must be 50/0.85 = 58.8 kV*

■ *No, the equipment that must be installed is:*
□ *rated voltage = 36 kV*
□ *impulse withstand = 170 kV*
□ *withstand at 50 Hz = 70 kV*

N.B.:
if you do not want to supply 36 kV equipment, we must have the appropriate test certificates proving that our equipment complies with the request.

Derating

Derating of the rated current according to temperature

As a general rule, derating is of 1 % I_r per degree above 40°C.
IEC standard 60 694 § 442 table 5 defines the maximum permissible temperature rise for each device, material and dielectric with a reference ambient temperature of 40°C.

■ **In fact, this temperature rise depends on three parameters:**
□ the rated current
□ the ambient temperature
□ the cubicle type and its IP (protection index).

Derating will be carried out according to the cubicle selection tables, because conductors outside of the circuit breakers act to radiate and dissipate calories.

Names and symbols of SI units of measure

Basic units

Magnitude	Symbol of the magnitude[1]	Unit	Symbol of the unit	Dimension
Basic units				
length	l, (L)	metre	m	L
mass	m	kilogramme	kg	M
time	t	second	s	T
electrical current	I	ampere	A	I
thermodynamic temperature[2]	T	kelvin	K	θ
quantity of material	n	mole	mol	N
light intensity	I, (I_v)	candela	cd	J
Additional units				
angle (plane angle)	α, β, γ …	radian	rad	N/A
solid angle	Ω, (ω)	steradian	sr	N/A

Common magnitudes and units

Name	Symbol	Dimension	SI Unit: name (symbol)	Comments and other units
Magnitude: space and time				
length	l, (L)	L	metre (m)	centimetre (cm): 1 cm = 10^{-2} m (microns must no monger be used, instead the micrometre (µm))
area	A, (S)	L^2	metre squared (m^2)	are (a): 1 a = 10^2 m^2 hectare (ha): 1 ha = 10^4 m^2 (agricult. meas.)
volume	V	L^3	metre cubed (m^3)	
plane angle	α, β, γ …	N/A	radian (rad)	gradian (gr): 1 gr = 2π rad/400 revolution (rev): 1 tr = 2π rad degree(°):1°= 2π rad/360 = 0.017 453 3 rad minute ('): 1' = 2π rad/21 600 = 2,908 882 • 10^{-4} rad second ("): 1" = 2π rad/1 296 000 = 4.848 137 • 10^{-6} rad
solid angle	Ω, (ω)	N/A	steradian (sr)	
time	t	T	second (s)	minute (mn) hour (h) day (d)
speed	v	L T^{-1}	metre per second (m/s)	revolutions per second (rev/s): 1 tr/s = 2π rad/s
acceleration	a	L T^{-2}	metre per second squared (m/s^2)	acceleration due to gravity: g = 9.80665 m/s^2
angular speed	ω	T^{-1}	radian per second (rad/s)	
angular acceleration	α	T^{-2}	radian per second squared (rad/s^2)	
Magnitude: mass				
mass	m	M	kilogramme (kg)	gramme (g) : 1 g = 10^{-3} kg ton (t) : 1 t = 10^3 kg
linear mass	ρ_1	L^{-1} M	kilogramme per metre (kg/m)	
mass per surface area	$\rho_{A'}$ (ρ_s)	L^{-2} M	kilogramme per metre squared (kg/m^2)	
mass per volume	ρ	L^{-3} M	kilogramme per metre cubed (kg/m^3)	
volume per mass	v	L^3 M^{-1}	metre cubed per kilogramme (m^3/kg)	
concentration	ρ_B	M L^{-3}	kilogramme per metre cubed (kg/m^3)	concentration by mass of component B (according to NF X 02-208)
density	d	N/A	N/A	
Magnitude: periodic phenomena				
period	T	T	second (s)	
frequency	f	T^{-1}	hertz (Hz)	1 Hz = $1s^{-1}$, f = 1/T
phase shift	φ	N/A	radian (rad)	
wavelength	λ	L	metre (m)	use of the angström (10^{-10} m) is forbidden. Use of a factor of nanometre (10^9 m) is recommended λ = c/f = cT (c = celerity of light)
power level	Lp	N/A	decibel (dB)	

e1 the symbol in brackets can also be used
2 the temperature Celsius t is related to the themrodynamic temperature T by the relationship: t = T - 273.15 K

