UNIVERSITÀ
DEGLI STUDI DI TRIESTE

dipartimento
di ingegneria
e architettura

Abnormal operations, switching devices, safety and protections

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Fundamentals of Modern Power Systems

Short circuit and overload in electrical systems

Overcurrents

Electrical equipment is characterized by the *nominal value* of the current, referred to operation under the conditions specified by the nameplate data.

Whenever **the equipment is affected by a current value higher than the nominal one**, it is a case of operation under **overcurrent** conditions.

In the case of power lines, reference is made to their current carrying capacity (i.e., *ampacity*).

Overcurrents are divided into:

- **Overload** – typical of an electrically healthy circuit, affected by a current slightly greater than the nominal one (generally within 6÷8 times); it is bearable for a certain time and mainly causes thermal stress;
- **Short circuit** – overcurrent due to a fault, i.e., an unwanted low-impedance contact between parts at different voltages; causes very high currents, with very intense thermal and mechanical stress, potentially causing a fire.

Overload – basic concepts

The phenomenon can be due to various causes, depending on the component involved. In some cases, the overload of a component leads to the same phenomenon on another component.

Some examples of overload causes: starting of asynchronous motors, application to an asynchronous motor of a torque higher than the nominal, connection of an excessive load to a power line.

The persistence of an overload regime involves operation with a current greater than the nominal for a time equal to the duration of the overload, or until the intervention of the protections.

This results in an increase in Joule losses, and the consequent increase in the temperature of the component, starting from the normal operating temperature.

Overload – basic concepts

In ideal conditions (homogeneous and thermally isotropic body, constant temperature at every point of the body, constant ambient temperature over time) the *ideal heating curve in overload conditions* can be obtained as:

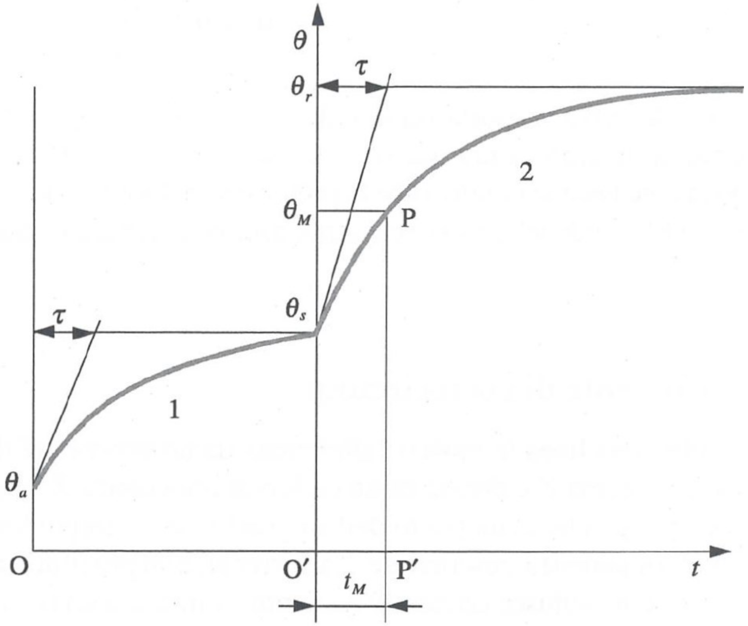
$$\theta = \theta_r - (\theta_r - \theta_s)e^{-\frac{t}{\tau}}$$

where θ_s initial temperature (service temperature), θ_r final temperature (temperature to which the component tends in overload mode), t time, τ thermal time constant of the system.

And $\tau = \frac{C_t}{\lambda A}$, with C_t thermal capacity of the component, λ overall heat transfer coefficient, A heat exchange surface.

In figure, θ_M is the *maximum permissible temperature of the component*.

Operation to the right of point P is intolerable, so t_M represents the *maximum permissible overload duration*.



Overload – basic concepts

Assuming that the amount of overload increases, there will be a greater value of power lost due to the Joule effect (P_C).

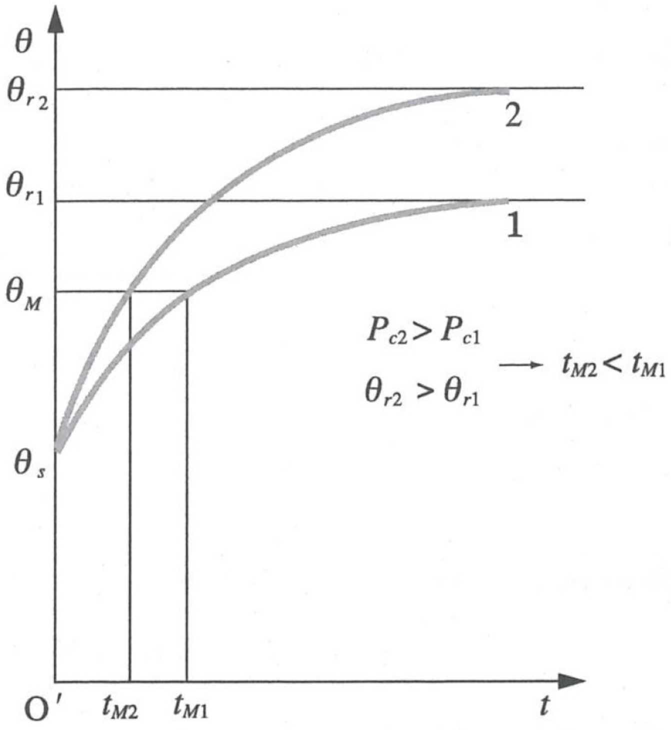
All other things being equal, the steady state temperature is given by

$$\theta_r = \theta_a + \frac{P_C}{\lambda A}$$

increases, and the curve shifts upwards (the time constant however remains the same!).

Therefore, for the same maximum permissible temperature, the permissible overload duration decreases.

This shows that the overload protection must be faster the higher the overload magnitude is (inverse time curve) and the smaller the margin between the permissible and operating temperatures is.



Short circuit – basic concepts

Short circuit currents are due to faults that bring parts with different voltages into contact, with a reduced interposed impedance.

Short circuit currents are characterized by a dynamic transient (due to the presence of inductive/capacitive elements in the circuit) and by a steady state condition.

The *total dynamic short-circuit current* can be calculated as follows:

$$i_{cc}(t) = \frac{E_M}{Z_{cc}}\left[\sin(\omega t + \gamma - \varphi_{cc}) + e^{-\left(\frac{t}{\tau}\right)}\sin(\varphi_{cc} - \gamma)\right]$$

with E_M maximum value of the impressed voltage, $\omega = 2\pi f$ angular frequency of the voltage, γ phase of the voltage at the time of the short circuit, $Z_{cc} = \sqrt{R_{cc}^2 + \omega^2 L_{cc}^2}$ impedance of the circuit upstream of the fault, $\varphi_{cc} = \tan^{-1}(\omega L_{cc}/R_{cc}), \tau = L_{cc}/R_{cc}$ circuit time constant.

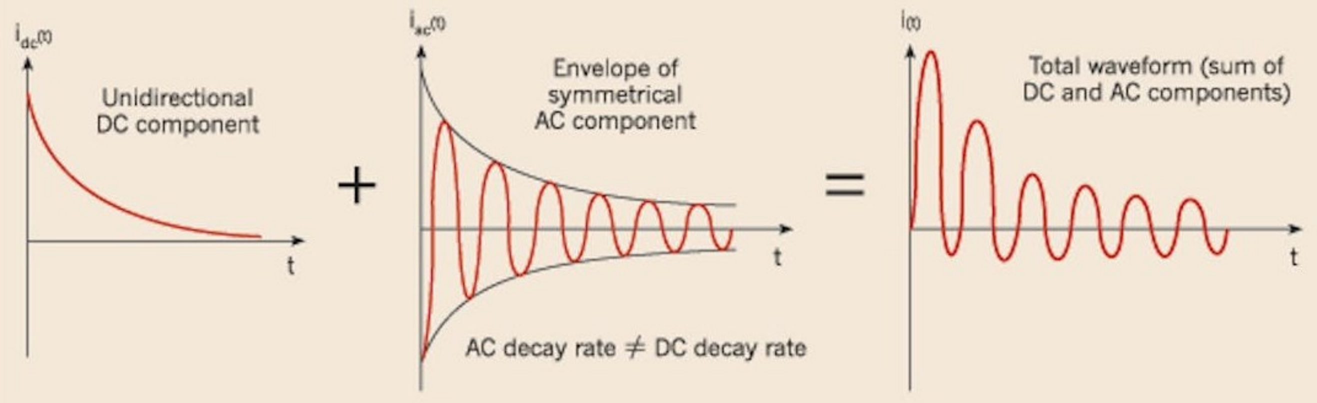
Short circuit – basic concepts

The transient short-circuit current can be divided into periodic and aperiodic components:

$$i_{cc}(t) = \frac{E_M}{Z_{cc}}\left[\underbrace{\sin(\omega t + \gamma - \varphi_{cc})}_{\text{periodic}} + \underbrace{e^{-\left(\frac{t}{\tau}\right)}\sin(\varphi_{cc} - \gamma)}_{\text{aperiodic}}\right]$$

periodic
(symmetrical AC component)

aperiodic
(unidirectional DC component)



Short circuit – basic concepts

During a short circuit, the current rises to a much higher value than that of normal operation. One of the effects of such high current on the system components is overheating.

