Technical collection

Medium Voltage technical guide

Basics for MV cubicle design

Schneider Electric

Medium Voltage technical guide

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

Goal

■ Present MV products and equipment and their environment.

■ Facilitate their choice, according to a normative system of reference.

■ Provide design rules used to calculate the dimensions or characteristics 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 some of the main 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

Presentation

Prefabricated metal-enclosed switchgear

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 the short-circuit 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 are achieved by using switchgear.

The classification of metal-enclosed switchgear is defined in the IEC standard 62271-200 with a functional approach, using several criteria.

- Accessibility to compartments by persons
- Level of Loss of Service Continuity when a main circuit compartment is opened
- Type of metallic or insulated barriers, between live parts and opened accessible compartment
- Level of internal arc withstand in normal operating conditions.

Voltage

Operating voltage U (kV)

It is applied across the equipment terminals.
It is the network voltage where the equipment is fitted.

Rated voltage U_r (kV)

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 higher than the operating voltage and, is associated with an insulation level.

Insulation level U_d (kV rms 1 min) and U_p (kV peak)

This defines the dielectric withstand of equipment to power frequency overvoltages and lightning impulses.

- **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 62271-1, 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 min: 50 kV rms
- Impulse withstand voltage 1.2/50 µs: 125 kV peak.

Prefabricated metal-enclosed switchgear

Standards

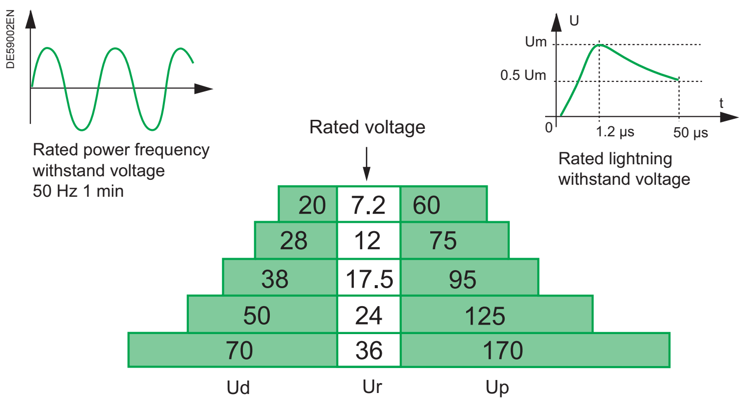
Apart from special cases, Schneider Electric equipment are compliant with tables 1a and 1b of IEC standard 62271-1 common specifications.

Rated voltage kV rms	Rated lightning impulse withstand voltage 1.2/50 µs 50 Hz kV peak		Rated power-frequency withstand voltage 1 min 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

The values of withstand voltages in the tables are considered for normal services conditions at altitudes of less than 1000 metres, 20°C, 11 g/m^3 humidity and a pressure of 101.3 kPa.
For other conditions, correction factors are applied for the test and in some cases, derating has to 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	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



Prefabricated metal-enclosed switchgear

Current

Rated normal current: I_r (A)

This is the rms value of current that equipment can withstand when permanently closed, without exceeding the temperature rise allowed in standards.
The table below gives the temperature rises authorised by the IEC 62271-1 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 in air		
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 Schneider Electric are: 400, 630, 1250, 2500 and 3150 A.*

Rated short-time withstand current: I_k (A)

This is the rms value of the current which the switchgear can carry in the closed position during a specified short time. Short time is generally 1 s, and sometimes 3 s.

Rated peak withstand current: I_p (A)

This is the peak current associated with the first major loop of the rated short-time withstand current which the switchgear can carry in the closed position.

Operating current: I (A)

This is calculated from the consumption of the devices connected to the considered circuit. It is the current that really flows 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 1250 kVA transformer feeder at 5.5 kV operating voltage.

□ calculating the operating current of the transformer feeder:

Apparent power:

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

$$I = \frac{S}{U\sqrt{3}} = \frac{1250}{5.5 \cdot 1.732} = 130\ \text{A}$$

□ calculating the operating current of the motor feeder:

cosφ = power factor = 0.9

η = motor efficiency = 0.9

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

Minimal short-circuit current: I_{sc} min (kA rms) of an electrical installation

(see explanation in “Short-circuit currents” chapter.)

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

(see explanation in “Short-circuit currents” chapter.)

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

(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 current	Fault current
Disconnector	Isolates		
Earthing disconnector	Connects to the earth		(short-circuit making capacity)
Switch	Switches	■	
Disconnector switch	Switches Isolates	■	
Fixed circuit breaker	Switches Protects	■	■
Withdrawable circuit breaker	Switches Protects Isolates if withdrawn	■	■
Fixed contactor	Switches	■	
Withdrawable contactor	Switches Isolates if withdrawn	■	
Fuse	Protects does not isolate		■ (once)

■ = *Yes*

Prefabricated metal-enclosed switchgear

Accessibility and service continuity

Some parts of a switchgear may be made accessible for the user, for various reasons from operation to maintenance, and such an access could impair the overall operation of the switchgear then decreasing the availability.
The IEC 62271-200 proposes user-oriented definitions and classifications intended to describe how a given switchgear can be accessed, and what will be the consequences on the installation.

The manufacturer shall state which are the parts of the switchgear which can be accessed, if any, and how safety is ensured. For that matter, compartments have to be defined, and some of them are going to be said accessible.

Three categories of accessible compartments are proposed:

- **Interlock** based access: the interlocking features of the switchboard ensure that the opening is only possible under safe conditions
- **Procedure** based access: the access is secured by means of, for instance, a padlock and the operator shall apply proper procedures to ensure a safe access
- **Tool** based access: if any tool is needed to open a compartment, the operator shall be aware that no provision is made to ensure a safe opening, and that proper procedures shall be applied. This category is restricted to compartments where no normal operation nor maintenance is specified.

When the accessibility of the various compartments are known, then the consequences of opening a compartment on the operation of the installation can be assessed; it is the idea of Loss of Service Continuity which leads to the LSC classification proposed by the IEC: *“category defining the possibility to keep other high-voltage compartments and/or functional units energised when opening a accessible high-voltage compartment”*.

If no accessible compartment is provided, then the LSC classification does not apply.

Several categories are defined, according to *“the extent to which the switchgear and controlgear are intended to remain operational in case access to a high-voltage compartment is provided”*:

- If any other functional unit than the one under intervention has to be switched off, then service is partial only: LSC1
- If at least one set of busbars can remain live, and all other functional units can stay in service, then service is optimal: LSC2
- If within a single functional unit, other(s) compartment(s) than the connection compartment is accessible, then suffix A or B can be used with classification LSC2 to distinguish whether the cables shall be dead or not when accessing this other compartment.

But is there a good reason for requesting access to a given function? That’s a key point.

Prefabricated metal-enclosed switchgear

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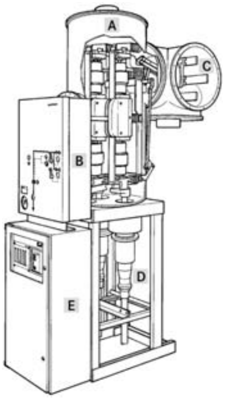

Example 1:
Here is a GIS solution with in (D) what is said to be “Base section with cable connection area” (AREVA WI). There is no connection compartment, and the only HV compartments are gas filled.
Then, there is no accessible compartment to be considered for LSC classification.
LSC is not relevant in that case, and service continuity during normal operation and maintenance is expected to be total.

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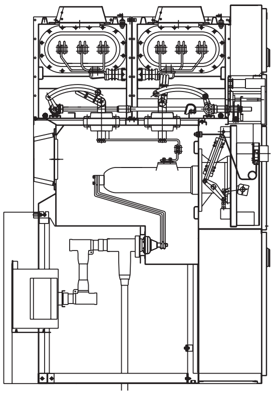

Example 2:
Here is a GIS solution (Schneider Electric CGset) with an air insulated connection (and possibly VT) compartment.
This compartment is accessible (with tools).
The other HV compartments are not accessible.
Access to the connection compartment is possible with the busbar(s) live, meaning all other functional units can be kept operating.
The LSC classification applies, and such solution is LSC2.

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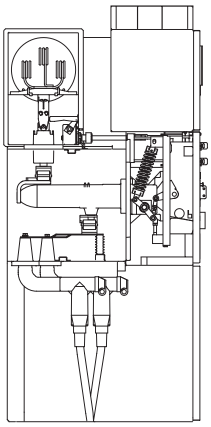

Example 3:
Here is a GIS solution (Schneider Electric GMset) with an air insulated connection (and possibly VT) compartment. This compartment is accessible and interlocked with the earthing function.
The circuit breaker can be extracted (tool access compartment), even if that is not considered as normal operation nor normal maintenance.
Access to one functional unit within a switchboard does not require any other functional unit to be switched off. Such solution is LSC2A.

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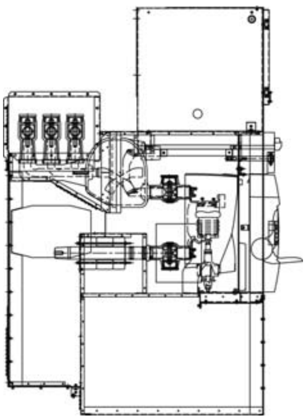

Example 4:
A mixed technology (Schneider Electric GenieEvo) with an air insulated connection compartment, and an air insulated main switching device which can be extracted with the busbar live, thanks to the disconnector.
Single line diagram is similar to example 2.
If both the connection compartment and the circuit breaker compartment are accessible, and access to any of them means the cables are first switched off and earthed. Category is LSC2A.

Prefabricated metal-enclosed switchgear

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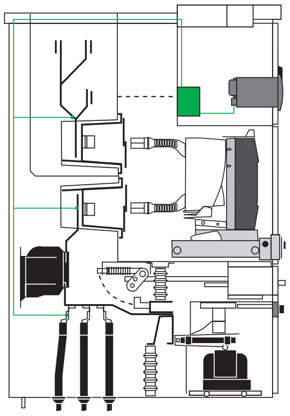

Example 5:
A very classic structure of withdrawable air-insulated switchgear (Schneider Electric MCset), with interlock accessible compartments for the connections (and CTs) and the main switching device.
The withdrawing function provides the independence of the main switching device compartment from the other HV compartments; then, the cables (and of course the busbar) can remain live when accessing the breaker.
The LSC classification applies, and category is LSC2B.

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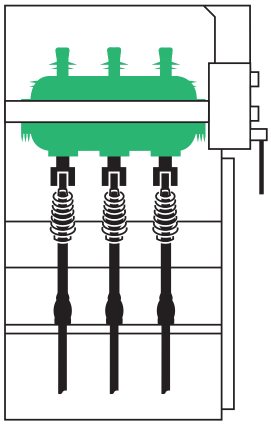

Example 6:
A typical secondary distribution switch-disconnector switchgear, with only one interlock accessible compartment for the connection (Schneider Electric SM6).
When accessing one compartment within the switchboard, all other functional units are kept in service. Category is again LSC2.

Similar situation occurs with most of the Ring Main Units solutions.

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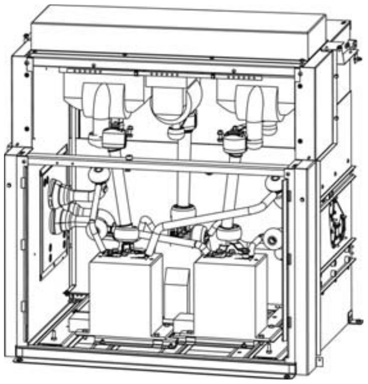


Example 7:
An unusual functional unit, available in some ranges: the metering unit which provides VTs and CTs on the busbar of an assembly (here a Schneider Electric RM6). This unit has only one compartment, accessible to possibly change the transformers, or their ratio. When accessing such a compartment, the busbar of the assembly shall be dead, then preventing any service continuity of the assembly. This functional unit is LSC1.

Design rules

Short-circuit power

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 flows.

■ 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.

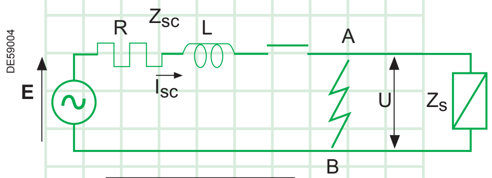
U	Operating voltage (kV)
Isc	Short-circuit current (kA rms) Ref: following pages

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

■ The customer generally imposes the value of short-circuit power 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.

Example 1:

25 kA at an operating voltage of 11 kV



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

Possible sources are:

■ Network incomer via power transformers.

■ Generator incomer.

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

Example 2:

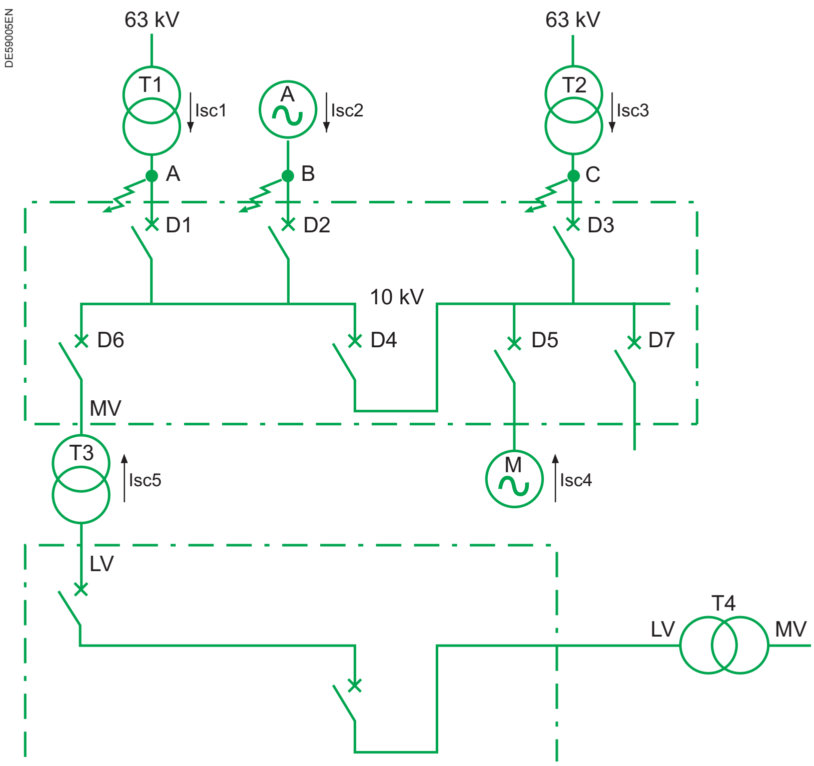
■ Feedback via LV I_{sc5} is only possible if the transformer (T4) is powered by another source.