Names and symbols of SI units of measure

Name	Symbol	Dimension	SI Unit: name (symbol)	Comments and other units
Magnitude: mechanical				
force	F	$L M T^{-2}$	Newton	1 N = 1 $m.kg/s^2$
weight	G, (P, W)			
moment of the force	M, T	$L^2 M T^{-2}$	Newton-metre (N.m)	N.m and not m.N to avoid any confusion with the millinewton
surface tension	γ, σ	$M T^{-2}$	Newton per metre (N/m)	1 N/m = 1 J/m^2
work	W	$L^2 M T^{-2}$	Joule (J)	1 J : 1 N.m = 1 W.s
energy	E	$L^2 M T^{-2}$	Joule (J)	Watthour (Wh) : 1 Wh = 3.6 • 10^3 J (used in determining electrical consumption)
power	P	$L^2 M T^{-3}$	Watt (W)	1 W = 1 J/s
pressure	σ, τ p	$L^{-1} M T^{-2}$	Pascal (Pa)	1 Pa = 1 N/m^2 (for the pressure in fluids we use bars (bar): 1 bar = 10^5 Pa)
dynamic viscosity	η, μ	$L^{-1} M T^{-1}$	Pascal-second (Pa.s)	1 P = 10^{-1} Pa.s (P = poise, CGS unit)
kinetic viscosity	ν	$L^2 T^{-1}$	metre squared per second (m^2/s)	1 St = 10^{-4} m^2/s (St = stokes, CGS unit)
quantity of movement	p	$L M T^{-1}$	kilogramme-metre per second (kg.m/s)	p = mv
Magnitude: electricity				
current	I	I	Ampere (A)	
electrical charge	Q	TI	Coulomb (C)	1 C = 1 A.s
electrical potential	V	$L^2 M T^{-3} I^{-1}$	Volt (V)	1 V = 1 W/A
electrical field	E	$L M T^{-3} I^{-1}$	Volt per metre (V/m)	
electrical resistance	R	$L^2 M T^{-3} I^{-2}$	Ohm (Ω)	1 Ω = 1 V/A
electrical conductivity	G	$L^{-2} M^{-1} T^3 I^2$	Siemens (S)	1 S = 1 A/V = $1\Omega^{-1}$
electrical capacitance	C	$L^{-2} M^{-1} T^4 I^2$	Farad (F)	1 F = 1 C/V
electrical inductance	L	$L^2 M T^{-2} I^{-2}$	Henry (H)	1 H = 1 Wb/A
Magnitude: electricity, magnetism				
magnetic induction	B	$M T^{-2} I^{-1}$	Tesla (T)	1 T = 1 Wb/m^2
magnetic induction flux	Φ	$L^2 M T^{-2} I^{-1}$	Weber (Wb)	1 Wb = 1 V.s
magnetisation	H_i, M	$L^{-1} I$	Ampere per metre (A/m)	
magnetic field	H	$L^{-1} I$	Ampere per metre (A/m)	
magneto-motive force	F, Fm	I	Ampere (A)	
resistivity	ρ	$L^3 M T^{-3} I^{-2}$	Ohm-metre (Ω.m)	1 $\mu\Omega.cm^2/cm$ = 10^{-8} Ω.m
conductivity	γ	$L^{-3} M^{-1} T^3 I^2$	Siemens per metre (S/m)	
permittivity	ε	$L^{-3} M^{-1} T^4 I^2$	Farad per metre (F/m)	
active	P	$L^2 M T^{-3}$	Watt (W)	1 W = 1 J/s
apparent power	S	$L^2 M T^{-3}$	Voltampere (VA)	
reactive power	Q	$L^2 M T^{-3}$	var (var)	1 var = 1 W
Magnitude: thermal				
thermodynamic temperature	T	θ	Kelvin (K)	Kelvin and not degree Kelvin or °Kelvin
temperature Celsius	t, θ	θ	degree Celsius (°C)	t = T - 273.15 K
energy	E	$L^2 M T^{-2}$	Joule (J)	
heat capacity	C	$L^2 M T^{-2} \theta^{-1}$	Joule per Kelvin (J/K)	
entropy	S	$L^2 M T^{-2} \theta^{-1}$	Joule per Kelvin (J/K)	
specific heat capacity	c	$L^2 T^{-2} \theta^{-1}$	Watt per kilogramme-Kelvin (J/(kg.K))	
thermal conductivity	λ	$L M T^{-3} \theta^{-1}$	Watt per metre-Kelvin (W/(m.K))	
quantity of heat	Q	$L^2 M T^{-2}$	Joule (J)	
thermal flux	Φ	$L^2 M T^{-3}$	Watt (W)	1 W = 1 J/s
thermal power	P	$L^2 M T^{-3}$	Watt (W)	
coefficient of thermal radiation	h_r	$M T^{-3} \theta^{-1}$	Watt per metre squared-Kelvin ($W/(m^2.K)$)	