Unlike overload, the current has a high intensity but lasts for a short period of time (depending on the intervention of the protections).

The system is therefore considered to be in adiabatic conditions (no heat exchange with the outside).

Beware: this condition is worse than reality.

Through a series of calculations that will not be demonstrated, we arrive at the following expression of the *Joule integral*, valid for cables:

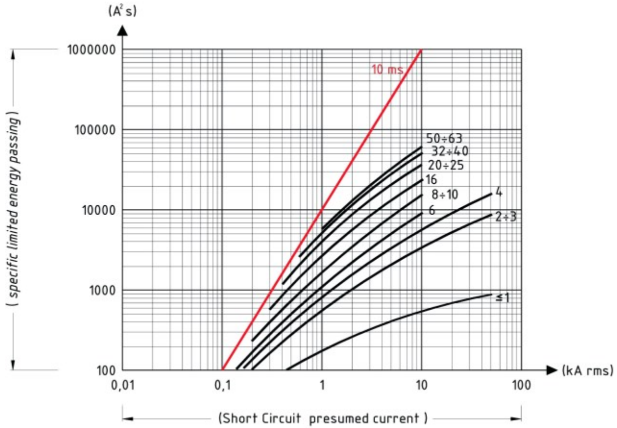
$$\int_0^{t_i} i^2 dt \leq K^2 S^2$$

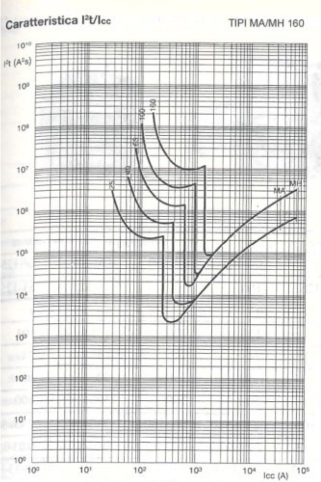
where i instantaneous current flowing in the cable; t_i upstream protection intervention time; K coefficient dependent on the type of cable insulation material; S cable section.

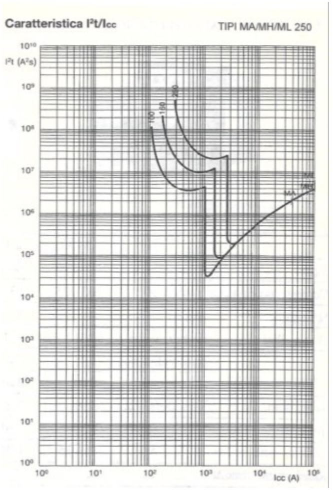
Short circuit – basic concepts

$$\int_0^{t_i} i^2 dt \leq K^2 S^2$$

The first term represents the **Joule integral specific of the protection device,** i.e. the thermal energy that is injected in the cable downstream the protection before the latter interrupts the circuit. It is a characteristic of the protection device and is provided by the manufacturer.







Short circuit – basic concepts

$$\int_0^{t_i} i^2 dt \leq K^2 S^2$$

The second term represents the **amount of thermal energy that the cable can withstand.**

The coefficient K can be calculated with the following expression:

$$K^2 = \frac{c}{\alpha \rho_0} \ln\left(\frac{1+\alpha\theta_f}{1+\alpha\theta_0}\right)$$

where: *c* specific heat per unit volume of the cable, α conductor temperature coefficient, α_0 resistivity at 0 °C of the conductor, θ_0 initial cable temperature, θ_f finale cable temperature.

Standards provides values, calculated under the hypothesis that $\theta_0 = \theta_S$ (service temperature), reported in the table:

Type of insulation	Temperature (°C)		Value of *K*	
	Initial	Final	Copper	Alluminium
PVC	70	160	115	92
EPR and XLPE	90	250	143	92
Presence of tin soldered joints or terminations	70	160	115	

Short circuit current calculation

Short circuit power

The *short circuit power* at a given point of an electrical system is the apparent power that the generators supply to the system in the event of a short circuit at that point.

In a three-phase systems it is: $S_{cc} = \sqrt{3} V I_{cc} = \frac{V^2}{Z_{cc}}$, with V phaste-to-phase voltage in the specific point, I_{cc} rms value of the steady-state fault current, Z_{cc} impedance of the circuit upstream of the fault.

For low voltage consumer power systems, to evaluate the short circuit current it is necessary to consider the impedance of the following elements:

- power supply network, down to the point of origin of the system (PCC - point of common coupling);
- presence of transformers (if the power system is equipped with its own substation);
- electric line from the PCC down to the point of failure.

Short circuit current calculation

Power supply network impedance

The power supply network upstream of the system's PCC can be seen as a voltage generator E_0 (which corresponds to the no-load phase voltage $V_0/\sqrt{3}$) with its internal impedance Z_R in series.

If the short circuit current at the PCC of the system I_{cc0} is known (provided by the electricity distribution company):

$$Z_R = \frac{V_0}{\sqrt{3} I_{cc0}}$$

If the apparent short-circuit power S_{cc0} is known (provided by the electricity distribution company):

$$Z_R = \frac{V_0^2}{S_{cc0}}$$

Short circuit current calculation

Transformer impedance

In case the line starts from the secondary terminals of a three-phase transformer, it is possible to calculate the transformer impedance thanks to its nameplate data:

- S_n nominal power
- V_{20} secondary no-load phase-to-phase voltage
- $V_{cc}\%$ Short circuit voltage in percentage
- $p_{cc}\%$ Copper power losses in percentage
- I_{2n} nominal current at secondary

$$R_e'' = \frac{V_{20}^2 p_{cc}\%}{100 S_n} \qquad Z_e'' = \frac{V_{20}^2 V_{cc}\%}{100 S_n} \qquad X_e'' = \sqrt{Z_e''^2 - X_e''^2}$$

The short-circuit current at the secondary terminals of a transformer can be calculated approximately, without taking into account the network impedance, as:

$$I_{cc} = \frac{100 I_{2n}}{V_{cc}\%}$$

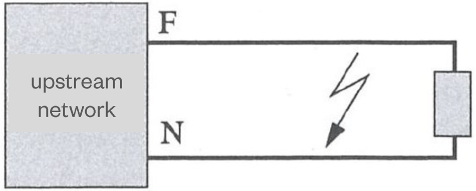
Short circuit current calculation

Short circuit current for a single-phase line

Only possible case (excluding ground faults): **phase-neutral fault**

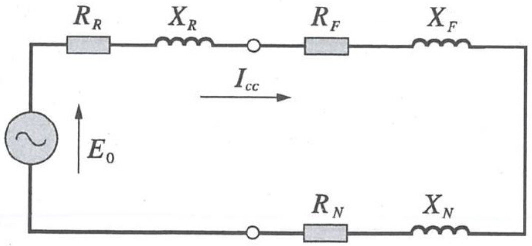
If:

- R_R and X_R upstream network resistance and reactance
- E_0 no-load voltage of the equivalent generator that models the network
- R_F and X_F resistance and reactance of the phase conductor up to the point of failure
- R_N and X_N resistance and reactance of the neutral conductor up to the point of failure



Neglecting the fault impedance we obtain:

$$I_{cc} = \frac{E_0}{\sqrt{(R_R + R_F + R_N)^2 + (X_R + X_F + X_N)^2}}$$



Short circuit current calculation

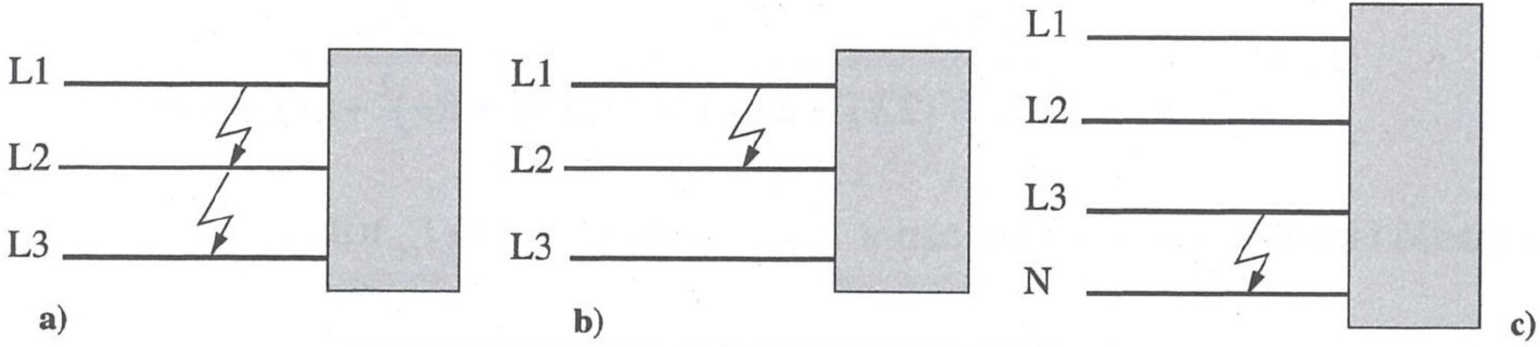
Short circuit current for a three-phase line

In this case the possible faults are:

a) three-phase fault,

b) phase-phase fault,

c) phase-neutral fault.