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

□ **circuit breaker D1** (s/c at A)
$I_{sc2} + I_{sc3} + I_{sc4} + I_{sc5}$

□ **circuit breaker D2** (c/c at B)
$I_{sc1} + I_{sc3} + I_{sc4} + I_{sc5}$

□ **circuit breaker D3** (c/c at C)
$I_{sc1} + I_{sc2} + I_{sc4} + I_{sc5}$



We have to calculate each of the I_{sc} 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 shall be calculated at each stage in the installation for the various configurations that are possible within the network, in order to determine the characteristics of the equipment that has to withstand or break this fault current.

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} min = (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 device. Its value allows us to choose the setting of thresholds for overcurrent protection relays and fuses; especially when the length of the 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 downstream 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 = 62.5 kA peak for a DC time-constant of 45 ms and a rated frequency of 50 Hz (IEC 62271-100)

□ **I_{dyn}** is equal to:
2.5 • I_{sc} at 50 Hz (IEC) and 45 ms DC time-constant or,
2.6 • I_{sc} at 60 Hz (IEC) and 45 ms DC time-constant or,
2.7 • I_{sc} (IEC) for higher DC time-constants
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 - 50 kA rms.
These are generally used in the specifications.

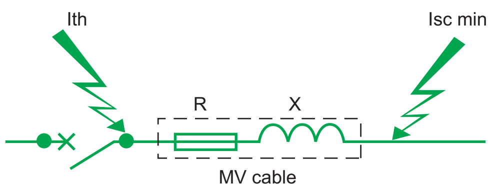
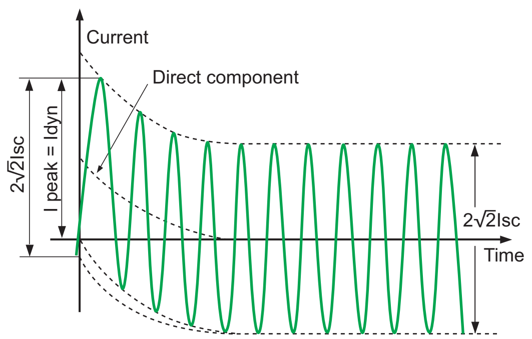


Figure 1



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:

$$I_{sc} = \frac{360}{\sqrt{3} \cdot 10} = 20.2 \text{ kA rms}$$

The difference depends on how we round up the value and on local habits.
The value 19 kA rms is probably the most realistic.
□ another explanation is possible: in medium and high voltage, IEC 60909-0 applies a coefficient of 1.1 when calculating maximal I_{sc}.

$$I_{sc} = 1.1 \cdot \frac{U}{\sqrt{3} + Z_{sc}} = \frac{E}{Z_{sc}}$$

Short-circuit currents

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

Transformer

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

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

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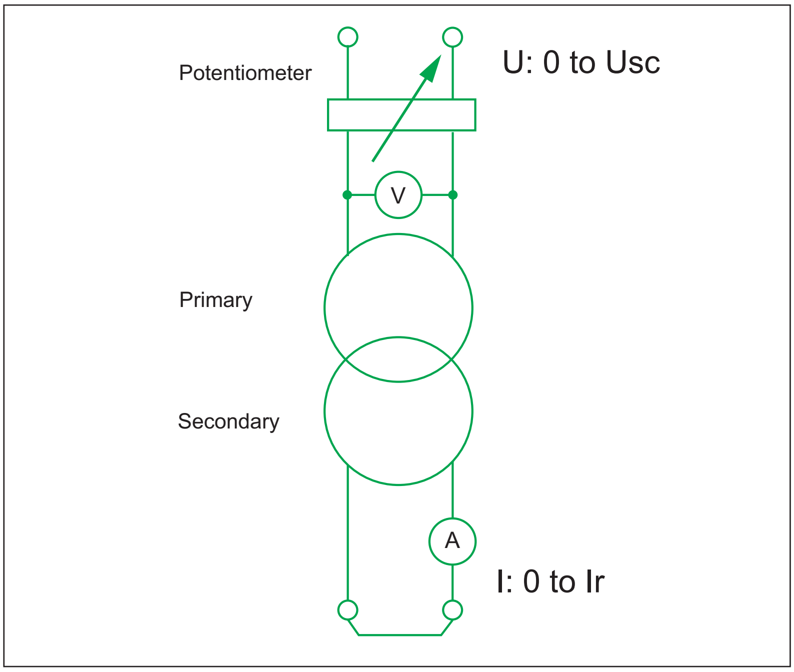

❶ The voltage transformer is not powered: U = 0
❷ **Place** the secondary in short-circuit
❸ Gradually **increase** voltage U at the primary up to the rated current I_r in the transformer secondary circuit.

The value U read across the primary is then equal to Usc

$$\text{Then } u_{sc}\ \% = \frac{U_{sc}}{U_r \text{ primary}}$$

■ 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
■ u_{sc} = 10%
■ Upstream power: infinite

$$I_r = \frac{S_r}{\sqrt{3}\ U \text{ no-load}} = \frac{20\,000}{\sqrt{3} \cdot 10} = 1150 \text{ A}$$

$$I_{sc} = \frac{I_r}{u_{sc}} = \frac{1150}{10 / 100} = 11\,500 \text{ A} = 11.5 \text{ kA}$$

Short-circuit currents

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:
□ **subtransient** (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.

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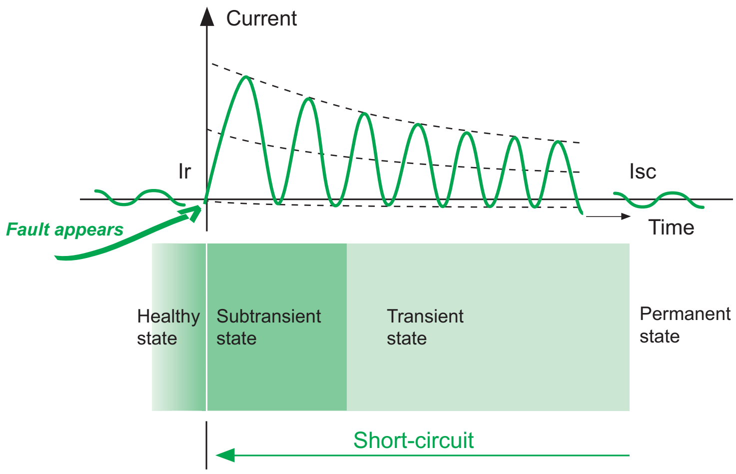

Example:
Calculation method for an alternator or a synchronous motor
■ Alternator 15 MVA
■ Voltage U = 10 kV
■ X'd = 20%

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

$$I_{sc} = \frac{I_r}{X_{sc}\ trans} = \frac{870}{20/100} = 4350\ A = 4.35\ kA$$

■ 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	Subtransient X"d	Transient X'd	Permanent Xd
X_{sc}	10 - 20%	15 - 25%	200 - 350%

Asynchronous motor

For asynchronous motors

■ The short-circuit current across the terminals equals the start-up current

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

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

$$I \approx 3 \sum I_r$$

The coefficient of 3, takes into account motors when they are stopped and the impedance to go up to the fault.

Short-circuit currents

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

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■ **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
$\rho = 1.8 \cdot 10^{-6}$ Ω cm	Copper
$\rho = 2.8 \cdot 10^{-6}$ Ω cm	Aluminium
$\rho = 3.3 \cdot 10^{-6}$ Ω cm	Almélec

■ **Synchronous generators**

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

X_{sc}	Subtransient	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; S_r = 630 kVA; U_{sc} = 4%
63 kV/11 kV; S_r = 10 MVA; U_{sc} = 9%

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

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

■ **Cables**

X = 0.10 at 0.15 W/km
Three-phased or single-phased

■ **Busbars**

X = 0.15 Ω/km

Short-circuit currents

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■ Synchronous motors and compensators

X_{sc}	Subtransient	Transient	Permanent
High speed motors	15%	25%	80%
Low speed motors	35%	50%	100%
Compensators	25%	40%	160%

■ Asynchronous motors only subtransient

$$Z_{(\Omega)} = \frac{I_r}{I_d} \cdot \frac{U^2}{S_r}$$

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

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

contribution to Isc 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:

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

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

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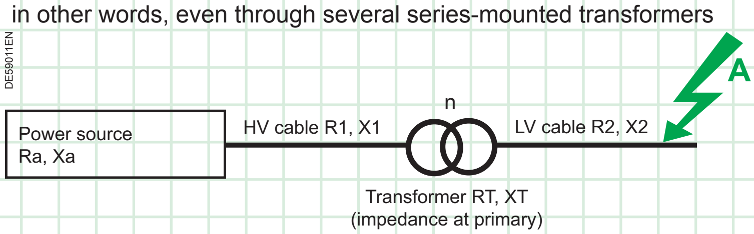


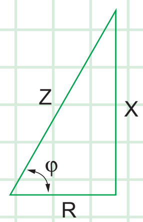
□ Impedance seen from the fault location A:

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

n: transformation ratio

■ Triangle of impedances

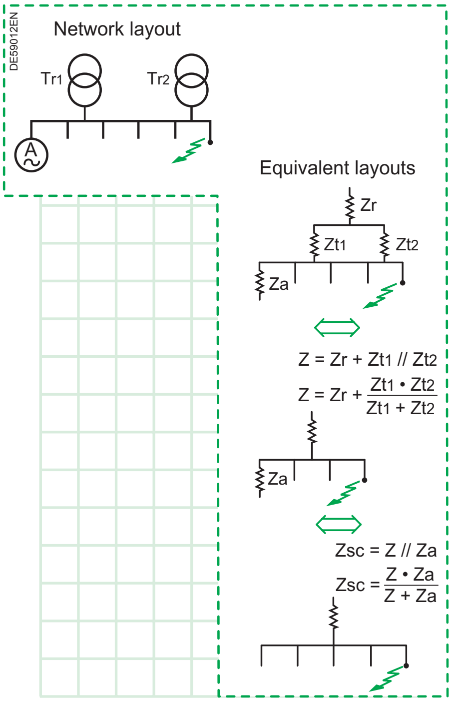
$$Z = \sqrt{(R^2 + X^2)}$$



Short-circuit currents

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 1:



Example 2:

- $Z_{sc} = 0.27\ \Omega$
- $U = 10$ kV

$$I_{sc} = \frac{10}{\sqrt{3} \cdot 0.27} = 21.38 \text{ kA}$$

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. to 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:**

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

I_{sc}	Short-circuit current	kA
U	Phase to phase voltage at the point in question before the appearance of the fault	kV
Z_{sc}	Short-circuit impedance	Ω

(Cf. to example 2 below)

Short-circuit currents

Here is a problem to solve!

Exercice data

Supply at 63 kV

Short-circuit power of the source: 2000 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%

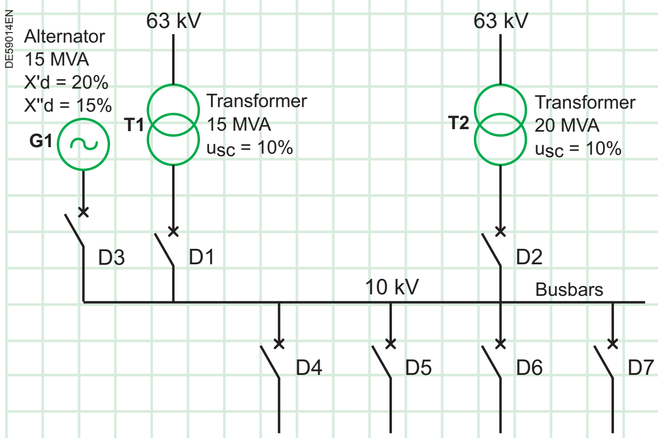
Alternator:
- voltage: 10 kV
- apparent power: 15 MVA
- X'd transient: 20%
- X"d subtransient: 15%

■ **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

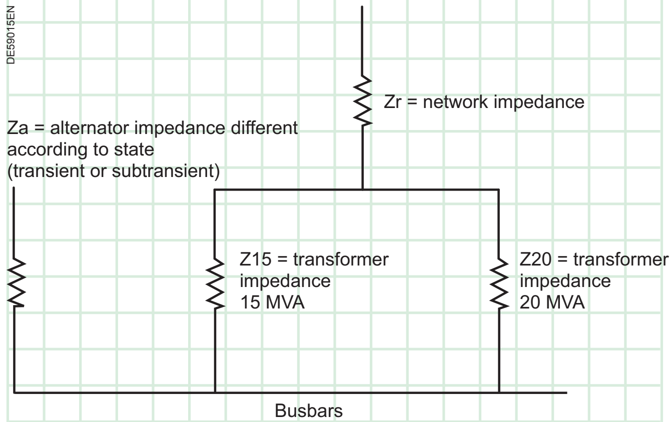


Here is the solution to the problem with the calculation method.