Names and symbols of SI units of measure

Correspondence between Imperial units and international system units (SI)

Magnitude	Unit	Symbol	Conversion
acceleration	foot per second squared	**ft/s^2**	1 ft/s^2 = 0.304 8 m/s^2
calory capacity	British thermal unit per pound	**Btu/Ib**	1 Btu/Ib = 2.326 • 10^3 J/kg
heat capacity	British thermal unit per cubit foot.degree Fahrenheit	**$Btu/ft^3.°F$**	1 $Btu/ft^3.°F$ = 67.066 1 • 10^3 $J/m^3.°C$
	British thermal unit per (pound.degree Fahrenheit)	**Btu/Ib°F**	1 Btu/Ib.°F = 4.186 8 • 10^3 J(Kg.°C)
magnetic field	oersted	**Oe**	1 Oe = 79.577 47 A/m
thermal conductivity	British thermal unit per square foot.hour.degree Fahrenheit	**$Btu/ft^2.h.°F$**	1 $Btu/ft^2.h.°F$ = 5.678 26 $W/(m^2.°C)$
energy	British thermal unit	**Btu**	1 Btu = 1.055 056 • 10^3 J
energy (couple)	pound force-foot	**Ibf/ft**	1 Ibf.ft = 1.355 818 J
	pound force-inch	**Ibf.in**	1 Ibf.in = 0.112 985 J
thermal flux	British thermal unit per square foot.hour	**$Btu/ft^2.h$**	1 $Btu/ft^2.h$ = 3.154 6 W/m^2
	British thermal unit per second	**Btu/s**	1 Btu/s = 1.055 06 • 10^3 W
force	pound-force	**Ibf**	1 Ibf = 4.448 222 N
length	foot	**ft, '**	1 ft = 0.304 8 m
	inch [(1)]	**in, "**	1 in = 25.4 mm
	mile (UK)	**mile**	1 mile = 1.609 344 km
	knot	**-**	1 852 m
	yard [(2)]	**yd**	1 yd = 0.914 4 m
mass	once (ounce)	**oz**	1 oz = 28.349 5 g [(6)]
	pound (livre)	**Ib**	1 Ib = 0.453 592 37 kg
linear mass	pound per foot	**Ib/ft**	1 Ib/ft = 1.488 16 kg/m
	pound per inch	**Ib/in**	1 Ib/in = 17.858 kg/m
mass per surface area	pound per square foot	**Ib/ft^2**	1 Ib/ft^2 = 4.882 43 kg/m^2
	pound per square inch	**Ib/in^2**	1 Ib/in^2 = 703,069 6 kg/m^2
mass per volume	pound per cubic foot	**Ib/ft^3**	1 Ib/ft^3 = 16.018 46 kg/m^3
	pound per cubic inch	**Ib/in^3**	1 Ib/in^3 = 27.679 9 • 10^3 kg/m^3
moment of inertia	pound square foot	**$Ib.ft^2$**	1 $Ib.ft^2$ = 42.140 $g.m^2$
pressure	foot of water	**ft H_2O**	1 ft H_2O = 2.989 07 • 10^3 Pa
	inch of water	**in H_2O**	1 in H_2O = 2,490 89 • 10^2 Pa
pressure - strain	pound force per square foot	**Ibf/ft^2**	1 Ibf/ft^2 = 47.880 26 Pa
	pound force per square inch [(3)]	**Ibf/in^2 (psi)**	1 Ibf/in^2 = 6.894 76 • 10^3 Pa
calorific power	British thermal unit per hour	**Btu/h**	1 Btu/h = 0.293 071 W
surface area	square foot	**sq.ft, ft^2**	1 sq.ft = 9.290 3 • 10^{-2} m^2
	square inch	**sq.in, in^2**	1 sq.in = 6.451 6 • 10^{-4} m^2
temperature	degree Fahrenheit [(4)]	**°F**	T_K = 5/9 (q °F + 459.67)
	degree Rankine [(5)]	**°R**	T_K = 5/9 q °R
viscosity	pound force-second per square foot	**$Ibf.s/ft^2$**	1 $Ibf.s/ft^2$ = 47.880 26 Pa.s
	pound per foot-second	**Ib/ft.s**	1 Ib/ft.s = 1.488 164 Pa.s
volume	cubic foot	**cu.ft**	1 cu.ft = 1 ft^3 = 28.316 dm^3
	cubic inch	**cu.in, in^3**	1 in^3 = 1.638 71 • 10^{-5} m^3
	fluid ounce (UK)	**fl oz (UK)**	fl oz (UK) = 28.413 0 cm^3
	fluid ounce (US)	**fl oz (US)**	fl oz (US) = 29.573 5 cm^3
	gallon (UK)	**gal (UK)**	1 gaz (UK) = 4.546 09 dm^3
	gallon (US)	**gal (US)**	1 gaz (US) = 3.785 41 dm^3