Short circuit current calculation

a) three-phase fault

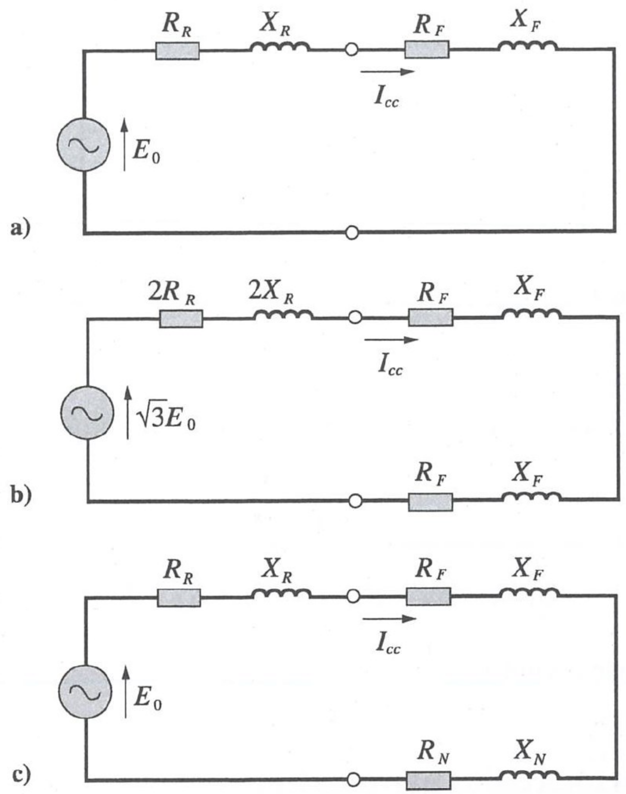
$$I_{cc} = \frac{E_0}{\sqrt{(R_R + R_F)^2 + (X_R + X_F)^2}}$$

b) phase-phase fault

$$I_{cc} = \frac{\sqrt{3}E_0}{2\sqrt{(R_R + R_F)^2 + (X_R + X_F)^2}}$$

c) phase-neutral fault

$$I_{cc} = \frac{E_0}{\sqrt{(R_R + R_F + R_N)^2 + (X_R + X_F + X_N)^2}}$$



Short circuit current calculation

Three-phase line powered by a MT/BT transformer

It is necessary to take into account the transformer parameters, calculated as shown above starting from the plate data.

The resistance and reactance of the transformer can therefore be incorporated into those of the network, provided that the values reported on the secondary are used for both:

$$R''_R = R_R + R''_e \qquad X''_R = X_R + X''_e$$

If the network parameters are negligible compared to those of the transformer (case of a system with a short-circuit power at the PCC that is very high compared to the system size), the short-circuit current can be calculated by ignoring the contribution of the network impedance.

Switching and protection devices

Classification of switching and protection devices against overcurrents

A **switching device** is a device capable of performing opening and closing operations on a circuit.

These operations can occur:

- *under load*, when the opening operation interrupts a pre-existing current and the closing operation establishes a current in the circuit;
- *under no load*, when the operation neither establishes nor interrupts currents.

Furthermore, they can occur:

- under *normal operating conditions*, to connect or disconnect the circuit from the rest of the system;
- under *abnormal operating conditions* due to faults in the system; in this case, the opening operation is more frequent, as a protection action for the system, but closing operations can also occur on a faulty circuit.

Classification of switching and protection devices against overcurrents

In relation to the type of control, we can distinguish:

- *manual control*, when the maneuver is carried out by the operator (directly on the device or by means of remote-control devices);
- *automatic control*, determined by the intervention of a protection device or by a control system.

Classification of switching and protection devices against overcurrents

Depending on the type of operations they are able to perform, switching devices are divided into::

- **Circuit breaker**
  Capable of conducting current continuously up to a certain value in normal operating conditions, and of opening and closing the circuit both in normal and fault conditions; in the latter case, up to a certain value of the fault current.
  Conduction in abnormal conditions is limited to the interruption time.
  It has two stable operating positions (open or closed) in which it can remain in the absence of external actions.
  The interruption of the circuit normally occurs inside the device and is normally not visible but must be deduced from external indications.
  The contacts are separated by the insulating medium specific to the used breaker technology.

Classification of switching and protection devices against overcurrents

- **Switch**
  Capable of making, continuously carrying and interrupting currents under normal operating conditions up to a specified value, including any specified overload conditions; can carry currents under abnormal conditions for a specified time and can be designed to close such currents; cannot interrupt fault currents.
  It has two stable operating conditions (open or closed).
- **Disconnector**
  Capable of continuously conduct a given value of the normal operating current and, for a specified time, a given value of the abnormal operating current; it can open and close currents of negligible intensity and in the open position must interrupt the galvanic continuity of the circuit, ensuring a given sectioning distance between the contacts (specific function of the disconnector).
  Generally, the operation takes place in the air, in a manner visible from the outside, and is carried out in a no-load condition.
  It is a bistable device.
  In LV it can be replaced by a breaker that has a clear indication of the position of the contacts.

Classification of switching and protection devices against overcurrents

- **Switch-disconnector (or onload disconnector)**
  It is a switch that has the interruption requirements of disconnectors (visible interruption of the galvanic continuity of the circuit).
- **Pull-out breaker**
  It is a breaker providing a third operating position in addition to the open and closed ones, i.e. the extracted one, with requirements compliant with the disconnector function.
- **Contactor**
  Capable of opening and closing currents under normal conditions up to a certain value, and possibly also overload currents.
  Characterized by a high operating frequency and has the only stable operating position of the main contacts in the open position.
  It can remain in the closed position only in the presence of an external control action.

Classification of switching and protection devices against overcurrents

In the field of low voltage switching and protection devices, the technical standards also provide the following definitions:

- **Automatic circuit breaker**
  Capable of making, conducting or interrupting currents under normal conditions and, in addition, of automatically making, conducting for a specified duration and interrupting currents under specified abnormal conditions.
- **Circuit-breakers for overcurrent protection for household and similar installations**
  Aimed at connecting and disconnecting a circuit to the power supply by manual operation, and to open the circuit automatically when the current exceeds a certain value.
  The adjective *similar* extends its use to all civil systems.

Classification of switching and protection devices against overcurrents

The use of fuses to integrate the performance and functions of switching devices, in particular to also ensure protection against overcurrents, leads to different combinations:

- **Switch with fuses**
  A combined unit in which fuses are connected in series with one or more poles of a switch.
- **Fuse switch**
  Switch in which a fuse (or a fuse holder with a fuse inserted) forms the moving contact.
- **Disconnector with fuses**
  A combined unit in which fuses are connected in series with one or more poles of a disconnector.
- **Fuse disconnector**
  Disconnector in which a fuse (or a fuse holder with a fuse inserted) forms the moving contact.

Classification of switching and protection devices against overcurrents

- **Switch-disconnector with fuses**
  A combined unit in which the fuses are placed in series with one or more poles of a switch-disconnector.
- **Fuse switch-disconector**
  A switch-disconnector in which a fuse (or a fuse holder with a fuse inserted) forms the moving contact.

Classification of switching and protection devices against overcurrents

A specific classification concerns the set of switching devices required for the insertion, disinsertion and overload protection of motors, which can also be found as an integrated unit:

- **Motor starter**
  Set of all the switching devices needed to start and stop the motor, in combination with those for overload protection.
- **Direct motor starter**
  Starter that in a single operation connects the motor to the supply line and applies the line voltage to the motor terminals.
- **Forward/reverse motor starter**
  Combined unit which, in addition to the motor starter functions, also features the functions of reversing the direction of rotation during engine operation.
- **Star-delta motor starter**
  Combined unit that in addition to the starter functions allows the star-delta starting of the motor.

Functional characteristics of breakers

Rated voltage

Voltage value to which the performance of the switch refers during closing and short-circuit interruption.

For multiphase circuits reference is made to the voltage between the phases.

For switches used in LV systems, two voltages are defined:

- *nominal (or rated) operating voltage*, is the voltage value that the manufacturer specifies for the device, together with the nominal operating current, and for which it guarantees the declared performance. Multiple voltage values can be associated with the same switch, each related to a specific level of short-circuit performance. The normal values of the nominal operating voltage established by the standards are: 230 V for single- and two-pole breakers; 230/400 V for single-pole breakers; 400 V for two-, three- and four-pole breakers.
- *rated insulation voltage*, is the voltage value for which the electrical insulation of the device is sized, verified by means of specific tests. Its value must not be lower than the highest of the operating voltages of the device; when it is not specified, the highest rated operating voltage is considered.