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 downstream of a circuit breaker (D4, D5, D6, D7), then the short-circuit current flowing through it is 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:

$$R_t = R$$

$$X_t = X$$

■ Knowing R_t and X_t, we can deduce the value of Z_t by applying the equation:

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

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

Short-circuit currents

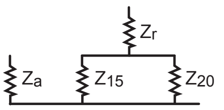
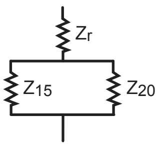
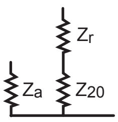
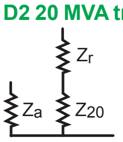
Component	Calculation	Z = X (ohms)
Network S_{sc} = 2000 MVA U op. = 10 kV	$Z_r = \frac{U^2}{S_{sc}} = \frac{10^2}{2000}$	**0.05**
15 MVA transformer (U_{sc} = 10%) U op. = 10 kV	$Z_{15} = \frac{U^2}{S_r} \cdot U_{sc} = \frac{10^2}{15} \cdot \frac{10}{100}$	**0.67**
20 MVA transformer (U_{sc} = 10%) U op. = 10 kV	$Z_{20} = \frac{U^2}{S_r} \cdot U_{sc} = \frac{10^2}{20} \cdot \frac{10}{100}$	**0.5**
15 MVA alternator U op. = 10 kV Transient state (X_{sc} = 20%) Subtransient state (X_{sc} = 15%)	$Z_a = \frac{U^2}{S_r} \cdot X_{sc}$ $Z_{at} = \frac{10^2}{15} \cdot \frac{20}{100}$ $Z_{as} = \frac{10^2}{15} \cdot \frac{15}{100}$	 Z_{at} = **1.33** Z_{as} = **1**
Busbars Parallel-mounted with the transformers Series-mounted with the network and the transformer impedance	$Z_{15} // Z_{20} = \frac{Z_{15} \cdot Z_{20}}{Z_{15} + Z_{20}} = \frac{0.67 \cdot 0.5}{0.67 + 0.5}$ $Z_r + Z_{et} = 0.05 + 0.29$	 Z_{et} = **0.29** Z_{er} = **0.34**

Parallel-mounting of the generator set
Transient state
 	
Subtransient state
	$Z_{er} // Z_{at} = \frac{Z_{er} \cdot Z_{at}}{Z_{er} + Z_{at}} = \frac{0.34 \cdot 1.33}{0.34 + 1.33}$
	
	$Z_{er} // Z_{at} = \frac{Z_{er} \cdot Z_{at}}{Z_{er} + Z_{at}} = \frac{0.34 \cdot 1}{0.34 + 1}$
		≈ 0.27
		
		≈ 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.

The breaking capacity is defined at the transient state. Subtransient period is very short (10 ms) and approximatively is the necessary duration for the protection relay to analyse the fault and give the trip order.

Circuit breaker	Equivalent circuit Z (ohm)	Breaking capacity in kA rms $I_{sc} = \frac{U^2}{\sqrt{3} \cdot Z_{sc}} = \frac{10}{\sqrt{3}} \cdot \frac{1}{Z_{sc}}$	Closing capacity 2.5 I_{sc} (in kA peak)
D4 to D7  $Z_t = [Z_r + (Z_{15}//Z_{20})] //Z_a$	Transient state Z = 0.27 Subtransient state Z = 0.25	**21.4**	21.4 • 2.5 = **53.5**
D3 alternator  $Z_t = Z_r + (Z_{15}//Z_{20})$	Z = 0.34	**17**	17 • 2.5 = **42.5**
D1 15 MVA transformer  $Z_t = (Z_r + Z_{20})//Z_a$	Transient state Z = 0.39 Subtransient state Z = 0.35	**14.8**	14.8 • 2.5 = **37**
D2 20 MVA transformer  $Z_t = (Z_r + Z_{15})//Z_a$	Transient state Z = 0.47 Subtransient state Z = 0.42	**12.3**	12.3 • 2.5 = **30.7**

Busbar calculation

Introduction

■ The dimensions of busbars are determined taking into account **normal operating conditions**.
The operation voltage (kV) of the installation 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 check that the supports (insulators) withstand the **mechanical effects** and that the bars withstand the **mechanical and thermal effects** due to short-circuit currents.
We also have to check that the natural period of vibration of 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			
S_{sc}	Network short-circuit power *		MVA
U_r	Rated voltage		kV
U	Operating voltage		kV
I_r	Rated current		A

*** N.B.:** *it 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 =* $\sqrt{3}$ *• Isc • U; see chapter on "Short-circuit currents").*

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

Physical busbar characteristics			
S	Bar 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*		K
Profile		Flat ☐	
Material		Copper ☐	Aluminium ☐
Arrangement		Flat-mounted ☐	Edge-mounted ☐
No. of bar(s) per phase:			

*** N.B.:** *see table 3 of standard IEC 62271-1 common specifications.*

In summary:

______ bar(s) of ______ x ______ cm per phase

Busbar calculation

DE59010

Temperature rise

Taken from table 3 of standard IEC 62271-1 common specifications.

Type of device, of material and of dielectric (Refer to points 1, 2 and 3)	**Temperature** θ (°C)	**(θ - θn)** with θn = 40°C
Bolt connected or equivalent devices (Refer to point 4)		
Bare copper, bare copper alloy or aluminium alloy		
In air	90	50
In SF6 *	105	65
In oil	100	60
Silver or nickel coated		
In air	115	75
In SF6	115	75
In oil	100	60
Tin-coated		
In air	105	65
In SF6	105	65
In oil	100	60

** SF6 (sulphur hexafluoride)*

Point 1 According to its function, the same part may belong to several categories as listed in table 3.

Point 2 For vacuum switching devices, the values of temperature and temperature-rise limits are not applicable for parts in vacuum. The remaining parts shall not exceed the values of temperature and temperature-rise given in table 3.

Point 3 Care shall be taken to ensure that no damage is caused to the surrounding insulation materials.

Point 4 When engaging parts having different coatings or one part is of bare material, the permissible temperature and temperature-rises shall be:
a) For contacts, those of the surface material having the lowest value permitted in item 1 of table 3.
b) For connections, those of the surface material having the highest value permitted in item 2 of table 3.

Busbar calculation

DE59010

Temperature rise

Extract from table 3 of standard IEC 62271-1 common specifications.

Type of device, of material and of dielectric (Refer to points 1, 2 and 3)	Temperature θ (°C)	$(\theta - \theta_n)$ with θ_n = 40°C
Contacts (Refer to point 4)		
Copper or bare copper alloy		
In air	75	35
In SF6 * (Refer to point 5)	90	50
In oil	80	40
Silver or nickel coated (Refer to point 6)		
In air	105	65
In SF6 (Refer to point 5)	105	65
In oil	90	50
Tin-coated (Refer to point 6)		
In air	90	50
In SF6 (Refer to point 5)	90	50
In oil	90	50

** SF6 (sulphur hexafluoride)*

Point 1 According to its function, the same part may belong to several categories as listed in table 3.

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a) for contacts, those of the surface material having the lowest value permitted in item 1 of table 3.
b) for connections, those of the surface material having the highest value permitted in item 2 of table 3.

Point 5 SF6 means pure SF6 or a mixture of SF6 and other oxygen-free gases.

Point 6 The quality of coating shall be such that a continuous layer of coating material remains in the contact area:
- After the making and breaking test (if any),
- After the short time withstand current test,
- After the mechanical endurance test,

according to the relevant specifications for each equipment. Otherwise, the contacts must be considered as “bare”.

Busbar calculation

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)

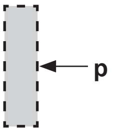
The MELSON & BOTH equation published in the "Copper Development Association" review allow us to define the permissible current in a conductor:

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

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 ($\theta_n \leq 40$°C)		**°C**
$(\theta - \theta_n)$	Permissible temperature rise*		**K**
S	Bar cross-section		**cm²**
p	Bar perimeter (see opposite diagram)		**cm**
ρ_{20}	Conductor resistivity at 20°C: ■ Copper ■ Aluminium	 1.83 µΩ cm 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)		

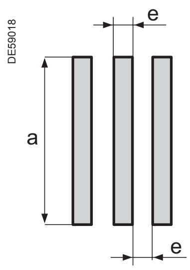
** **N.B.**: see table 3 of standard IEC 62271-1 in the previous pages.*



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 =	

Busbar calculation

■ **Coefficient k2** is a function of surface condition of the bars:
□ 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 forced 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 alternating 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 = ☐ • ☐ • ☐ • ☐ • ☐ • ☐ = ☐

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

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

I = ☐ A

The chosen solution ☐ bar(s)

of ☐ • ☐ cm per phase

Is appropriate if I_r of the required busbars ≤ I

Busbar calculation

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:

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

□ With:

$\Delta\theta_{sc}$	Short-circuit temperature rise		
c	Specific heat of the metal: ■ Copper ■ Aluminium	 0.091 kcal/kg • °C 0.23 kcal/kg • °C	
S	Bar cross-section		cm^2
n	Number of bar(s) per phase		
I_{th}	Short-time withstand current: (maximum short-circuit current, rms value)		A rms
t_k	Short-time withstand current duration (1 to 3 s)		s
δ	Density of the metal: ■ Copper ■ Aluminium	 8.9 g/cm^3 2.7 g/cm^3	
ρ_{20}	Conductor resistivity at 20°C: ■ Copper ■ Aluminium	 1.83 μΩ cm 2.90 μΩ cm	
$(\theta - \theta_n)$	Permissible temperature rise		K

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

$\Delta\theta_{sc} = \square$ K

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

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

$\theta_t = \square$ °C

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).

Example:

How can we find the value of I_{th} for a different duration?
Knowing: $(I_{th})^2 \cdot t$ = constant

■ **If I_{th2} = 26.16 kA rms 2 s, what does I_{th1} correspond to for t = 1 s ?**

$(I_{th2})^2 \cdot t$ = constant

$(26.16 \cdot 10^3)^2 \cdot 2 = 137 \cdot 10^7$

so $I_{th1} = \sqrt{\left(\frac{constant}{t}\right)} = \sqrt{\left(\frac{137 \cdot 10^7}{1}\right)}$

I_{th1} = 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

Busbar calculation

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

Electrodynamic withstand

Forces between parallel-mounted conductors

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

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

With:

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

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

S_{sc}	Bar cross-section		kVA
I_{th}	Short-time withstand current		A rms
U	Operating voltage		kV
l	Distance between insulators for same phase		cm
d	Phase to phase distance		cm
k	2.5 for 50 Hz ; 2.6 for 60 Hz and 2.7 for special time constants greater than 45 ms		

Giving: I_{dyn} = ______ A and F1 = ______ daN

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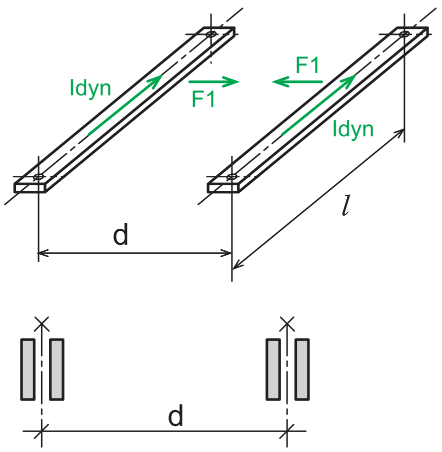

Forces at the head of supports or busducts

Equation to calculate the forces on a support:

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

With:

F	Force		daN
H	Insulator height		cm
h	distance from insulator head to bar centre of gravity		cm

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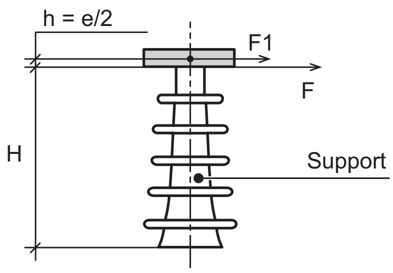


Calculation of forces if there are N supports

■ The force **F** absorbed by each support is at maximum 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:

N	2	3	4	≥ 5
k_n	0.5	1.25	1.10	1.14

Giving: F = ______ (F_1) • ______ (k_n) = ______ daN

■ 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

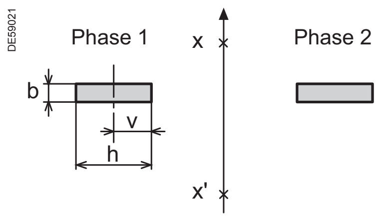
Mechanical busbar strength

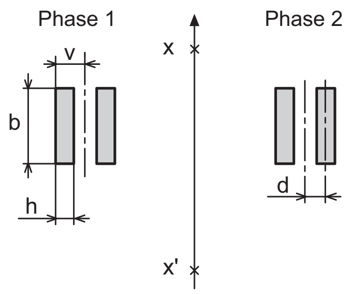
By making the assumption that the ends of the bars are sealed, they are subjected to a bending moment whose resultant stress is:

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

With:

η	Is the resultant stress, it must be **less than** the **permissible stress** for the bars this is: ■ Copper 1/4 hard 1200 daN/cm² ■ Copper 1/2 hard 2300 daN/cm² ■ Copper 4/4 hard 3000 daN/cm² ■ Tin-plated alu 1200 daN/cm²		
F_1	Force between conductors		daN
l	Distance between insulators for 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)		cm³
v	Distance between the fibre that is neutral and the fibre with the highest stress (the furthest)		





xx': perpendicular to the plane of vibration

■ **One bar per phase:**

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

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

■ **Two bars per phase:**

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

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

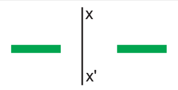
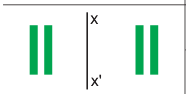
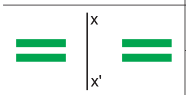
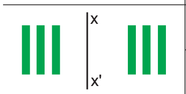
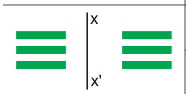
S	Bar cross-section (in cm²)