(1) 12 in = 1 ft
(2) 1 yd = 36 in = 3 ft
(3) Or p.s.i.: pound force per square inch
(4) T_K = temperature kelvin with q°C = 5/9 (q°F - 32)
(5) °R = 5/9 °K
(6) Apart from mass of precious metals (silver, gold, for example) where the carat is used (1 carat = 3.110 35 10^{-2} kg)

The standards mentioned in this document

Where can you order IEC publications?

Central Offices of the International Electrotechnical Commission 1, rue de Varembé Geneva - Switzerland.

The documentation department (Factory A2) at Merlin Gerin can provide you with information on the standards.

■ International Electrotechnical Vocabulary	**IEC 60 050**
■ High voltage alternating current circuit breakers	**IEC 60 056**
■ Current transformers	**IEC 60 185**
■ Voltage transformers	**IEC 60 186**
■ Alternating current disconnectors and earthing disconnectors	**IEC 60 129**
■ High voltage switches	**IEC 60 265**
■ Metal-enclosed switchgear for alternating current at rated voltage of over 1 kV and less than or equal to 72.5 kV	**IEC 60 298**
■ High-voltage alternating current combined fuse-switches and combined fuse-circuit breakers	**IEC 60 420**
■ High-voltage alternating current contactors	**IEC 60 470**
■ Specifications common to high-voltage switchgear standards	**IEC 60 694**
■ Calculation rules in industrial installations	**IEC 60 909**
■ Derating	**ANSI C37 04**

IEC - ANSI comparison

The following comparison is based on different circuit breaker characteristics.