Functional characteristics of breakers

Voltages for insulation coordination

Breakers must also have the required insulation to resist overvoltages that may arise in the system in which they are installed (discussed later).

To define the standardised insulation levels of equipment, thus also specifying the voltage values to be used in dielectric tests and to which the component insulation must resist, the following quantities are used:

- *maximum voltage for the equipment*, is the highest effective value of the voltage between the phases for which the equipment is designed regarding its insulation, and on which the standardized values of the test voltages depend;
- *standard short-time withstand voltage at industrial frequency*, indicates the rms value of the sinusoidal voltage with frequency between 48 and 62 Hz and duration 60 s, to be applied in the insulation test at industrial frequency;
- *lightning impulse withstand voltages* , indicates the peak (crest) value of the impulse voltage to be applied in the relevant insulation test.

Functional characteristics of breakers

Rated current

It represents the value of current that the breaker can conduct in assigned voltage, usage and environmental conditions to which the characteristics of the device refer.

It is linked to the thermal behavior of the switch which heats up during operation and tends to a steady temperature, linked to the value of the current and the installation conditions.

Since the thermal behavior depends on the current, the duration of its application, and the ambient temperature, the regulation takes it into account by considering various definitions for the nominal current.

- *Rated free air thermal current* is the value of current that the breaker can conduct without the overtemperatures of its various parts exceeding the values established by the standard.
  It refers to a duration long enough to reach thermal equilibrium, but not exceeding 8 hours without interruption operations (eight-hour service), with an ambient temperature generally of 40 °C, in free air without casing, other than that of the component itself.
  If the breaker is installed in an electrical panel, its performance decreases due to the reduced heat exchange and the *rated enclosed thermal current* must be considered.

Functional characteristics of breakers

- *Rated current*, refers to uninterrupted service lasting more than eight hours, without intermediate operations, in free air at an ambient temperature generally of 40°C.

Nel caso di interruttori automatici per impianti domestici e similari è definita soltanto la *corrente nominale*, concettualmente simile alla corrente ininterrotta nominale, indicata con il simbolo I_n e detta anche corrente nominale d'impiego.

In the case of circuit-breakers for overcurrent protection for household and similar, only the rated current is defined, which is conceptually similar to the above defined one.

For breakers with a voltage higher than 1000 V in alternating current, only the *rated current* is defined.

Functional characteristics of breakers

Interrupting (or breaking) capacity

The most demanding opening intervention for a circuit breaker is the maneuver during the short circuit, when the current assumes values much higher than the nominal operation. The intervention of the circuit breaker modifies both the trend and the value of the short circuit current downstream of the device, mainly due to the electric arc that occurs when the contacts open, which introduces a series impedance of unknown and variable value into the circuit. To refer the characteristics of a circuit breaker to something defined and not variable, the *prospective short circuit current* is therefore considered, i.e., the current that would be present if the circuit breaker had zero internal impedance.

In this context, the *interrupting (or breaking) capacity* of a circuit breaker is defined, i.e., the value of the maximum short circuit current (usually expressed in kA) that the circuit breaker is able to interrupt.

Depending on the type of circuit breaker and the test conditions, the symbols and meanings relating to the interrupting capacity change.

Functional characteristics of breakers

In summary:

- the *ultimate breaking capacity* represents the highest value of the breaking capacity of the device. It is not required that after the trip the circuit breaker be able to carry its nominal current (the circuit breaker can be damaged in the opening process).
- the *rated service short circuit breaking capacity*, on the other hand, is that for which the circuit breaker continues to be able to carry its nominal current after the trip (the circuit breaker must not be damaged during the opening).

For AC circuit breakers with a voltage higher than 1 kV, a single value is specified (the *rated breaking capacity*), as the capacity to carry the nominal current after the trip is always required.

The breaking capacity can also be expressed in MVA, multiplying the current value by the nominal insulation voltage.

Functional characteristics of breakers

Rated short circuit making capacity

In the event of a fault pre-existing before the closing of a circuit breaker, the latter must be able to establish the short-circuit current. The *rated short-circuit making capacity* is therefore defined as the maximum peak value of the prospective short circuit current that the circuit breaker is able to close at the nominal frequency, under specified voltage and power factor conditions.

The standards for LV circuit breakers provide minimum values for the ratio between the making capacity and the ultimate breaking capacity, together with the short-circuit power factor.

Example from CEI 17-5:

Ultimate breaking capacity (kA)	Power factor	Rated short circuit making capacity (value x I_{cu})
$4{,}5 < I_{cu} \leq 6$	0,70	1,53
$6 < I_{cu} \leq 10$	0,50	1,70
$10 < I_{cu} \leq 20$	0,30	2,00
$20 < I_{cu} \leq 50$	0,25	2,10
$50 < I_{cu}$	0,20	2,20

Functional characteristics of breakers

Rated short-time withstand current

For various reasons, breakers installed in electrical systems do not always intervene immediately when a fault occurs but can be delayed. Specifically, those specifically designed for delayed operation are classified as *category B breakers,* and those that intervene without an intentional delay are classified as *category A*. The difference is given by the fact that delayed breakers, if closed during the fault, are traversed for a certain time by high currents.

The *rated short-time withstand current* is the value of current that a switch is able to conduct, without being damaged, for a specified duration and under the prescribed conditions of use. Reference is made to the effective value of the prospective short-circuit current, considered constant for the entire expected delay time.

In MV and HV, the value of 3 s is frequently used as the reference duration, and the value of the short-time withstand current is equal to the rated short-circuit interruption current.

In LV if the short-time admissible current is equal to the nominal short-circuit breaking capacity, the duration of 1 s is used; otherwise, in addition to the value, the time must also be specified.

For category A circuit breakers, this current is not provided, as they never carry fault currents that are not interrupted by them.

Disconnectors and switches

The voltage ratings are identical to breaker ones, except for the *withstand voltage between the open contacts*, which is specific to the disconnectors. This is defined as industrial frequency and impulse.

As regards the currents, we can distinguish:

- *Rated operating current* (or *rated thermal current*), is the rms value of the current that can flow continuously without the temperature of the device exceeding the expected limits. Normal values in MV are 400 A, 630 A, 800 A, 1250 A, 1600 A, 2500 A.
- *Rated short-time withstand current* is the rms value of the symmetrical short-circuit current that the device is able to withstand for a predetermined time (usually 1 s), which is the intervention time of the associated breaker. For MV the values range from 12,5 to 60 kA.
- *Rated short-time permissible peak current*, similar to the previous one, but it concerns the peak value of the short-circuit current and much shorter times (milliseconds). The values range from 40 to 125 kA in MV.

Disconnectors and switches

- *Rated breaking capacity*, defined for switches, switch-disconnectors, and for on-load disconnectors, similar to that defined for circuit breakers. The value is quite small and depends on the type of service of the component; normally it is at most equal to the rated current of the device.
- *Rated short-circuit making (or establishment) capacity*, defined for switch-disconnectors and for on-load disconnectors, which can close even with a short-circuit in progress, and is similar to that of circuit breakers.

From a construction point of view, they can be similar to switches but without the provisions for extinguishing the arc (operating switches), or they can be simple free air contacts.

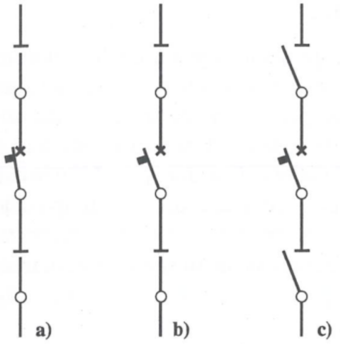
Disconnectors and switches

The operation of the disconnectors can be manual, with an electric motor, or pneumatic, depending on the types and operating voltages. Since it must be carried out without load, it must be coordinated with that of the breakers.

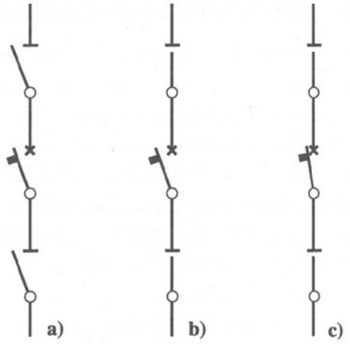
The operations are entrusted to trained personnel and, to avoid errors, mechanical blocks are mounted that make it mandatory to respect given sequences in the operations.

The disconnectors are sometimes equipped with *earthing knives* that, for safety, connect the sectioned part of the electrical system to the earth. Their operation is opposite and coordinated with that of the line disconnectors.