Check:

η [ ] $< \eta$ **Bars Cu or Al** [ ] **(in daN/cm²)**

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*			Bar 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	cm²	10	8	4.8	4	2.4	5	4	3	2.5
	m Cu	daN/cm	0.089	0.071	0.043	0.036	0.021	0.044	0.036	0.027	0.022
	A5/L	daN/cm	0.027	0.022	0.013	0.011	0.006	0.014	0.011	0.008	0.007
	**I**	cm⁴	0.83	0.66	0.144	0.083	0.018	0.416	0.213	0.09	0.05
	I/v	cm³	1.66	1.33	0.48	0.33	0.12	0.83	0.53	0.3	0.2
	**I**	cm⁴	83.33	42.66	25.6	21.33	12.8	10.41	8.33	6.25	5.2
	I/v	cm³	16.66	10.66	6.4	5.33	3.2	4.16	3.33	2.5	2.08
	**I**	cm⁴	21.66	17.33	3.74	2.16	0.47	10.83	5.54	2.34	1.35
	I/v	cm³	14.45	11.55	4.16	2.88	1.04	7.22	4.62	2.6	1.8
	**I**	cm⁴	166.66	85.33	51.2	42.66	25.6	20.83	16.66	12.5	10.41
	I/v	cm³	33.33	21.33	12.8	10.66	6.4	8.33	6.66	5	4.16
	**I**	cm⁴	82.5	66	14.25	8.25	1.78	41.25	21.12	8.91	5.16
	I/v	cm³	33	26.4	9.5	6.6	2.38	16.5	10.56	5.94	4.13
	**I**	cm⁴	250	128	76.8	64	38.4	31.25	25	18.75	15.62
	I/v	cm³	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 bars will not resonate.

f	Resonant frequency in Hz		
E	Modulus of elasticity: ■ For copper ■ For aluminium A5/L	 $1.3 \cdot 10^6$ daN/cm² $0.67 \cdot 10^6$ daN/cm²	
m	Linear mass of the bar (choose the value on the table above)		**daN/cm**
l	Length between 2 supports or busducts		**cm**
I	Moment of inertia of the bar cross-section relative to the axis x'x, perpendicular to the vibrating plane (see formula previously explained or choose the value in the table above)		**cm⁴**

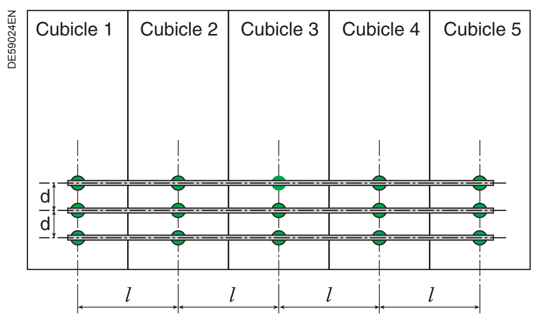
Giving f = ______ Hz

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

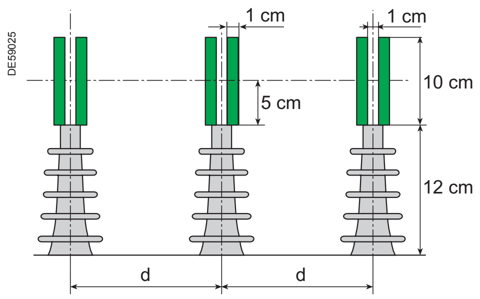
Busbar calculation

Here is a busbar calculation to check.

Top view



Side view



Drawing 1

Busbar calculation example

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	Bar cross-section (10 • 1)	*10*	**cm^2**
d	Phase to phase distance	*18*	**cm**
l	Distance between insulators for same phase	*70*	**cm**
θ_n	Ambient temperature	*40*	**°C**
$(\theta - \theta_n)$	Permissible temperature rise (90-40-50)	*50*	**K**
Profile	Flat		
Material	Bars in copper 1/4 hard, with a permissible stress η = 1200 daN/cm^2		
Arrangement	Edge-mounted		
Number of bar(s) per phase:		*2*	

■ The busbars must be able to withstand a rated current **I_r = 2500 A** on a permanent basis and a short-time withstand current **I_{th} = 31500 A rms** for a time of **tk = 3 seconds**.

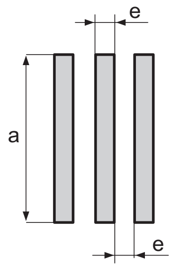
■ Rated frequency **fr = 50 Hz**

■ Other characteristics:
□ parts in contact with the busbars can withstand a maximum temperature of **θmax = 100°C**
□ the supports used have a bending resistance of **F' = 1000 daN**

Busbar calculation

Let's check
the thermal withstand
of the busbars!

DE59018



For the rated current (Ir)

The MELSON & BOTH equation allow 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)		
θ_n	Ambient temperature	*40*	°C
$(\theta - \theta_n)$	Permissible temperature rise*	*50*	K
S	Bar cross-section	*10*	cm^2
P	Bar perimeter	*22*	cm
ρ_{20}	Conductor resistivity at 20°C: *copper*	*1.83 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)		

*** N.B.:** see table 3 of standard IEC 62271-1 common specifications.*

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 =	*0.10*
Number of bars per phase =	*2*
Giving k1 =	*1.80*

Busbar calculation

■ **Coefficient k2** is a function of surface condition of the bars:
□ 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 forced 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 alternating 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 = *2* **giving k6 =** *1*

In fact we have:

$$K = 1.80 \cdot 1 \cdot 1 \cdot 0.8 \cdot 1 \cdot 1 = 1.44$$

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

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

I = *2689* **A**

The chosen solution *2* bar(s) of *10 • 1* cm per phase is appropriate:

I_r < I either 2500 A < 2689 A

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

■ We assume that for the whole duration (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:

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

With:

c	Specific heat of the metal: *copper*	*0.091 kcal/kg °C*	
S	Bar cross-section	*10*	cm^2
n	Number of bar(s) per phase	*2*	
I_{th}	Short-time withstand current: (maximum short-circuit current, rms value)	*31500*	A rms
t_k	Short-time withstand current duration (1 to 3 s)	*3*	in s
δ	Density of the metal: *copper*	*8.9 g/cm³*	
ρ_{20}	Conductor resistivity at 20°C: *copper*	*1.83 μΩ cm*	
$(\theta - \theta_n)$	Permissible temperature rise	*50*	K

□ The temperature rise due to the short-circuit is:

$$\Delta\theta_{sc} = \frac{0.24 \cdot 1.83 \; 10^{-6} \cdot (31500)^2 \cdot 3}{(2 \cdot 10)^2 \cdot 0.091 \cdot 8.9}$$

$\Delta\theta_{sc}$ = 4 K

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 = 40 + 50 + 4 = 94 °C

For I = 2689 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 I_r = 2500 A at most and not 2689 A.

Busbar calculation

■ **Let us fine tune the calculation for θ_t for I_r = 2500 A**
(rated current for the busbars)

□ the MELSON & BOTH equation, allows us to deduce the following:

$$I = \text{constant} \cdot (\theta - \theta_n)^{0.61} \text{ and}$$
$$I_r = \text{constant} \cdot (\Delta\theta)^{0.61}$$

$$\text{Therefore} \quad \frac{I}{I_r} = \left(\frac{\theta - \theta_n}{\Delta\theta}\right)^{0.61}$$

$$\frac{2689}{2500} = \left(\frac{50}{\Delta\theta}\right)^{0.61}$$

$$\frac{50}{\Delta\theta} = \left(\frac{2689}{2500}\right)^{\frac{1}{0.61}}$$

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

$$\boxed{\Delta\theta = 44.3°C}$$

□ temperature θ_t of the conductor after short-circuit, for a rated current I_r = 2500 A is:

$$\theta_t = \theta_n + \Delta\theta + \Delta\theta_{sc}$$
$$= \boxed{40} + \boxed{44.3} + \boxed{4}$$
$$= \boxed{88.3} \text{ °C for } I_r = 2500 \text{ A}$$

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).

Busbar calculation

Let's check the electrodynamic withstand of the busbars.

Forces between parallel-mounted conductors

The electrodynamic forces during a 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 for same phase	70	cm
d	Phase to phase distance	18	cm
k	For 50 Hz according to IEC	2.5	
I_{dyn}	Peak value of short-circuit current $= k \cdot I_{th} = 2.5 \cdot 31\,500 =$	78 750	A

$F1 = 2 \cdot (70/18) \cdot 78\,750^2 \cdot 10^{-8} =$ **482.3** daN

Forces at the head of supports or busducts

Equation to calculate the 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 maximum equal to the calculated force **F1** (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 ≥5 = **N**
- we know **N**, let us define k_n with the help of the table below:

N	1	3	4	≥5
k_n	0.5	1.25	1.10	1.14

Giving: F = 683 **(F_1) •** 1•14 **(k_n) =** 778 **daN**

The supports used have a bending resistance **F' = 1000 daN** calculated force **F = 778 daN**.

The solution is OK

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 stress is:

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

With:

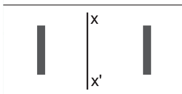
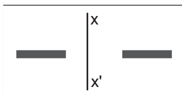
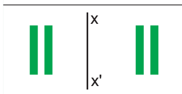
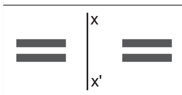
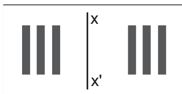
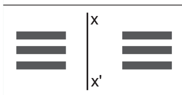
η	Is the **resultant stress in daN/cm²**		
l	Distance between insulators for same phase	*70*	cm
I/v	Is the modulus of inertia between a bar or a set of bars (value chosen in the table below)	*14.45*	cm³

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

$$\eta = 195 \text{ daN/cm}^2$$

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

The solution is OK

Arrangement				Busbar dimensions 100 x 10 (mm)
	S		cm²	*10*
	m	Cu	daN/cm	*0.089*
		A5/L	daN/cm	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

Busbar calculation

Let us check
that the chosen bars
do not resonate.

Inherent resonant frequency

The inherent resonant frequencies to avoid for bars 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	Resonant frequency in Hz		
E	Modulus of elasticity:		
m	Linear mass of the bar (choose the value on the table above)	0.089	daN/cm
l	Length between 2 supports or busducts	70	cm
I	Moment of inertia of the bar section relative to the axis x'x, perpendicular to the vibrating plane	21.66	cm^4

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

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

f = 406 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 I_r = 2500 A and I_{th} = 31.5 kA 3 s

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

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 shape of the parts
- The distance:
  - ambient air between the live parts
  - insulating air interface between the live parts.

Ambient conditions are taken into account to evaluate the insulation performance in laboratories

Pressure

The performance level of gas insulation, is related to pressure.
For a device insulated in ambient air, a drop in pressure causes a drop in insulating performance.

Humidity (IEC 60060-1 and 62271-1)

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 (SF6, N2 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 insulation material expands by between 5 and 15 times more than a conductor.

Dielectric type tests

Dielectric type tests are impulse tests (BIL) and short duration power-frequency withstand voltage tests. The voltage to apply depends on atmospheric conditions, compared to the standard reference atmosphere.

$$U = U_o \cdot K_t \quad (0.95 \le K_t \le 1.05)$$

U	is the voltage to be applied during a test on external conditions
U_o	is the rated voltage (BIL or power frequency test)
K_t	= 1 for the standard reference atmosphere Standard reference atmosphere: ■ Temperature t_o = 20°C ■ Pressure b_o = 101.3 kPa (1013 mbar) ■ Absolute humidity h_o = 11 g/m^3

Example:

- **t_o** = 22°C
- **b_o** = 99.5 kPa (995 mbar)
- **h_o** = 8 g/m^3 then K_t = 0.95.

Partial discharge

The measurement of partial discharges (IEC 62271-200) is a suitable means of detecting certain weaknesses.
However, it is not possible to establish a reliable relationship between the results of partial discharge measurement and the life expectancy. Therefore, it is not possible to give acceptance criteria for partial discharge tests carried out on a complete product.

On site, other factors may influence the insulation performance

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.

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!
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 can increase the phenomenon of partial discharges.
The level of pollution is also linked to the possible use outdoors.

Altitude

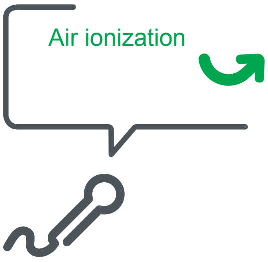
For installations at an altitude higher than 1000 m, the insulation withstand level of external insulation at the service location shall be determined by multiplying the rated insulation levels by a factor **K_a** in accordance with figure 1 of IEC 62271-1 standard.
In some cases, derating of the product is necessary.

Example:
at **H** = 2000 m
K_a = 1.15

Dielectric withstand

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:



Air ionization → Ozone production → Breakdown of moulded insulating surface skin

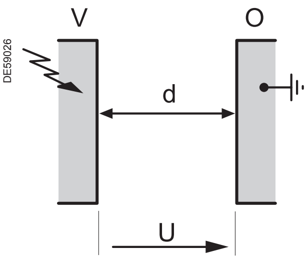
Distance between parts

Ambient air between live parts

■ For installations in which, for various reasons, we cannot test under impulse conditions, the table in publication IEC 60071-2 table VI - A 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 dielectric withstand when the altitude is less than 1000 m.

■ Distances in air* between live parts and metallic earthed structures versus BIL voltage under dry conditions:



Rated lightning impulse withstand voltage (BIL)	Minimum distance in air phase to earth and phase to phase
U_p (kV)	d (mm)
40	60
60	90
75	120
95	160
125	220
145	270
170	320

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 into account the design tolerances, short circuit effects, wind effects, operator safety, etc.