Overview of the main differences

Theme	ANSI	IEC
asymmetrical breaking capacity on faults across the terminals	50% with current derating	30% without derating
insulation level: impulse wave	imposes chopped waves for outdoor equipment 115% U_w/3 s 129% U_w/2 s	
short-time withstand current peak value	2.7 I_{sc}	2.5•I_{sc} at 50 Hz 2.6•I_{sc} at 60 Hz 2.7•I_{sc} for special cases
Transient Recovery voltage(1)	around twice as severe	
electrical endurance	4 times K.S.I_{sc}	3 times I_{sc}
mechanical endurance	1 500 to 10 000 according to U_a and I_{sc}	2 000
motor overvoltages	no text	standard test circuit

(1) the ANSI peak voltage is 10% greater than the voltage defined by the IEC.
The E_2/t_2 slope is 50% greater than the U_c/t_3 slope.
However, the largest part of the graph is the initial part where the SF6 reconstitutes itself.
The two standards easily allow the SF6 to reconstitute itself.

Rated voltages

According to IEC

■ Standardised values for U_r (kV): **3.6 - 7.2 - 12 - 17.5 - 24 - 36 kV**

According to ANSI

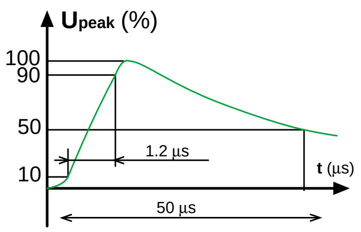
■ The ANSI standard defines a class and a voltage range factor K which defines a range of rated voltages at **constant power**.

Standardised values for U_r (kV)				
	class (kV)	**U_{max} (kV)**	**U_{min} (kV)**	**K**
Indoor equipment	4.16	4.76	3.85	1.24
	7.2	8.25	6.6	1.25
	13.8	15	11.5	1.3
	38	38	23	1.65
Outdoor equipment	15.5			1
	25			1
	38			1

Rated installation level

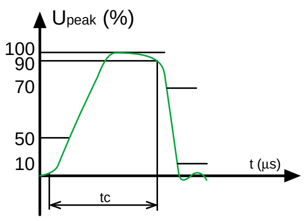
According to IEC

Rated voltage (kV)	Rated lightning withstand voltage (kV)	Rated power frequency withstand voltage 50 Hz 1 mm (kV)
7.2	60	20
12	75	28
17.5	95	38
24	125	50
36	170	70



Standardised wave 1.2/50 µs

IEC - ANSI comparison



Onde coupée suivant ANSI pour le matériel d'extérieur

According to ANSI

Rated voltage (kV)	Rated lightning withstand voltage (kV)	Rated power frequency withstand voltage 50 Hz 1 mm (kV)
Indoor equipment		
4.16	60	19
7.2	95	36
13.8	95	36
38	150	80
Outdoor equipment		
15.5	110	50
25.8	125	60
	150	
38	150	80
	200	

N.B.
■ *BIL: Basic Insulation Level*
The outdoor equipment is tested with chopped waves.

■ *The impulse withstand is equal to:*
1.29 BIL for a duration of tc = 2 µs
1.15 BIL for a duration tc = 3 µs

Rated normal current

According to IEC

■ Values of rated current: **400 - 630 - 1250 - 1600 - 2500 - 3150 A**

According to ANSI

■ Values of rated current: **1200 - 2000 - 3000 A**

Short-time withstand current

According to IEC

■ Values of short-circuit rated breaking capacity:
6.3 - 8 - 10 - 12.5 - 16 - 20 - 25 - 31.5 - 40 - 50 - 63 kA

According to ANSI

■ Values of short-circuit rated breaking capacity:
□ indoor equipment: **12.5 - 20 - 25 - 31.5 - 40 kA**
□ outdoor equipment:

Class (MVA)	Breaking capacity (kA)	
	I at U_{max}	**KI at U_{min}**
250	29	36
350	41	49
500	18	23
750	28	36
1000	37	46
1500	21	35
2750	40	40

Peak value of short-time current and closing capacity

According to IEC

■ The peak value of short-time withstand current is equal to:
□ **2.5•I_{sc}** at 50 Hz
□ **2.6•I_{sc}** at 60 Hz
□ **2.7•I_{sc}** for special cases.