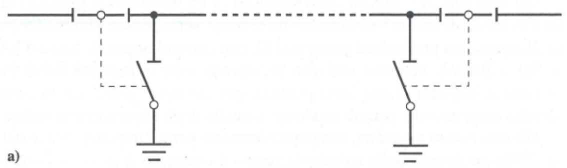
opening sequence



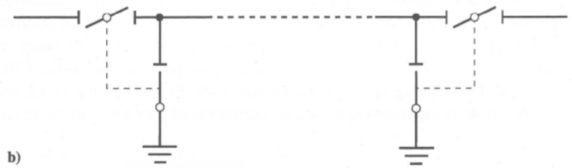
closing sequence



working line



open and grounded line



Disconnectors and switches

In three-phase networks with grounded neutral, the voltage to ground is lower than the nominal voltage (ratio $1/\sqrt{3}$) so the earthing knives are shorter. Characteristic quantities for the earthing knives are the symmetrical short-time admissible current (from 10 to 40 kA for MV devices) and peak current (from 25 to 100 kA in MV).

On-load disconnectors also have a breaking capacity and a making capacity similarly to circuit breakers, although very modest. Since they are not suitable for interrupting short-circuit currents, they can be used in place of the disconnector plus circuit breaker pair only if equipped with fuses with high breaking capacity.

LV automatic circuit breakers

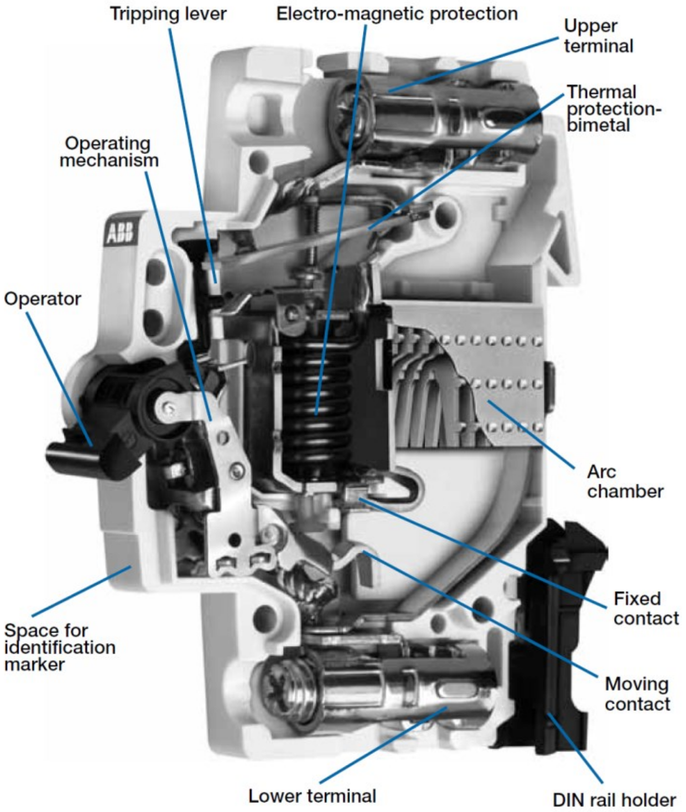
In LV civil and industrial systems, automatic circuit breakers are used, i.e. switching and protection devices formed by the union of a breaker and one or more overcurrent relays. This allows the functions of manual switching and automatic protection to be incorporated into the same device.

In addition, in the open position the distance between the contacts is sufficient to also ensure the disconnector function.

The interruption of the electric arc almost always occurs in the air, with the use of a *deion-type architecture* (explained in the following slides).

Specific product standards cover the functional characteristics of low voltage automatic circuit breakers.

Example of an automatic modular thermal magnetic breaker →

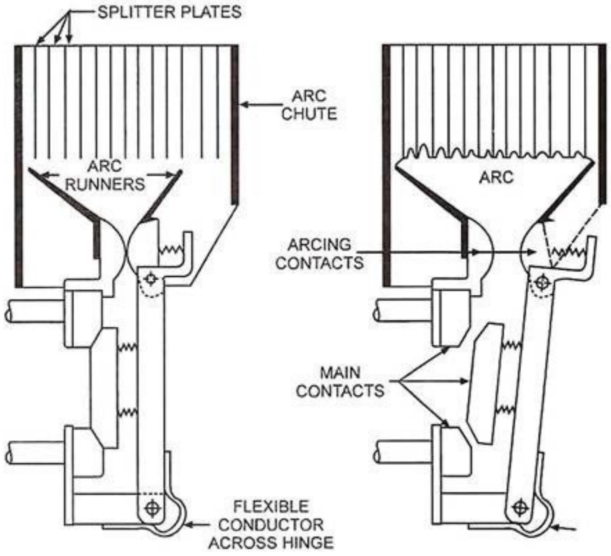


LV automatic circuit breakers

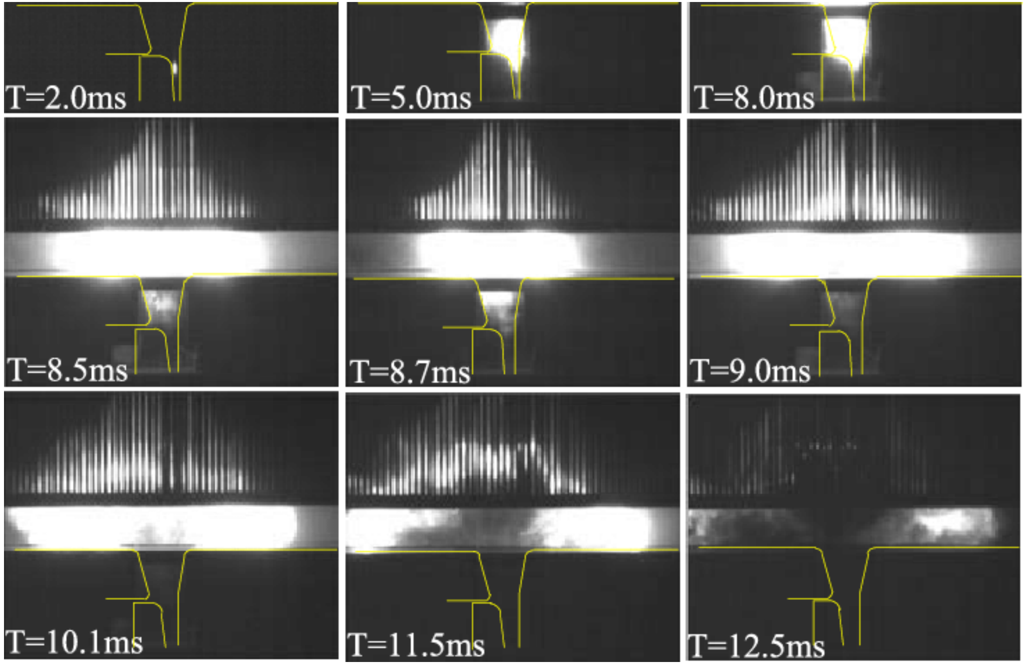
Magnetic deionization (*deion*) air breakers

The arc is formed and extinguished in air at atmospheric pressure. The shape of the contacts causes the current flowing through them to develop a magnetic field that pushes the arc (which is equivalent to a conductor carrying current) into a series of separated extinction chambers. These significantly lengthens and divides the arc, as well as cool it (being them made of ceramic material with high thermal capacity). The movement of the arc also draws fresh, non-ionized air between the main contacts, ensuring insulation recovery.

For high power applications, *blower coils* are also used, inserted at the start of the maneuver, where the current to be interrupted flows, to increase the magnetic field that pushes the arc upwards.



LV automatic circuit breakers



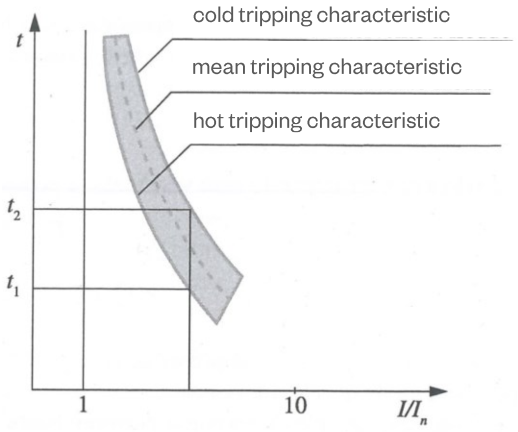
Thermal overcurrent relay

Based on the controlled deformation of two materials with different thermal expansion coefficients (bimetallic strip). The current circulating in the circuit heats the strip by Joule effect, which activates a release device. This can be a switch coupled to the relay (direct action), or it is possible to use the relay signal to control another device (indirect action).

It is an inverse time release: the higher the current, the higher the heating, the sooner the relay reaches the temperature necessary for its intervention.

The intervention speed depends on the initial temperature of the relay. If it is the ambient temperature (*cold intervention*), the intervention time will be longer than that obtainable with a relay already warm due to the current circulating in it (*hot intervention*). For this reason, the tripping characteristic is actually an area, delimited by the two cold and hot curves. The one used to define the commercial values is the *average tripping characteristic*.

It is a relay suitable for overload protection, given the proportionality between intervention time and amount of current, and given its slowness.