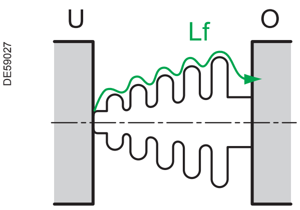
These indications are relative to a distance through a single air gap, without taking into account the breakdown voltage by tracking across the surfaces, related to pollution problems.

Dielectric digital analysis

Thanks to numerical simulation software, it is possible to design more compact products if the maximum electrical field is less than given criteria.

Insulator particular case

Sometimes insulators are used between live parts or between live parts and metallic earthed structures. The choice of an insulator shall take into account the level of pollution.
These levels of pollution are described in Technical Specification IEC TS 60815-1 clause 8. Selection and dimensionning of high-voltage insulators intended for use in polluted conditions - Part 1 - definitions, information and general principles.



Lf : tracking path

Protection index

The rated current of
an equipment is generally defined
for a usual index protection.
For higher index protection, a current
derating has to be considered.

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 water. The IP code is a coding system to indicate the protection index.

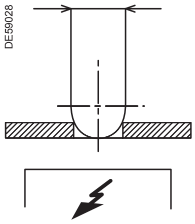
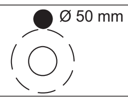
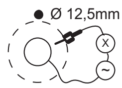
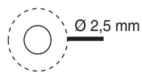
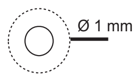
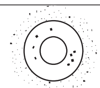
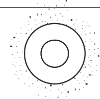
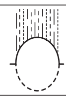
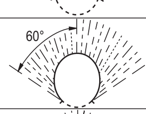
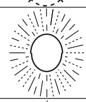
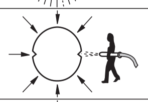
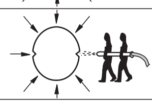
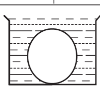
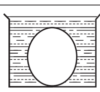
Applicational scope

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	Numerals or letters	Meaning for protection of equipment	of people	Representation
Code letter	**IP**			
First characteristic numeral		**Against penetration of solid foreign bodies**	**Against access to hazardous parts with**	
DE59028 	0	(not protected)	(not protected)	
	1	≥ 50 mm diameter	back of hand	DE59031 
	2	≥ 12.5 mm diameter	Finger	DE59032 
	3	≥ 2.5 mm diameter	Tool	DE59033 
	4	≥ 1 mm diameter	Wire	DE59034 
	5	Dust protected	Wire	DE59035 
	6	Dust-tight	Wire	DE59036 
Second characteristic numeral		**Against ingress of water with harmful effects**		
	0	(not protected)		
	1	Vertically dripping		DE59037 
	2	Dripping (15° tilted)		DE59038 
	3	Spraying		DE59039 
	4	Splashing		DE59040 
	5	Jetting		DE59041 
	6	Powerful jetting		DE59042 
	7	Temporary immersion		DE59043 
	8	Continuous immersion		DE59044 
Additional letter (optional)			**Against access to hazardous parts with:**	
	A		Back of hand	
	B		Finger	
	C		Tool	
	D		Wire	
Additional letter (optional)		**Additional information specific to:**		
	H	High voltage equipment		
	M	Motion during water test		
	S	Stationary during water test		
	W	Weather condition		

Protection index

IK code

Introction

■ The degrees of protection provided by enclosures for electrical equipment against external impacts are defined in IEC standard 62262.

■ The classification of the degrees of protection in IK codes only applies to enclosures of electrical equipment of rated voltage up to and including 72.5 kV.
According to IEC 62262, the degree of protection applies to the complete enclosure. If parts of the enclosure have different degrees of protection, they shall be precised separately.

Definitions

■ The protection index corresponds 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 index against mechanical impact can be checked by different types of hammer; pendulum hammer, spring hammer or vertical hammer.
The test devices and the methods are described in IEC standard 60068-2-75 “Environmental testing, Test Eh: hammer tests”.

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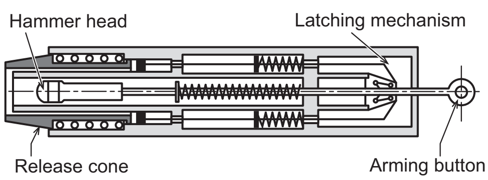
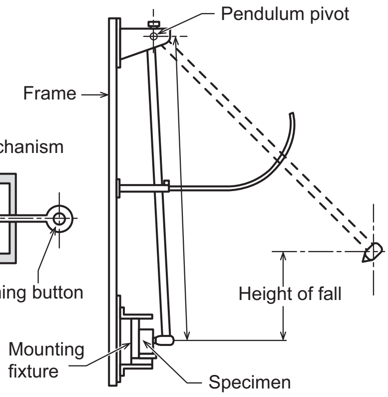


Spring hammer



Pendulum hammer

The various IK codes and their meaning

IK code	IK 00*	IK 01	IK 02	IK 03	IK 04	IK 05	IK 06	IK 07	IK 08	IK 09	IK 10
Energies in joules		0.14	0.2	0.35	0.5	0.7	1	2	5	10	20
Hammer radius mm		10	10	10	10	10	10	25	25	50	50
Hammer material		P	P	P	P	P	P	A	A	A	A
Steel = A											
Polyamide = P											
Hammer											
Pendulum		■	■	■	■	■	■	■	■	■	■
Spring loaded		■	■	■	■	■	■				
Vertical								■	■	■	■

■ = yes
(*) Not protected according to this standard.

Switchgear definition

Medium voltage circuit breaker

IEC 62271-100 and
ANSI C37-04, C37-06, C37-09
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 stress caused by the short-circuit current during 1 or 3 s
- The electrodynamic stress caused by the peak of short-circuit current:
  - 2.5 • I_{SC} for 50 Hz (standard time constant of 45 ms)
  - 2.6 • I_{SC} for 60 Hz (standard time constant of 45 ms)
  - 2.7 • I_{SC} (for longer time constant)
- 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 (cf § 4 IEC 62271-100)

a) Rated voltage
b) Rated insulation level
c) Rated frequency
d) Rated normal current
e) Rated short-time withstand current
f) Rated peak withstand current
g) Rated duration of short-circuit
h) Rated supply voltage of closing and opening devices and of auxiliary circuits
i) Rated supply frequency of closing and opening devices and of auxiliary circuits
j) Rated pressures of compressed gas supply and/or of hydraulic supply for operation, interruption and insulation, as applicable
k) Rated short-circuit breaking current
l) Transient recovery voltage related to the rated short-circuit breaking current
m) Rated short-circuit making current
n) Rated operating sequence
o) Rated time quantities.

Special rated characteristics

Rated characteristics to be given in the specific cases indicated below
p) Characteristics for short-line faults related to the rated short-circuit breaking current, for circuit breakers designed for direct connection to overhead lines, irrespective of the type of network on the source side, and rated at 15 kV and above and at more than 12.5 kA rated short-circuit breaking current
q) Rated line-charging breaking current, for three-pole circuit breakers intended for switching overhead transmission lines (mandatory for circuit breakers of rated voltages equal to or greater than 72.5 kV).
r) Rated cable-charging breaking current, for three-pole circuit breakers intended for switching cables (mandatory for circuit breakers of rated voltages equal to or less than 52 kV).

Rated characteristics to be given on request
s) Rated out-of-phase making and breaking current
t) Rated single capacitor bank breaking current
u) Rated back-to-back capacitor bank breaking current
v) Rated capacitor bank inrush making current
w) Rated back-to-back capacitor bank inrush making current.

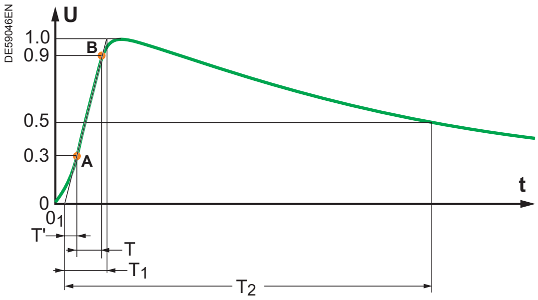
The rated characteristics of the circuit breaker are referred to the rated operating sequence.

Rated voltage (cf. § 4.1 IEC 62271-1)

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 U_r (kV) : **3.6 - 7.2 -12 - 17.5 - 24 - 36 kV.**

Medium voltage circuit breaker



$T_1 = 1.67\ T$
$T' = 0.3\ T_1 = 0.5\ T$

Figure 6: full lightning impulse

Rated insulation level (cf. § 4.2 IEC 62271-1)

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

Rated voltage	Impulse withstand voltage	Power frequency withstand voltage
(U_r in kV)	(U_p in kV)	(U_d 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 62271-1)

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 not exceeding 40°C
(cf. § 4.4.2 table 3 IEC 62271-1).

Rated short-time withstand current (cf. § 4.5 IEC 62271-1)

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

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 the rated duration of short-circuit.

■ Values of rated breaking current under maximum short-circuit (kA):
6.3 - 8 - 10 - 12.5 - 16 - 20 - 25 - 31.5 - 40 - 50 - 63 kA.

Rated peak withstand current (cf. § 4.6 IEC 62271-1) and making current (cf. § 4.103 IEC 62271-100)

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 time constants greater than 45 ms.

Rated short-circuit duration (cf. § 4.7 IEC 62271-1)

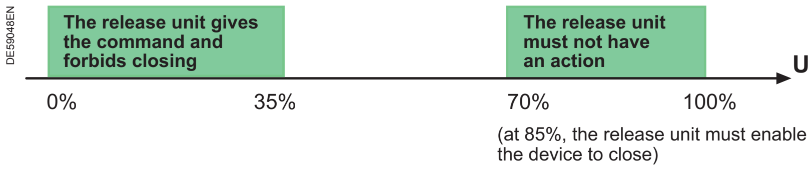
The standard value of rated duration of short-circuit is 1 s.
Other recommended values are 0.5 s, 2 s and 3 s.

Medium voltage circuit breaker

Rated supply voltage for closing and opening devices and auxiliary circuits (cf. § 4.8 IEC 62271-1)

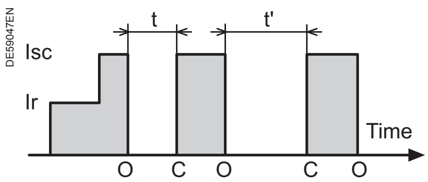
■ Values of supply voltage for auxiliary circuits:
□ for direct current (dc): **24 - 48 - 60 - 110 or 125 - 220 or 250** volts,
□ for alternating current (ac): **120 - 230** volts.

■ The operating voltages must lie within the following ranges (cf. § 5.6.4 and 5.8 of IEC 62271-1):
□ motor and closing release units:
85% to 110% of U_r in dc and ac
□ opening release units:
70% to 110% of U_r in dc
85% to 110% of U_r in ac
□ undervoltage opening release unit:



Rated frequency (cf. § 4.3 and 4.9 IEC 62271-1)

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.



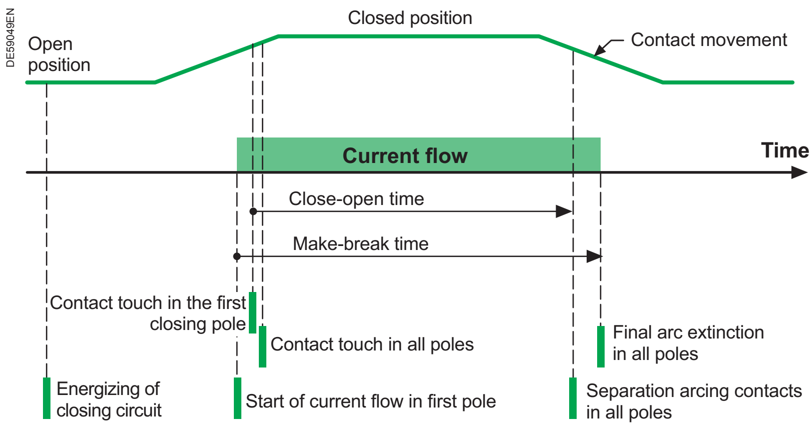
Rated operating sequence (cf. § 4.104 IEC 62271-100)

■ 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: O - 3 min - CO - 3 min - CO
□ fast 1: O - 0.3 s - CO - 3 min - CO
□ fast 2: O - 0.3 s - CO - 15 s - CO
***N.B.:** other sequences can be requested.*

■ **Close/Open 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 s or 15 s or 3 min).

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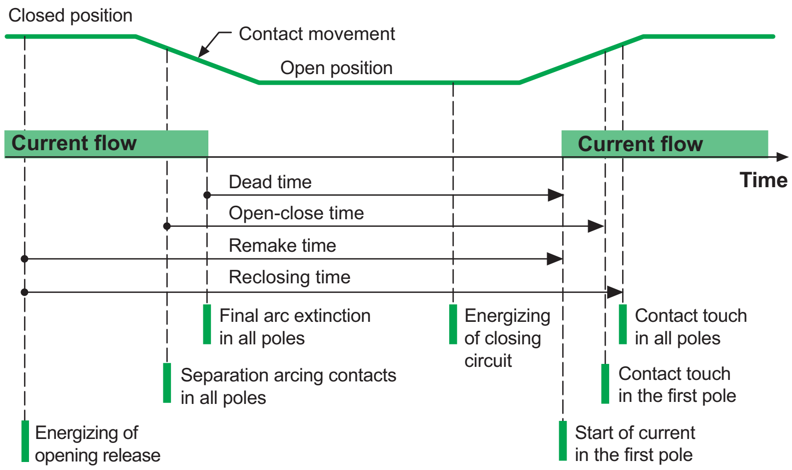

Example 1:

■ For a circuit breaker with a minimum opening time of 45 ms (T_{op}) to which we add 10 ms (T_r) due to relaying, the graph gives a percentage of the aperiodic component of around 30% for a time constant τ_1 = 45 ms:

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

Example 2:

■ Supposing that $\%_{DC}$ of a MV circuit breaker is equal to 65% and that the symmetric short-circuit current that is calculated (I_{sym}) is equal to 27 kA.