According to ANSI

■ The peak value of short-time withstand current is equal to:
□ **2.7 K I_{sc}** at peak value
□ **1.6 K I_{sc}** at rms. value.
(K : voltage factor)

Rated short-circuit duration

According to IEC

■ The rated short-circuit duration is equal to **1 or 3 seconds.**

According to ANSI

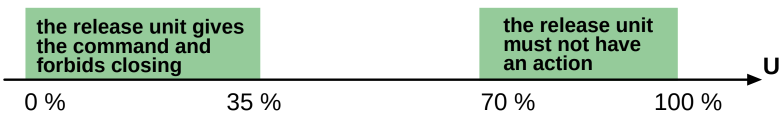
■ The rated short-circuit duration is equal to **3 seconds.**

Rated supply voltage for closing and opening devices and auxiliary circuits

According to IEC

■ Supply voltage values for auxiliary circuits:
□ for direct current (dc): **24 - 48 - 60 - 110 or 125 - 220 or 250 volts**
□ for alternating current (ac): **120 - 220 - 230 - 240 volts.**

■ Operating voltages must fall within the following ranges:
□ Motor and closing release units:
-15% to +10% of U_r in dc et ac
□ opening release units:
-15% to +10% of U_r in ac; **-30% to +10% of U_r** in dc
□ undervoltage opening release units



(at 85%, the release unit must enable the device to close)

According to ANSI

■ Supply voltage values for auxiliary circuits:
□ for direct current (dc): **24 - 48 - 125 - 250 volts.**
□ for alternating (ac): **120 - 240 volts**

■ Operating voltage must fall within the following ranges:

Voltage	Voltage range (V)
Motor and closing release units	
48 Vsc	36 to 56
125 Vsc	90 to 140
250 Vsc	180 to 280
120 Vac	104 to 127
240 Vac	208 to 254
Opening release units	
24 Vsc	14 to 28
48 Vsc	28 to 56
125 Vsc	70 to 140
250 Vsc	140 to 220
120 Vac	104 to 127
240 Vac	208 to 254

Rated frequency

According to IEC

■ Rated frequency: **50 Hz.**

According to ANSI

■ Rated frequency: **60 Hz.**

Short-circuit breaking capacity at the rated operating sequence

■ ANSI specifies 50% asymmetry and IEC 30%. In 95% of applications, 30% is sufficient. When 30% is too low, there are specific cases (proximity of generators) for which the asymmetry may be greater than 50%.

■ For both standard systems, the designer has to check the circuit breaker breaking capacity. The difference is not important because without taking account of the asymmetry factor "S", it is equal to 10%.

ANSI: $I_{asym} = I_{sym} \sqrt{(1 + 2\,A^2)} = 1.22\,I_{sym}\ (A = 50\%)$

IEC: $I_{asym} = I_{sym} \sqrt{(1 + 2\,A^2)} = 1.08\,I_{sym}\ (A = 30\%)$

According to IEC

■ Short-circuit breaking tests must meet the following 5 test sequences:

Sequence n°	% I_{sym}	% aperiodic component
1	10	≤ 20
2	20	≤ 20
3	60	≤ 20
4	100	≤ 20
5*	100	30