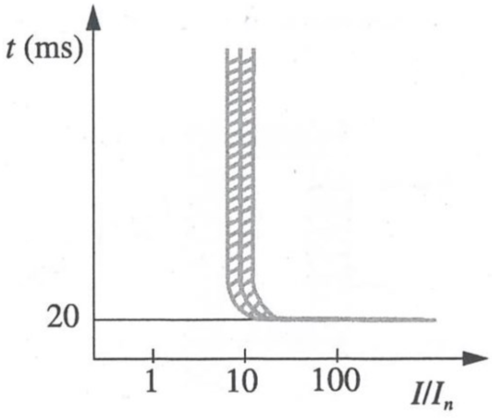


Magnetic overcurrent relay

Based on the force that an electromagnet exerts on a mobile iron core, counteracted by a calibrated spring. The current circulating in the electromagnet generates the force that, if greater than that of the spring, triggers the relay. The current for which this occurs is called *magnetic calibration current*.

The intervention can be made proportional to the current to be controlled in two ways:

- By *directly inserting* the coil, which is then traversed by all the current to be measured;
- By *indirect insertion*, when a current transformer (CT) is interposed or a shunt is used (thus limiting the section of the electromagnet turns when the current to be measured is high).



By connecting the shunt coil to the line, with an appropriate calibrated resistance in series, it is possible to use the same device to create a voltage relay.

The intervention time is independent of the current, as long as it is sufficiently high to make the relay intervene. Therefore it is a time-independent device with instantaneous tripping.

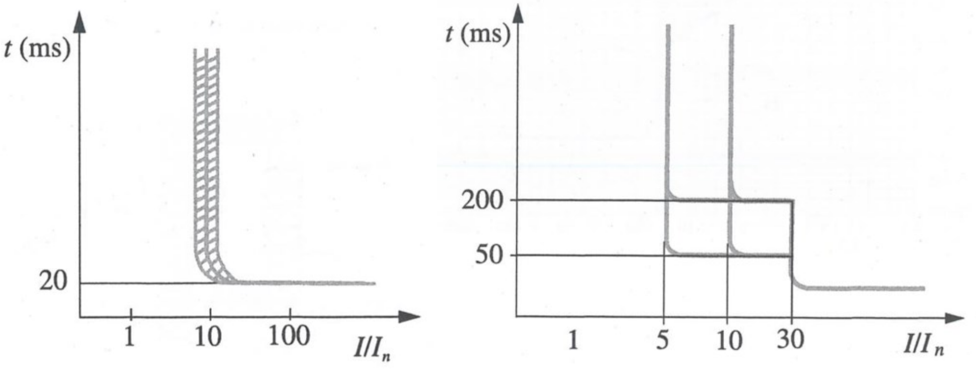
Magnetic overcurrent relay

The intervention threshold is adjusted by adjusting the spring tension, or by varying the shunt ratio (if used). The intervention time depends only on the inertia of the parts that make up the device, unless a delay device is inserted (delayed relay).

There is a certain tolerance with respect to the rated value, represented by the shaded areas in the figure.

Magnetic relays can be fixed, adjustable in terms of the intervention current threshold, adjustable in terms of intervention time, fully adjustable.

Being instantaneous tripping, magnetic relays are suitable for protection against short-circuit currents (high magnitude and short duration tolerable). However, they are not suitable for overload protection (tripping even for temporary overloads, such as starting motors, or alternatively ineffective protection)



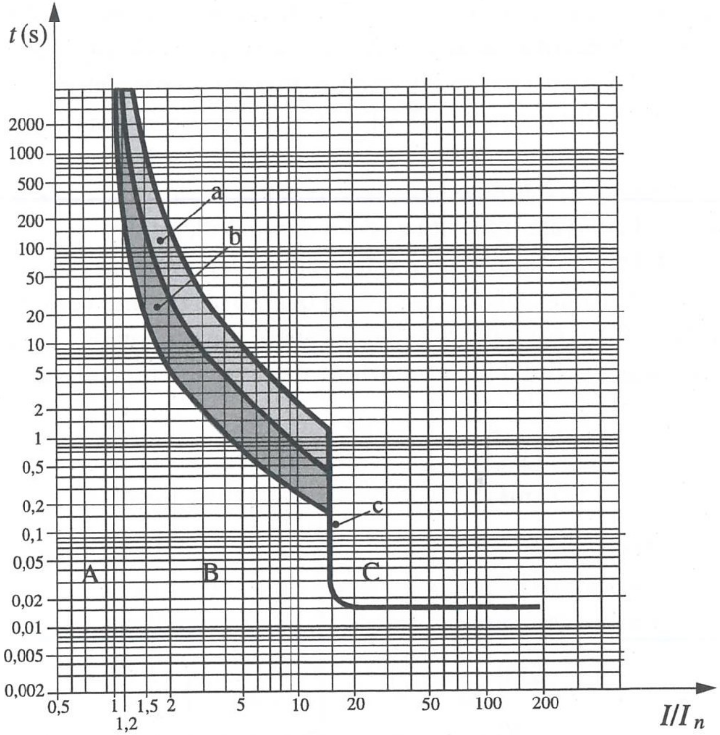
Thermal-magnetic overcurrent circuit breaker

By combining a breaker with a thermal and a magnetic relay, you get a *thermal magnetic overcurrent circuit breaker*, a very common device for integrated protection from overloads and short circuits. The regulation is such that the thermal relay intervenes for low overcurrents (about 3÷15 times I_n), and the magnetic one for higher ones.

The tripping characteristic depends on the intervention thresholds chosen. The figure shows an example of the tripping characteristic of a non-adjustable thermo-magnetic protection, with the threshold of the magnetic relay I_m set to 15 times the rated current.

A distinction is made between zone A (non-intervention zone), zone B (overload protection zone, thermal relay intervention), and zone C (short circuit protection zone, magnetic relay intervention).

In fact, in zone C both relays could intervene, but it is the magnetic one that acts as it has a shorter intervention time.

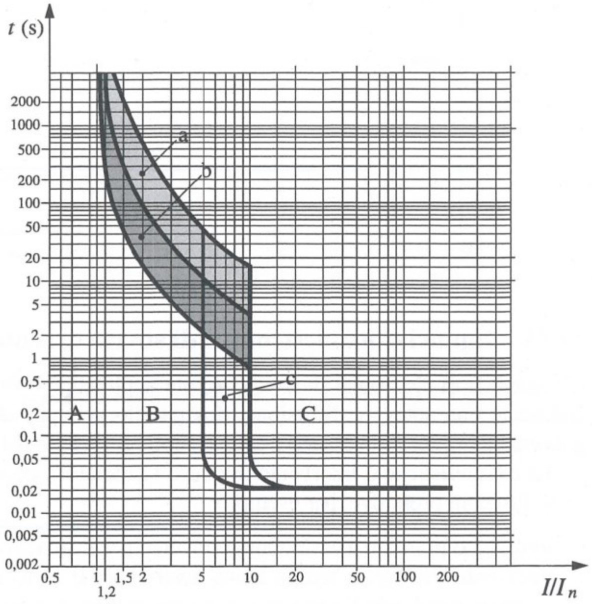


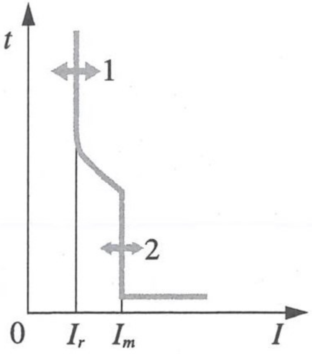
Thermal-magnetic overcurrent circuit breaker

If the switch has an adjustable magnetic intervention threshold, the characteristic becomes as the one shown in the figure. As already written, some breakers have also the possibility to adjust the thermal intervention threshold. This translates into the characteristic also moving the threshold between zone A and zone B.

This type of breakers is selected referring to the operating current and the ampacity of the line to be protected. The nominal current of the device is selected at first, greater than the ampacity of the line, and then the thermal and magnetic intervention thresholds are selected, according to the principles that will be shown later.

In the case of using this device for the protection of asynchronous motors, it is also necessary to take into account the machine starting (the relay must not trip during motor starting, when it absorbs 5-10 times the rated current for a short time).





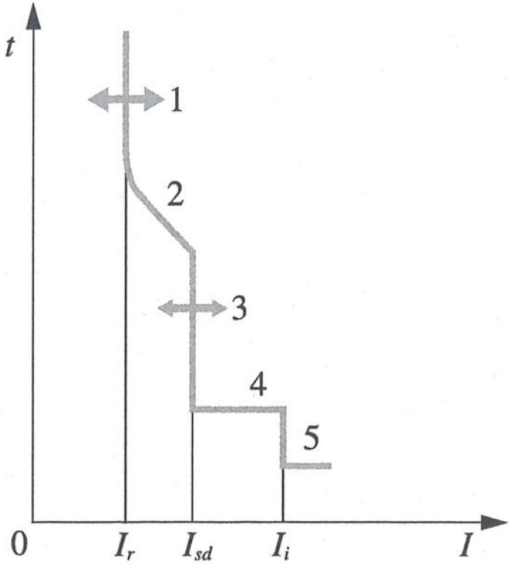
Electronic overcurrent relay

The use of electronic overcurrent relays is starting to become significantly widespread even in LV, thanks to the increasingly reduced costs of integrated digital electronics. These relays consist of a current sensor, a microprocessor with a specific program, and a controlled coil that triggers the circuit breaker (indirect action relay).