What does I_{asym} 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:

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

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

Rated short-circuit breaking current

(cf. § 4.101 IEC 62271-100)

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 time, 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 (t)

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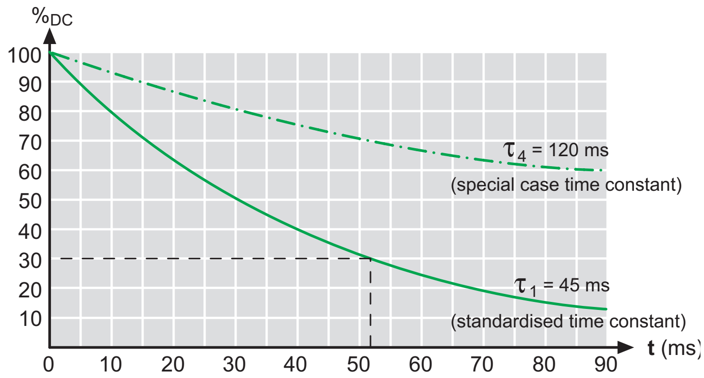
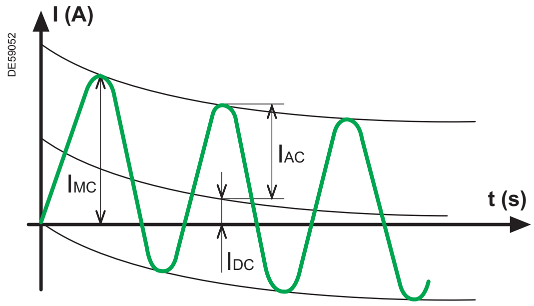


t: circuit breaker opening duration (T_{op}), increased by half a period at the power frequency (T_r).

■ As standard the IEC defines MV equipment for a time constant of 45 ms, for a peak value of maximum current equal to 2.5 • I_{SC} at 50 Hz or 2.6 • I_{SC} at 60 Hz. In this case use the τ_1 graph.



■ For low resistive circuits such as generator incomers, τ can be higher, with a peak value of maximum current equal to 2.7 • I_{SC}.
In this case use the τ_4 graph.
For all time constants τ 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 - 63 kA.

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

Sequence	% I_{sym}	% 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):

$$I_{asym}^2 = I_{sym}^2 \cdot I^2_{DC}$$

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

Rated Transient Recovery Voltage (TRV)

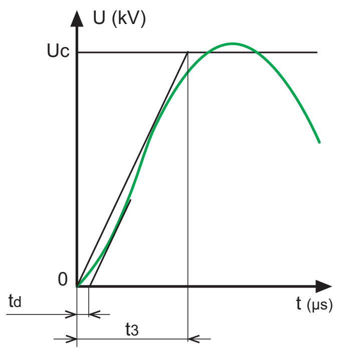
(cf. § 4.102 IEC 62271-100)

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 transient recovery voltages whose value remains below the rated TRV.

■ **First pole-to-clear 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 first open pole. The ratio of this voltage to a single phase circuit voltage is called the first pole-to-clear factor, it is equal to 1.5 for voltages up to 72.5 kV (isolated neutral of the supply circuit).

Medium voltage circuit breaker

DE59053



■ **Value of rated TRV for class S1 circuit breaker (intended to be used in cable systems)**

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

Rated voltage	TRV peak value	Time	Delay	Rate of rise of TRV
(U_r in kV)	(U_c in kV)	(t_3 in µs)	(t_d in µs)	(U_c/t_3 in kV/µs)
7.2	12.3	51	8	0.24
12	20.6	61	9	0.34
17.5	30	71	11	0.42
24	41.2	87	13	0.47
36	61.7	109	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 rate of rise	U_c/t_3 in kV/µs

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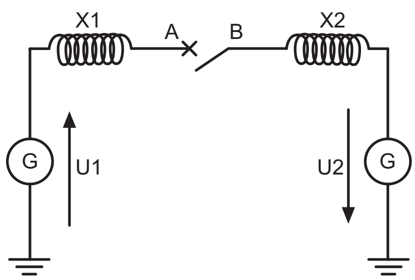

$U_A - U_B = U_1 - (-U_2) = U_1 + U_2$
if $U_1 = U_2$ then $U_A - U_B = 2U$

Rated out-of-phase breaking current

(cf. § 4.106 IEC 62271-100)

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

■ 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 power frequency recovery voltage is equal to:

□ $2 / \sqrt{3}\ U_r$ for networks with an effectively earthed neutral system

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

■ Peak value of TRV for class S1 circuit breaker, for networks other than those with effectively earthed neutral system:

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

Rated voltage	TRV value	Time	Rate of increase
(U_r in kV)	(U_c in kV)	(t_3 in µs)	(U_c/t_3 in kV/µs)
7.2	18.4	102	0.18
12	30.6	122	0.25
17.5	44.7	142	0.31
24	61.2	174	0.35
36	91.9	218	0.42

Rated cable-charging breaking current

(cf. § 4.107 IEC 62271-100)

The specification of a rated breaking current for a circuit breaker switching unloaded cables is mandatory for circuit breakers of rated voltage lower than 52 kV.

■ Normal rated breaking current values for a circuit breaker switching unloaded cables:

Rated voltage	Rated breaking curren for no-load cables
(U_r in kV)	**(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 62271-100)

The specification of a rated breaking current for a circuit breaker intended for switching unloaded overhead lines is mandatory for circuit breakers of rated voltage ≥ 72.5 kV.

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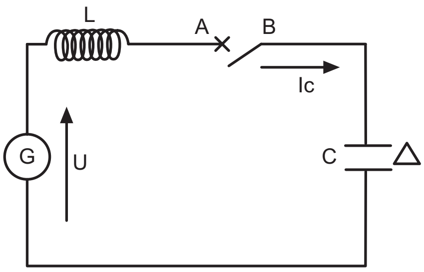

Rated single capacitor bank breaking current

(cf. § 4.107 IEC 62271-100)

The specification of a capacitor bank breaking current for a circuit breaker is not compulsory. Due to the presence of harmonics, the breaking current for capacitors is lower or equal to 0.7 times the device's rated current.

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

■ Two classes of circuit breakers are defined according to their restrike performances:

□ class C1: low probability of restrike during capacitive current breaking

□ class C2: very low probability of restrike during capacitive current breaking.

Rated back-to-back capacitor bank breaking current

(cf. § 4.107 IEC 62271-100)

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

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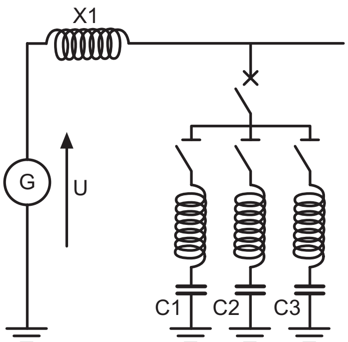


Rated capacitor bank inrush making current

(cf. § 4.107 IEC 62271-100)

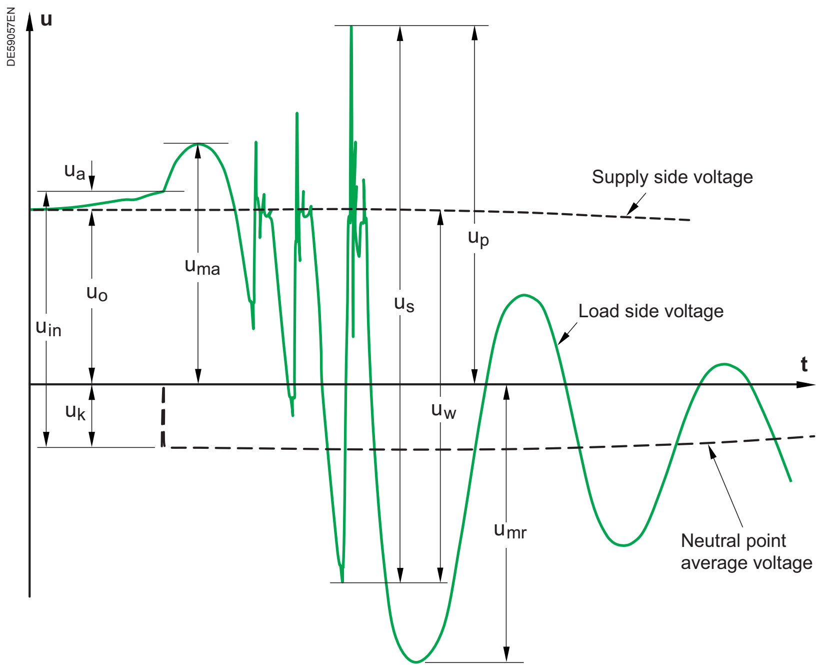
The rated making current for capacitor banks is the peak current value that the circuit breaker must be capable of making at the rated voltage. The value of the circuit breaker's rated making current must be greater than the inrush current for the capacitor bank. Formulas for calculation of inrush currents for single and back-to-back capacitor banks can be found in Annex H of IEC 62271-100. Typically the values of peak current and frequency for inrush currents are in the order of a few kA and some 100 Hz for single capacitor banks, and in the order of a few 10 kA and some 100 kHz for back-to-back capacitor banks.

Switching of small inductive current

(no rating assigned, cf. § 4.108 IEC 62271-100 and IEC 62271-110)

The breaking of low inductive currents (several amperes to several hundreds of amperes) may cause overvoltages. Surge protection should be applied in some cases according to the type of circuit breaker in order to ensure that the overvoltages do not damage the insulation of the inductive loads (unloaded transformers, motors).

■ The figure shows the various voltages on the load side

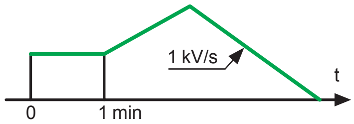


u_o	Power frequency voltage crest value to earth
u_x	Neutral voltage shift at first-pole interruption
u_a	Circuit breaker arc voltage drop
u_{in}	$= u_o + u_a + u_c$ Initial voltage at the moment of current chopping
u_{ma}	Suppression peak voltage to earth
u_{mr}	Load side voltage peak to earth
u_w	Voltage across the circuit breaker at re-ignition
u_p	Maximum overvoltage to earth (could be equal to u_{ma} or u_{mr} if no re-ignitions occur)
u_s	Maximum peak-to-peak overvoltage excursion at re-ignition

Medium voltage circuit breaker

■ **Insulation level of motors**
IEC 60034 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) front time 0.5 μs
Relative to earth	($2\ U_r + 1$) kV $2U_r + 1 \Rightarrow 2(2U_r + 1) \Rightarrow 0$ 14 kV ⇒ 28 kV ⇒ 0	($4\ U_r + 5$) kV 4.9 pu + 5 = 31 kV at 6.6 kV front time 1.2 μs



Normal operating conditions (cf. § 2 IEC 62271-1)

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

■ **Temperature**

°C	Installation	
Instantaneous ambient	**Indoor**	**Outdoor**
Minimal	–5°C	–25°C
Maximal	+40°C	+40°C

■ **Humidity**

Average relative humidity for a period (max value)	Indoor equipment
24 hours	95%
1 month	90%

■ **Altitude**
The altitude does not exceed 1000 metres.

Electrical endurance

Two classes are defined (cf. § 3.4 IEC 62271-100):

■ Class E1 with basic electrical endurance

■ Class E2 with extended electrical endurance, for circuit breakers which do not require maintenance of the interrupting parts of the main circuit during their expected operating life. Schneider Electric circuit breakers are tested according to class E2.

Mechanical endurance

Two classes are defined (cf. § 3.4 IEC 62271-100):

■ Class M1 with normal mechanical endurance (2000 operations)

■ Class M2 with extended mechanical endurance (10 000 operations).
Schneider Electric circuit breakers are tested according to class M2.

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 (K_n)

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

N.B.: *current transformers must be in conformity with IEC standard 60044-1 but can also be defined by other standards (ANSI, BR…).*

■ It comprises one or several primary windings and 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's 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 (U_{pr})

■ **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:

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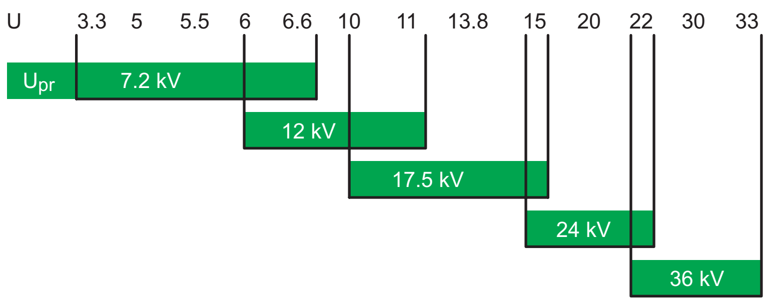


■ **Special case:**
If the CT is a **ring CT** installed on a bushing or on a cable, the dielectric insulation is provided by the cable or bushing insulation.

Current transformer

Primary operating current (I_{ps})

An installation's primary operating current I (A) (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: $\cos \varphi = 0.8$; $\eta = 0.8$.

□ 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 0.3 and $1.2 \cdot I_{rTC}$. In order to protect this motor, the required setting must correspond to the motor's rated current.

■ If we suppose that I_r for the motor = 25 A, the required setting is therefore 25 A;

□ if we use a 100/5 CT, the relay will never see 25 A because:
$100 \cdot 0.3 = 30 > 25$ A.