** for circuit breakers opening at least 80 ms*

IEC - ANSI comparison

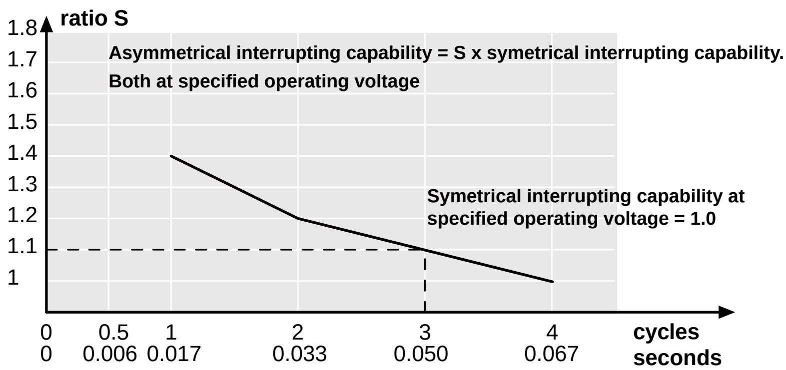
According to ANSI

■ The circuit breaker must be able to break:

□ the rated short circuit current at the rated maximum voltage
□ K times the rated short-circuit current (maxi symmetrical interrupting capability with K: voltage range factor) at the operating voltage (maximum voltage/K)
□ between the two currents obtained by the equation:

$$\frac{\text{maxi symetrical current}}{\text{rated short-circuit current}} = \frac{\text{rated maxi voltage}}{\text{rated voltage}} = K$$

We therefore have a constant breaking power (in MVA) over a given voltage range. Moreover, the asymmetrical current will be a function of the following table taking S = 1.1 for Merlin Gerin circuit breakers.



■ Rated short-circuit breaking capacity (kA)

Sequence n°	current broken	% aperiodic component
1	10	50 - 100
2	30	< 20
3	60	50 - 100
4	100	< 20
5	KI to V/K	< 20
6	SI to V	50 - 100
7	KSI to V/K	50 - 100
8	electrical endurance	
9/10	reclosing cycle at ASI and AKSI	
11	C - 2 s - O at KI	
12	rated Isc duration = KI for 3 s	
13/14	single phase testing at KI and KSI (0.58 V)	

Example:

■ *Isc = 40 kA*
■ *% asymmetry = 50%*
■ *Iasym = 1.1 • 40 = 44 kA*
■ $Isym = \frac{44}{\sqrt{1 + 2(50\%)^2}} = \frac{44}{1,22} = 36\ kA$

Sequence 6 will therefore be tested at 36 kA + 50% asymmetry, this being 44 kA of total current.

Short-circuit breaking testing must comply with the 14 test sequences above, with:

I	:	symmetrical breaking capacity at maximum voltage
R	:	reclosing cycle coefficient (Reclosing factor)
K	:	voltage range factor: $K = \frac{V_{max}}{V_{min}}$
S	:	asymmetrical factor: $\frac{I_{asym}}{I_{sym}} = 1.1$ for Merlin Gerin circuit breakers
V	:	maximum rated voltage

Coordination of rated values

According to IEC

Rated voltage	Rated short-circuit breaking current	Rated operating current					
U_r (kV)	I_{sc} (kA)	I_r (A)					
3.6	10	400					
	16		630	1250			
	25			1250	1600	2500	
	40			1250	1600	2500	3150
7.2	8	400					
	12.5	400	630	1250			
	16		630	1250	1600		
	25		630	1250	1600	2500	
	40			1250	1600	2500	3150
12	8	400					
	12.5	400	630	1250			
	16		630	1250	1600		
	25		630	1250	1600	2500	
	40			1250	1600	2500	3150
	50			1250	1600	2500	3150
17.5	8	400	630	1250			
	12.5		630	1250			
	16		630	1250			
	25			1250			
	40			1250	1600	2500	3150
24	8	400	630	1250			
	12.5		630	1250			
	16		630	1250			
	25			1250	1600	2500	
	40			1250	1600	2500	3150
36	8		630				
	12.5		630	1250			
	16		630	1250	1600		
	25			1250	1600	2500	
	40			1250	1600	2500	3150