The tripping characteristics can vary greatly, and correspond to different protective functions, which can be obtained by appropriate choices of trip thresholds and trip times.

Some examples are:

- Inverse time long delayed trip for overload;
- Inverse time short delayed trip for selective short circuit protection;
- Instantaneous time-independent trip for short circuit;
- Etc.



Other protection relays

There are a whole series of protections, even not specifically electrical, that are used in power systems.

Given the number of different protections that are integrated into an electrical system, the *ANSI/IEEE C37.2 standard* has defined a numerical classification (the standard defines acronyms and numbers for the classification of devices and functions used in electrical stations and substations, in power production facilities, and in user and conversion systems).

The latest revision of the standard is provided as attachment.

LV automatic circuit breakers

Automatic circuit breakers can be divided into:

- *Air circuit breakers*, with the various parts insulated in air. They have considerable size and are mainly intended for industrial uses, such as breakers downstream of MV/LV transformers and generators, as well as line outputs with rated currents greater than 1÷2 kA. They have high rated currents (up to approximately 8 kA) and breaking capacities of up to 100÷150 kA.
- *Molded case circuit breakers*, enclosed in an insulating plastic casing divided into compartments to ensure insulation between the various phases and with the mass. They are smaller than the previous ones, but have comparable performance, with nominal currents up to 4 kA and interrupting capacities up to 200 kA. Used mainly for industrial systems, they are used in the civil field only for systems of a certain power (for example shopping centers) when it is not possible to use modular devices.
- *Modular breakers*, created for civil and tertiary systems but also widespread in the industrial field. They have standardized modular dimensions based on the number of poles and a snap-on fixing device on DIN rail, making installation and replacement very easy. They make it possible to prepare electrical panels of small and standardized dimensions based on the number of modules required. They have nominal currents up to 100÷160 A and interrupting powers from 4,5 to 25 kA.

Technical characteristics of LV automatic circuit breakers

In addition to the characteristics already presented above for generic circuit breakers, for LV automatic circuit breakers there are additional ones to consider.

These are:

- Tripping characteristic;
- Conventional tripping and non-tripping current;
- Specific let-through energy.

Technical characteristics of LV automatic circuit breakers

Tripping characteristic

The standards do not establish the form of the time-current characteristic of low voltage circuit breakers, but indicate the limit values within which these characteristics must fall.

For switches for domestic and similar uses, the European standards provide for three types of characteristic, indicating the test conditions and a certain number of pairs of time-current values that the devices must satisfy.

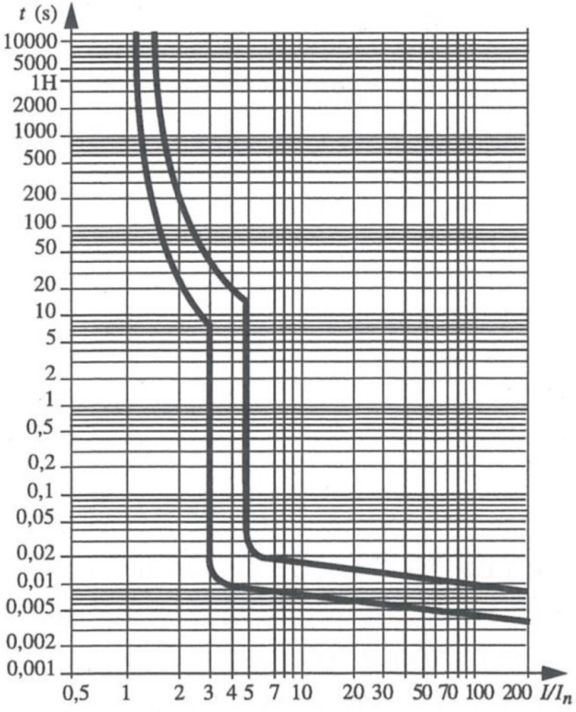
In particular, instantaneous intervention without intentional delay must occur for currents:

- *Characteristic B* - greater than 3 and up to 5 times the nominal current;
- *Characteristic C* - greater than 5 and up to 10 times the nominal current;
- *Characteristic D* - greater than 10 and up to 20 times the nominal current.

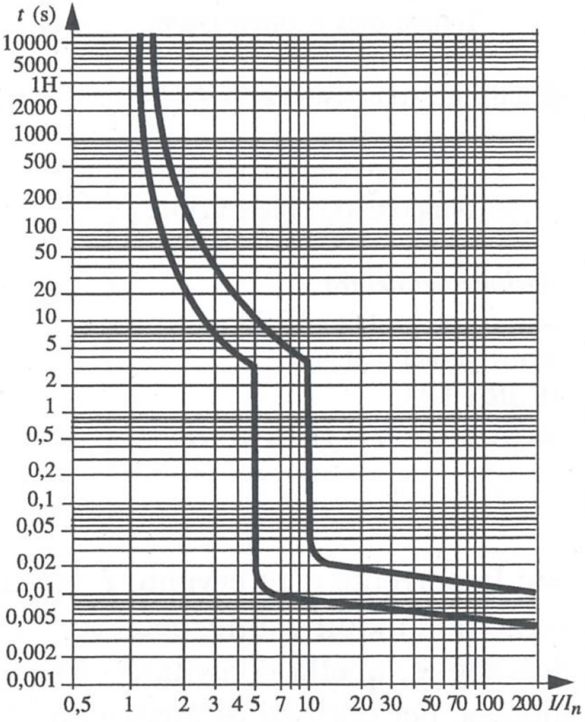
Characteristic B is suitable for users that can give rise to limited overload (for example lights); characteristic C is the one in common use; characteristic D is suitable for loads with high starting currents (for example asynchronous motors).

Technical characteristics of LV automatic circuit breakers

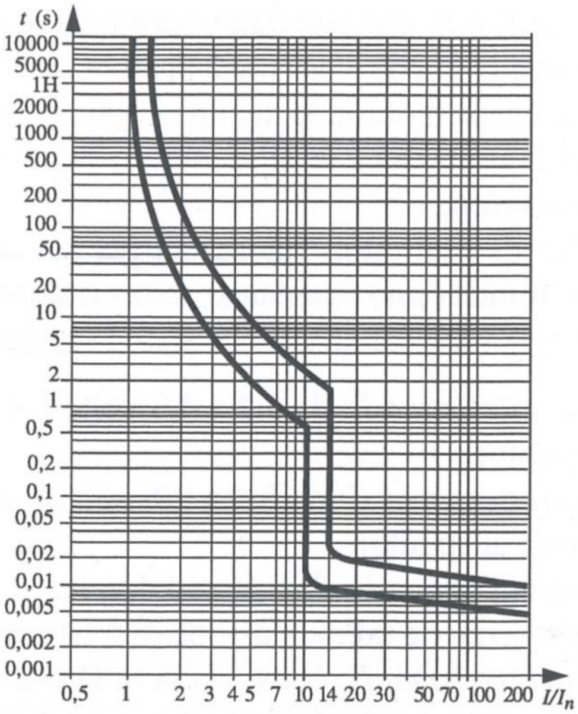
Characteristic B



Characteristic C



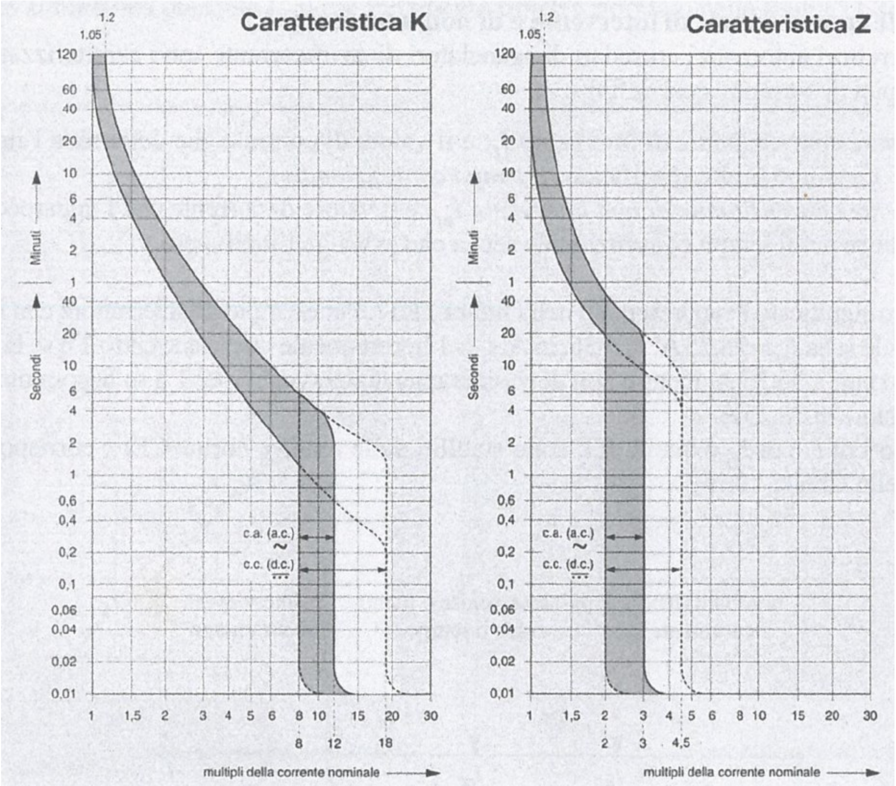
Characteristic D



Technical characteristics of LV automatic circuit breakers

There are also breakers on the market with tripping characteristics different from those standardized in the European field, for example the *characteristics K* and *Z*, provided for by the DIN-VDE 0660 standards.