□ if on the other hand, we choose a CT 50/5, we will have:

$$0.3 < \frac{25}{50} < 1.2$$

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

Rated primary current (I_{pr})

The rated current (I_{pr}) 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 should be able to wihtstand 1.2 times the rated current on a constant basis to avoid too high temperature rise in the switchgear installation.*

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:

■ S_{sc} = 250 MVA
■ U = 15 kV

$$I_{th\ 1\ s} = \frac{S_{sc} \cdot 10^3}{U \cdot \sqrt{3}} = \frac{250 \cdot 10^3}{15 \cdot \sqrt{3}} = 9600\ A$$

■ **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
K_{si} > 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 0.2 - 0.5
■ Switchboard metering: class 0.5 - 1
■ Overcurrent protection: class 5P
■ Differential protection: class PX
■ 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: $P = R \cdot I^2$ and $R = \rho \cdot L/S$ 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 mm^2

Example:

■ Cable section:	2.5 mm^2
■ Cable length (feed/return):	5.8 m
■ Consumed power by the cabling:	1 VA

□ Indicative secondary cabling consumption

Cables (mm^2)	Consumption (VA/m)	
	1 A	5 A
2.5	0.008	0.2
4	0.005	0.13
6	0.003	0.09
10	0.002	0.05

■ **Consumption of metering or protection devices**

Consumption of various devices are given in the manufacturer's technical data sheet.

□ Indicative metering consumptions

Device		Max. consumption in VA (per circuit)
Ammeter	Electromagnetic	3
	Electronic	1
Transducer	Self-powered	3
	External powered	1
Meter	Induction	2
	Electronic	1
	Wattmeter, varmeter	1

□ Indicative protection consumptions

Device	Max. consumption in VA (per circuit)
Static overcurrent relay	0.2 to 1
Electromagnetic overcurrent relay	1 to 8

Current transformer

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 VA.

Instrument security factor (FS)

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

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

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

■ A transducer is generally designed to withstand a short-time current of 50 I_r, i.e. 250 A for a 5 A device.
To be sure that this device will not be destroyed in the case of a primary fault, the current transformer must be saturated before 50 I_r in the secondary.
A safety factory of 10 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.

Current transformer

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:

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

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.

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

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

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

I_{re}	Relay threshold setting

□ if the maximum short-circuit current is less than 10 I_{re}:

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

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

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

I_{r2}	instantaneous high setting threshold for the module

Differential protection

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

■ Class PX is often requested in the form of:

$$E_k \leq a \cdot I_f \, (R_{ct} + R_b + R_r)$$

The exact equation is given by the relay manufacturer.

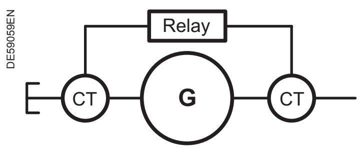
Values characterising the CT

E_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 E_k?

■ The short-circuit current is chosen as a function of the application:
□ generator set differential
□ motor differential
□ transformer differential
□ bar differential.

■ **For a generator set differential:**



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

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

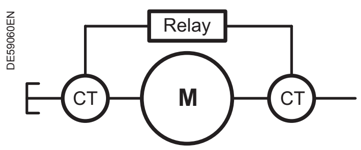
□ if the $I_{r\ gen}$ is known: we will take

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

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

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

■ **For motor differential:**



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

$$I_{sc} = I_{\text{start-up}} \qquad I_f = \frac{I_{sc}}{K_n}$$

□ 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

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

Reminder

I_r	Rated current

Current transformer

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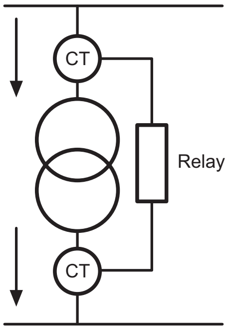

■ **For a transformer differential**

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:

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

■ **For bar differential**

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

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

■ **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}.

LPCT: Electronic current transformers

LPCT's (Low Power Current Transformers) meet IEC standard IEC 60044-8.
These are current sensors with a direct voltage output which has the advantage of having a very wide range of applications, simplifying selection.

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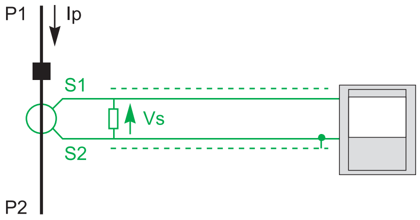

LPCT low power current transformers

LPCT's are specific current sensors with a direct voltage output of the "Low Power Current Transformers" type, in conformity with standard IEC 60044-8. LPCT's provide metering and protection functions.
They are defined by:
- The rated primary current
- The extended primary current
- The accuracy limit primary current or the accuracy limit factor.

These have a linear response over a large current range and do not start to saturate until beyond the currents to be broken.

Examples of LPCT characteristics according to IEC standard 60044-8

These characteristics are summarized in the curves below. They show the maximum error limits (as an absolute value) on the current and the phase corresponding to the accuracy class for the given examples.

Example for metering class 0.5
- Rated primary current I_{pn} = 100 A
- Extended primary current I_{pe} = 1250 A
- Secondary voltage V_{sn} = 22.5 mV (for 100 A on the secondary)
- Class 0.5:
  - □ accuracy on:
    - – the primary current module 0.5% (error ⩽ ± 0.5%)
    - – the primary current phase 60 min (error ⩽ 30 minutes)

over a range of 100 A to 1250 A
- □ accuracy 0.75% and 45 min at 20 A
- □ accuracy 1.5% and 90 min at 5 A.

which are two metering points specified by the standard.

Example for class 5P protection
- Primary current I_{pn} = 100 A
- Secondary voltage V_{sn} = 22.5 mV
- Class 5P:
  - □ accuracy on:
    - – the primary current module 5% (error ⩽ ± 5%)
    - – the primary current phase 60 min (error ⩽ 60 minutes)

on a range of 1.25 kA to 40 kA.

The LPCT and Sepam guarantees a very high coverage range and flexibility of usage.
Example: protection system with CLP1 or CLP2 and Sepam guaranteeing a usage range of 5 A to 1250 A.

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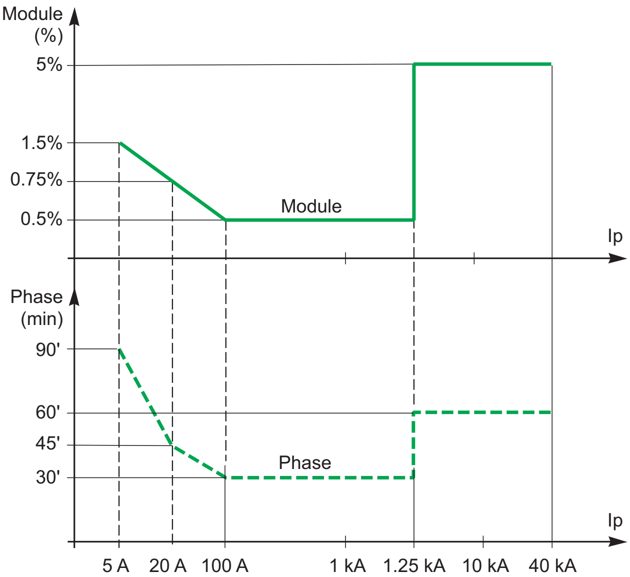


Accuracy characteristics of a LPCT (example of Schneider Electric's CLP1): the accuracy classes are given for extended current ranges (here class 0.5 for metering from 100 to 1250 A and protection class 5P from 1.25 to 40 kA).

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 60044-2 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 (V_F)

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** $\frac{3000\ V}{\sqrt{3}} / \frac{100\ V}{\sqrt{3}}$ $\quad U_{pr} = \frac{U}{\sqrt{3}}$
- **or phase to phase** $3000\ V / 100V$ $\quad U_{pr} = U$

Voltage transformer

Rated secondary voltage (U_{sr})

■ 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 $\sqrt{3}$.

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

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 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 60044-2

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 60044-2

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 ($kT \times U_{pr}$)
□ 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 $kT \cdot U_{pr}$	Between 2% and 5% U_{pr}	Between 5% U_{pr} and $kT \cdot U_{pr}$	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 VT

Voltage ratio error

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

$$\text{Voltage error \%} = \frac{(K_n\, U_{sr} - U_{pr}) \bullet 100}{U_{pr}}$$

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 product 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 has to be considered:**
□ in terms of the insulation level, for altitudes over 1000 metres
□ in terms of the rated current, when the ambient temperature exceeds 40°C and for a protection index over IP3X, (see chapter on "Protection indices").
These different types of derating can be cumulated if necessary.

N.B.: *there are no standards specifically dealing with derating.*
However, table 3 of IEC 62271-1 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.

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 min.

■ 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

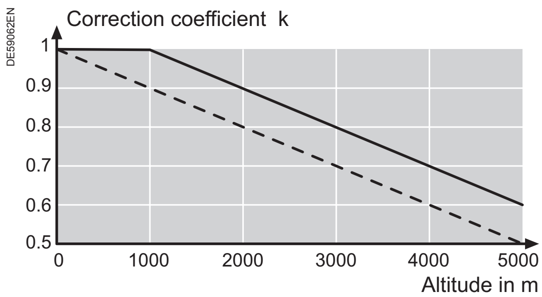
N.B.:
In some cases, 24 kV equipment may be used if appropriate test reports proving the compliance with the request are available.

Insulation derating according to altitude

Standards give a derating for all equipment installed at an altitude greater than 1000 metres.
As a general rule, we have to derate by 1.25% U peak every 100 metres above 1000 metres.
This applies for the lightning impulse withstand voltage and the power frequency withstand voltage 50 Hz - 1 min. 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 into account when the circuit breaker is installed in cubicles. In this case, external insulation is in air.

■ **Schneider Electric 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).



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 62271-1 table 3 defines the maximum permissible temperature rise for each device, material and dielectric medium 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.

Units of measure

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	Q
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	A
Solid angle	Ω, (ω)	Steradian	sr	W

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 longer 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 (agriculture measure)
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/21600 = 2.908 882 • 10^{-4} rad Second ("): 1" = 2π rad/1296 000 = 4.848 137 • 10^{-6} rad
Solid angle	Ω, (ω)	N/A	Steradian (sr)	
Time	t	T	Second (s)	Minute (min) 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	$\rho^{A'}$ (ρs)	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	d = ρ/ρ water
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 recommanded λ = c/f = cT (c = celerity of light)
Power level	Lp	N/A	Decibel (dB)	

(1) The symbol in brackets can also be used

(2) The temperature Celsius t is related to the thermodynamic temperature T by the relationship: t = T - 273.15

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 = 1Ω^{-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 μΩ.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)	
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
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 = 0.3048 m/s^2
Calory capacity	British thermal unit per pound	**Btu/lb**	1 Btu/lb = 2.326 • 10^3 J/kg
Heat capacity	British thermal unit per cubit foot.degree Fahrenheit	**$Btu/ft^3.°F$**	1 $Btu/ft^3.°F$ = 67.0661 • 10^3 $J/m^3.°C$
	British thermal unit per (pound.degree Fahrenheit)	**Btu/lb°F**	1 Btu/lb.°F = 4.1868 • 10^3 J(kg.°C)
Magnetic field	Oersted	**Oe**	1 Oe = 79.5774 7 A/m
Thermal conductivity	British thermal unit per square foot.hour.degree Fahrenheit	**$Btu/ft^2.h.°F$**	1 $Btu/ft^2.h.°F$ = 5.67826 $W/(m^2.°C)$
Energy	British thermal unit	**Btu**	1 Btu = 1.055056 • 10^3 J
Energy (couple)	Pound force-foot	**lbf/ft**	1 lbf.ft = 1.355818 J
	Pound force-inch	**lbf.in**	1 lbf.in = 0.112985 J
Thermal flux	British thermal unit per square foot.hour	**$Btu/ft^2.h$**	1 $Btu/ft^2.h$ = 3.1546 W/m^2
	British thermal unit per second	**Btu/s**	1 Btu/s = 1.05506 • 10^3 W
Force	Pound-force	**lbf**	1 lbf = 4.448222 N
Length	Foot	**ft, '**	1 ft = 0.3048 m
	Inch (1)	**in, "**	1 in = 25.4 mm
	Mile (UK)	**mile**	1 mile = 1.609344 km
	Knot	**-**	1852 m
	Yard (2)	**yd**	1 yd = 0.9144 m
Mass	Once (ounce)	**oz**	1 oz = 28.3495 g
	Pound (livre)	**lb**	1 lb = 0.45359237 kg
Linear mass	Pound per foot	**lb/ft**	1 lb/ft = 1.48816 kg/m
	Pound per inch	**lb/in**	1 lb/in = 17.858 kg/m
Mass per surface area	Pound per square foot	**lb/ft^2**	1 lb/ft^2 = 4.88243 kg/m^2
	Pound per square inch	**lb/in^2**	1 lb/in^2 = 703.0696 kg/m^2
Mass per volume	Pound per cubic foot	**lb/ft^3**	1 lb/ft^3 = 16.01846 kg/m^3
	Pound per cubic inch	**lb/in^3**	1 lb/in^3 = 27.6799 • 10^3 kg/m^3
Moment of inertia	Pound square foot	**$lb.ft^2$**	1 $lb.ft^2$ = 42.140 $g.m^2$
Pressure	Foot of water	**ft H_2O**	1 ft H_2O = 2.98907 • 10^3 Pa
	Inch of water	**in H_2O**	1 in H_2O = 2.49089 • 10^2 Pa
Pressure - stress	Pound force per square foot	**lbf/ft^2**	1 lbf/ft^2 = 47.88026 Pa
	Pound force per square inch (3)	**lbf/in^2 (psi)**	1 lbf/in^2 = 6.89476 • 10^3 Pa
Calorific power	British thermal unit per hour	**Btu/h**	1 Btu/h = 0.293071 W
Surface area	Square foot	**sq.ft, ft^2**	1 sq.ft = 9.2903 • 10^{-2} m^2
	Square inch	**sq.in, in^2**	1 sq.in = 6.4516 • 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	**$lbf.s/ft^2$**	1 $lbf.s/ft^2$ = 47.88026 Pa.s
	Pound per foot-second	**lb/ft.s**	1 lb/ft.s = 1.488164 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 = 1.63871 • 10^{-5} m^3
	Fluid ounce (UK)	**fl oz (UK)**	fl oz (UK) = 28.4130 cm^3
	Fluid ounce (US)	**fl oz (US)**	fl oz (US) = 29.5735 cm^3
	Gallon (UK)	**gal (UK)**	1 gaz (UK) = 4.54609 dm^3
	Gallon (US)	**gal (US)**	1 gaz (US) = 3.78541 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