According to ANSI

Maximum rated voltage	Rated short-circuit breaking current at U_{max}	Minimum rated voltage	Rated short-circuit breaking current at U_{min}	Rated operating current				
U_{max} (kV)	I_{sc} (kA)	(kV)	I_{sc} (kA)	I_r (A)				
4.76	18	3.5	24		1200			
	29	3.85	36		1200	2000		
	41	4	49		1200		3000	
8.25	7	2.3	25	600	1200	2000		
	17	4.6	30		1200			
	33	6.6	41		1200	2000		
15	9.3	6.6	21		1200			
	9.8	4	37		1200			
	18	11.5	23		1200	2000		
	19	6.6	43		1200	2000		
	28	11.5	36		1200	2000		
	37	11.5	48		1200		3000	
15.5	8.9	5.8	24	600				
	18	12	23		1200			
	35	12	45		1200			
	56	12	73			2000	3000	4000
25.8	5.4	12	12	600				
	11	12	24		1200			
38	22	23	36		1200		3000	
	36	24	57		1200			

IEC- ANSI comparison

Derating

According to IEC

■ Refer to "Switchgear definition/Derating" chapter.

According to ANSI

■ The ANSI standard C37 04 gives for altitudes greater than 1 000 metres:

□ a correction factor for the applicable voltage on the rated insulation level and on the rated maximum voltage,

□ a correction factor for the rated operating current.
The table of correction factors according to altitude
(Altitude Corrections Factors: ACF).

Altitude		ACF for:	
(ft)	(m)	voltage	continous current
3 300	1 000	1.00	1.00
5 000	1 500	0.95	0.99
10 000	3 000	0.8	0.96

***N.B.:** "sealed system" type circuit breakers,*
it is not necessairy to apply the voltage ACF on the maximum rated voltage

Electrical endurance

Merlin Gerin circuit breakers can withstand I_{sc} at least 15 times.
IEC and ANSI standards impose values well below this because they take account of oil breaking circuit breakers.
These values are not very high and should the customer request it,
we must provide those for the device being considered.

According to IEC

■ The electrical endurance is equal to **3 times I_{sc}**.

According to ANSI

■ The electrical endurance is equal to **4 times K.S.I_{sc}**.

I_{sc}	:	symmetrical breaking capacity at maximum voltage
S	:	asymmetrical factor
K	:	voltage range factor

Mechanical endurance

According to IEC

■ Mechanical endurance is of 2 000 switching cycles.

According to ANSI

■ Mechanical endurance is of between 1 500 and 10 000 switching cycles according to the voltage and the breaking capacity.

Construction

According to IEC

■ The IEC does not impose any particular constraints, however, the manufacturer has responsibility of determining what is required in terms of materials (thicknesses, etc) to meet performance requirements in terms of strength.

According to ANSI

■ ANSI imposes a thickness of 3 mm for sheet metal.

Equipment is designed to operate under the following normal conditions

Normal operating conditions

Temperature

Standards	0°C ambient instantaneous	Installation indoor	 outdoor
IEC	minimal	- 5°C	- 25°C
	maximal	+ 40°C	+ 40°C
	maximum average daily value	35°C	35°C
ANSI	minimal	- 30°C	
	maximal	+ 40°C	

N.B.:
For all equipment operating under conditions other than those described above, derating must be provided (see derating chapter).

Altitude

According to IEC

■ The altitude must not exceed 1 000 metres, otherwise the equipment should be derated.

According to ANSI

■ The altitude must not exceed 3 300 feet (1 000 metres), otherwise the equipment should be derated.

Humidity

According to IEC

Average relative humidity value over a period	Indoor equipment
24 hours	95 %
1 month	90 %

According to ANSI

■ No specific constraints.

Reference to Schneider Electric documentation

- ***MV partner***
  (Pierre GIVORD)
- ***Protection of electrical networks***
  (Christophe PREVE)
- ***Protection of electrical networks***
  (édition HERMES fax 01 53 10 15 21)
  (Christophe PREVE)
- ***Medium voltage design***
  (André DELACHANAL)
- ***Cahiers techniques***
  - ***n°158*** *calculating short-circuit currents*
  - ***n°166*** *enclosures and protection indices (Jean PASTEAU)*

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