Standards

The standards mentioned in this document

Where can you order
IEC publications?
IEC central office 3, rue de Varembé
CH - 1211 Geneva 20 Switzerland
www.iec.ch

■ Common specifications	**IEC 62271-1**
■ Short-circuit currents in three-phase AC systems calculation of currents	**IEC 60909-0**
■ High voltage test techniques General definitions and test requirements	**IEC 60060-1**
■ Alternating current circuit breakers	**IEC 62271-100**
■ Insulation coordination Application guide	**IEC 60071-2**
■ Inductive load switching	**IEC 62271-110**
■ Current transformers	**IEC 60044-1**
■ LPCT Electronic current transformer	**IEC 60044-8**
■ Inductive voltage transformers	**IEC 60044-2**
■ AC metal-enclosed switchgear and controlgear for rated voltages above 1 kV and up to and including 52 kV	**IEC 62271-200**
■ Selection and dimensionning of high-voltage insulators intended for use in polluted conditions - Part 1 - Definitions, information and general principles	**IEC TS 60815-1**
■ Degrees of protection provided by enclosures	**IEC 60529**
■ Degrees of protection provided by enclosures for electrical equipment against external mechanical impacts (IK code)	**IEC 62262**

IEC – ANSI/IEEE comparison

IEC - ANSI/IEEE harmonization process

Basically, the differences between IEC and ANSI/IEEE standards come from their respective philosophies.
IEC standards are based on a functional approach. Devices are defined by their performances and this allows various technological solutions.
ANSI/IEEE standards were based on the description of technological solutions. These solutions are used by the legal system as "minimum safety and functional requirements".

For years, IEC and ANSI/IEEE organizations have begun an harmonization process on some topics.
This is now supported by an agreement on joint IEC – IEEE development project, established in 2008.

Due to the process of harmonization, the standards are today in a transition phase.
This harmonization allows simplifying the standard on places where the "minor" differences exist. This is specifically true for the definitions of short circuit current and transient recovery voltages.
ANSI/IEEE has developed standards for special applications such as for instance "Autoreclosers" and "Generator Circuit_breakers".
These documents will be transformed into equivalent IEC standards after harmonization of definitions and ratings.

Harmonization should not be understood as Unification. IEC and IEEE are by nature very different organisations. The structure of the former is based on National Committees whereas the latter is based on Individuals.
Therefore IEC and ANSI/IEEE will keep their own revised harmonized standards also in the future.
Physically different network characteristics (overhead lines or cable networks, in- or out-door application) and local habits (voltage ratings and frequencies) will continue to impose their constraints on the switchgear equipment.

Rated voltages

In addition to the most common rated voltages used in IEC (see medium voltage circuit breaker section), a second list has been defined to cover IEEE usual rated voltages.

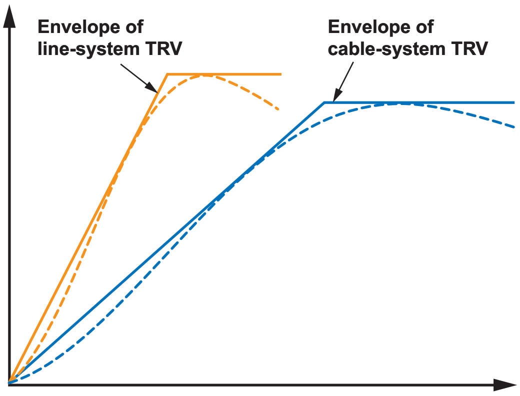
Series II (Voltages based on the current practice in some areas, like North America): 4.76 kV - 8.25 kV - 15 kV - 15.5 kV - 25.8 kV - 27 kV - 38 kV - 48.3 kV.

On the same way, two other series of insulation levels have been defined accordingly.

According to IEC/IEEE Range I Series II

Rated voltage (kV)	Rated lightning withstand voltage (kV)	Rated power frequency withstand voltage 50/60 Hz (kV)	
Indoor			
4.76	60	19	
8.25	95	36	
15	95	36	
27	125	60	
38	150	80	
Outdoor			
		Dry	**Wet**
15.5	110	50	45
25.8	150	60	50
38	200	80	75

IEC – ANSI/IEEE comparison



TRV harmonization

One of the main purpose was to define common switching and breaking tests in both IEC and ANSI/IEEE standards.

Since 1995, three main actions have been undertaken:

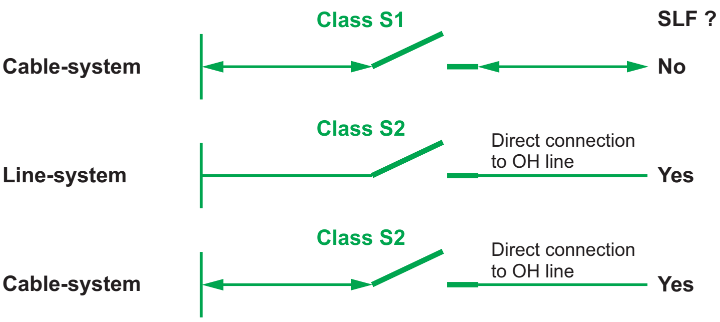
- Harmonization of TRVs for breaking tests of circuit breakers rated 100 kV and higher,
- Harmonization of TRVs for breaking tests of circuit breakers rated less than 100 kV.
- Harmonization of ratings and test requirements for capacitive current switching.

IEC introduced 2 classes of circuit breakers, defined by 2 TRV characteristics in IEC 62271-100 (2007): ANSI/IEEE will be using the same classes in the next revision

- S1 for cable-systems
- S2 for line-systems,

As some S2 breakers of voltages below 52 kV may be directly connected to an overhead line, they have to pass a short line fault breaking test.

Classes of circuit breakers



***N.B.:** short-line fault breaking performance is required for class S2*

Capacitive switching

Capacitive switching tests are also harmonized.
Class C1 of circuit breakers with low probability of restrikes and a new class C2 of circuit breakers with very low probability of restrike were introduced. The rated values and acceptance criteria still remain different for the two standards.

Assembled products

There is no harmonization for assembled products. Assembled products include metal-enclosed or insulation enclosed MV switchgear or Gas insulated switchgear. Today no coordinated action exists to harmonize the assemblies standards in IEC and IEEE/ANSI. Therefore many salient differences persist. These are caused by network and local habits as stated earlier.

IEC/ANSI major discrepancies

Identified differences

Two main categories are listed, according to the influence on the design or on the qualification tests. In each case of design difference, it should be clear if the point is a requirement which does exist in one system and not in the other, or if a requirement is expressed in conflicting manners between the two systems. For testing procedure differences, the question concerns the possibility to cover one system requirements by the qualification according to the other system.

Ratings

■ **C37.20.2**, which covers metalclad switchgear, considers a minimal bus rating of 1200 A for metal-clad (withdrawable).

Short-circuit withstand is expressed in two different ways:
□ IEC defines the rms value of the alternative component (duration to be assigned) and the peak value
□ ANSI defines the rms value to the alternative component for 2 seconds, and the “momentary current” which means the rms value, including DC component, during major first peak.

■ **C37.20.3**, which covers metal-enclosed switches, considers the “normal” short time withstand current duration to be 2 s (the preferred value for the IEC is 1 s).

Design

■ **Max. allowed temperatures differ**; reference for IEC is provided by 62271-1; reference for ANSI is provided by IEEEstd1, as well as C37.20.2, C37.20.3, C37.20.4.
□ acceptable temperature rises are much lower in ANSI than IEC.
For instance, for bare copper-copper joints, the C37.20.3 (& C37.20.4) specifies a max. overhaul temperature of 70°C, while IEC accepts up to 90°C. Furthermore, ANSI considers all plating materials as equivalent (tin, silver, nickel) while IEC specifies different acceptable values.
ANSI/IEEE requires that the lower temperature limit be used when two different contact surfaces are mated. Special values are provided by ANSI when connecting an insulated cable (value lower than the equivalent joint between two bare bars)
□ acceptable temperatures for accessible parts are also lower for ANSI (50°C versus 70°C, when touched for normal operation, and 70°C versus 80°C, when not touched during normal operation). Not accessible external parts have also a maximum allowed temperature in ANSI: 110°C.
□ ANSI C37.20.2, C37.20.3 defines max. air temperature in cable compartments (65°C); no known equivalence for IEC
□ ANSI C37.20.2 defines max. accessible surfaces temperatures (operation 50°C/ accessible 70°C/ not accessible 110°C), to be checked for IEC

■ **Mechanical endurance for withdraw operations** is stated as 100 operations for ANSI C37.20.2, 50 for ANSI C37.20.3. It is the same for IEC 62271-200, except if the withdraw capability is intended to be used as disconnecting function (to be stated by the manufacturer), then minimum 1000 operations as for disconnectors.

IEC – ANSI/IEEE comparison

■ **Other design discrepancies**
□ insulating materials have minimum fire performances stated in ANSI, not currently in the IEC.
□ ANSI C37.20.2 and C37.20.3 requires ground bus with momentary and short-time current capability. IEC accepts current flowing through the enclosure, and the performance test is performed as a functional test (if bus is made of copper, minimum cross section is expressed).
□ ANSI C37.20.2 requires that VT are fitted with current limiting fuses on HV side.
□ ANSI C37.20.3 requires the CTs to be rated at 55°C.
□ ANSI C37.20.2 and C37.20.3 specify minimum thickness for metal sheets (steel equivalent: 1.9 mm everywhere, and 3 mm between vertical sections and between "major parts" of primary circuit; larger values apply for large panels). IEC 62271-200 does not specify any material nor thickness for the enclosure and partitions, but functional properties (electrical continuity, by means of a DC test with maximum drop of voltage).
□ ANSI C37.20.2 specifies minimum number of hinges and latch points according to dimensions.
□ ANSI metalclad shall have insulated primary conductors (minimum withstand = phase to phase voltage)
□ ANSI metalclad shall have barriers between sections of each circuit. That applies to the busbar, the compartment of which shall be split in "sections" along the switchboard
□ for ANSI, withdrawable CBs shall be prevented by interlock from complete draw-out until their mechanism is discharged
□ ANSI expresses dimensional requirements for the connection points of switches (NEMA CC1-1993)
□ position indicators differ by color and markings
□ auxiliary power supplies shall have a short-circuit protection within the switchgear for ANSI C37.20.3
□ ANSI: primary connections of VTs shall incorporate fuses. Secondary connections according to the application.

Basic testing procedures

■ For withdrawable cubicles, power frequency dielectric test between upstream and downstream conductors in the withdrawn position are specified as 110% of the value phase to ground in ANSI in all cases. For IEC, a test at the open gap value of disconnectors is required only if the withdraw capability is intended to be used as disconnecting function (to be stated by the manufacturer).

■ Momentary current test to be at least 10 periods long for ANSI, peak current withstand test to be at least 300 ms long for the IEC (and making tests to have at least 200 ms current after).

■ For ANSI, all insulating materials, bulk or applied, need to demonstrate minimum flame-resistance (C37.20.2 § 5.2.6 and 5.2.7). The topic is not yet addressed by the IEC, but under discussion for the revision of the "common specifications" standard.

■ For ANSI, paint on external ferrous parts needs to demonstrate protection against rust by mean of salted fog test.

■ Switches according to ANSI C37.20.3 and C37.20.4 shall withstand an "open gap" dielectric test voltages (both power frequency and impulse) 10% higher than the phase to ground value; in IEC, similar requirement is expressed only for disconnectors.

■ BIL tests have different sequences and criteria between IEC and ANSI (2/15 in IEC, 3 by 9 in ANSI). Equivalence between the two approaches is a controversial issue, and could not be considered valid.

■ ANSI/IEEE temperature rise tests: cross sections of the supplying and shorting connections are defined by the standards, with no tolerances... Therefore, they can't comply with both standards at the same time.

IEC – ANSI/IEEE comparison

- For routine tests, auxiliary circuits are checked at 1500 V x 1 min in ANSI (C37.20.3) instead of 2 kV x 1 min for IEC.
- ANSI switches according to C37.20.4 shall perform load-breaking tests before any of the optional rating tests (fault making for integral switch-fuse, cable charging switching current, unloaded transformer switching current).
- Dielectric test as condition check after power tests or mechanical endurance tests is specified at 80% of the rated power frequency withstand voltage by IEC (common clauses), and only at 75% by ANSI (C37.20.4).
- Fuse to checked current to ground during power tests of switches is specified differently in IEC and ANSI (100 mm long and 0.1mm diameter for IEC, 3 A rating or 2 inches long and #38AWG for ANSI).

References

- **MV Partner B11:**
  - introduction to prefabricated equipment (Pierre Givord)
- **MV Partner B13:**
  - instrument transformers (Venanzio Ferraro)
- **MV Partner B32:**
  - medium voltage switchgear application guide (Pierre Givord)
- **Technical leaflets:**
  - n°158 calculating short-circuit currents
  - n°166 enclosures and protection indices (Jean Pasteau)

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