It is noted that the K characteristic is similar to the D, while the Z has very low intervention thresholds (lower than B) and is suitable for the protection of power supplies for electronic circuits, which have very limited overcurrents.



Technical characteristics of LV automatic circuit breakers

For industrial switches, reference is made to different standards than those of the switches seen previously, as it is possible to adjust the intervention thresholds of the thermal and magnetic relays.

In relation to the intervention current of the magnetic relay, the various curves are defined as follows:

- *Characteristic B*: from 3.2 to 4.8 I_n (4 I_n ± 20%), for circuits with low inrush currents;
- *Characteristic C*: from 6.4 to 9.6 I_n (8 I_n ± 20%), for R-L circuits with medium inrush currents;
- *Characteristic D*: from 9.6 to 14.4 I_n (12 I_n ± 20%), for circuits with high inrush currents (power supply of transformers, motors, capacitor banks, etc.);
- *Characteristic K*: like curve D, but with conventional tripping current $I_f = 1.2\ I_n$;
- *Characteristic Z*: from 2.4 to 3.6 I_n (3 I_n ± 20%), for electronic circuits.

(ref. following slide)

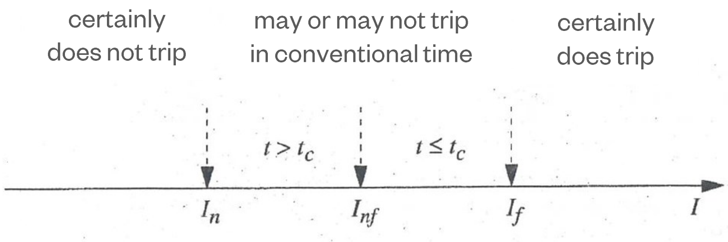
Technical characteristics of LV automatic circuit breakers

Conventional tripping and non-tripping currents

Circuit breakers equipped with overcurrent releases are also characterized by:

- *Conventional tripping current* I_f: it is the current value that determines tripping within a specified time limit t_c (*conventional time*); → (can be considered as the asymptote of the thermal characteristic)
- *Conventional non-tripping current* I_{nf}: it is the current value that the device can conduct for the conventional time without tripping.

The values are established by the relevant standards.

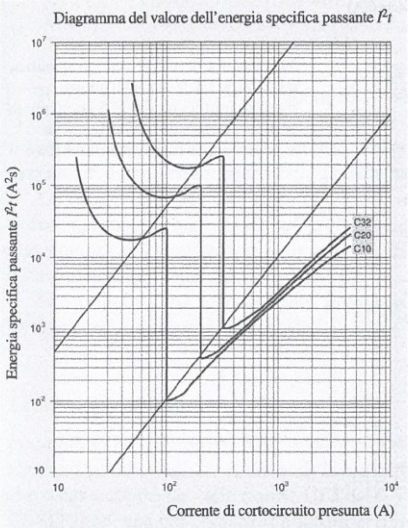


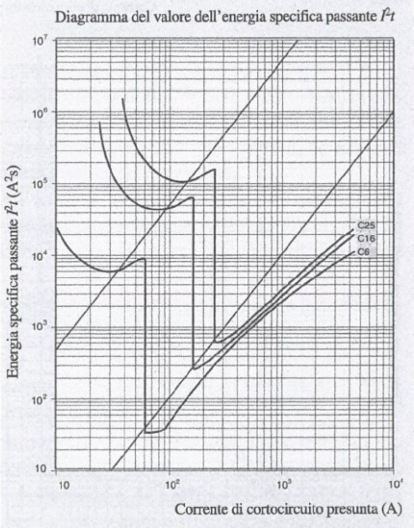
Type of device		I_{nf}	I_f	t_c
Thermal relays		1,05 I_n	1,2 I_n	2 h
Adjustable automatic breakers	$I_r \leq 63$ A	1,05 I_r	1,3 I_r	1 h
	$I_r > 63$ A	1,05 I_r	1,3 I_r	2 h
Non adjustable automatic breakers	$I_n \leq 63$ A	1,13 I_n	1,45 I_n	1 h
	$I_n > 63$ A	1,13 I_n	1,45 I_n	2 h
I_r calibration current; I_n rated current				

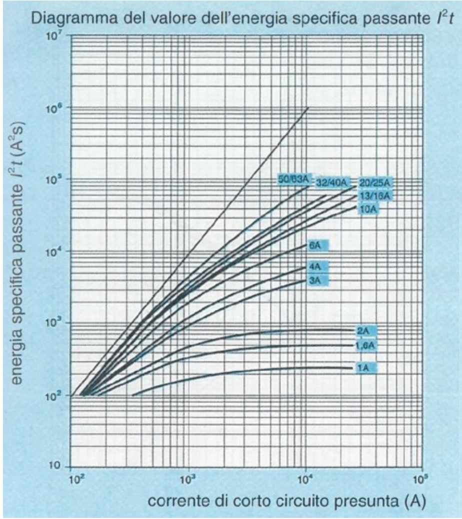
Technical characteristics of LV automatic circuit breakers

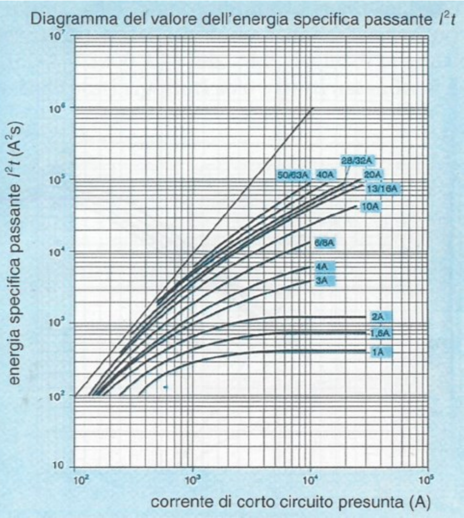
Specific let-through energy

For a circuit breaker equipped with an overcurrent release, the specific let-through energy represents the specific thermal energy (Joule integral) that the device lets flow during the short circuit, before the current is interrupted. Each manufacturer provides graphs of this energy for their products.









Contactors

Contactors are switching devices commonly used in LV systems for controlling motors, capacitor banks, rheostats, etc.

Their characteristics are established by various specific standards, depending on the type of contactor.

If the switching occurs by moving electrical contacts, we speak of electromechanical contactors, if by switching electronic devices we speak of static contactors.

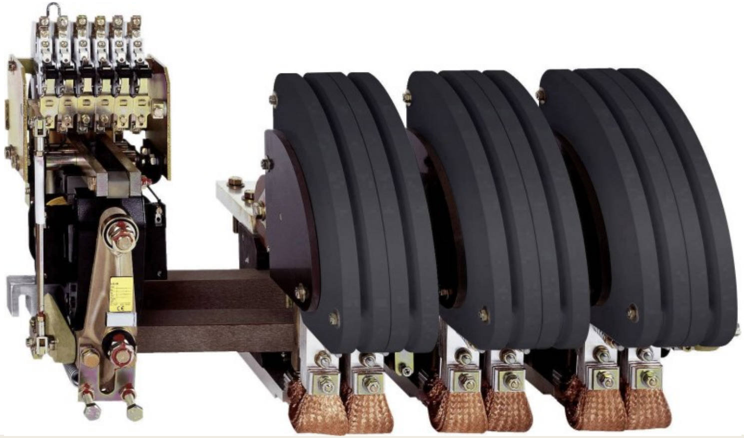
Electromechanical contactors consist of a fixed electromagnetic core with a coil wound around it through which the control current flows, and a moving ferromagnetic part opposed by a spring, which is attracted by the electromagnetic force, thus acting on the contacts.

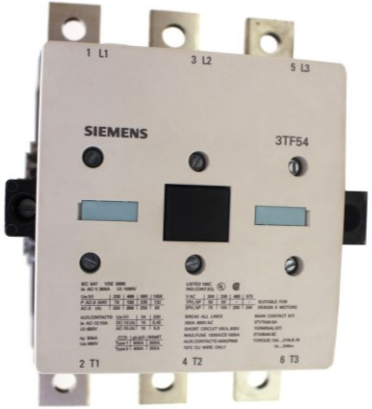
The contactor is equipped with main contacts (usually normally open), responsible for supplying power to the connected user, and auxiliary contacts (both normally open and closed) for the signaling and control circuits.

Contactors

Constructively, electromechanical contactors can be made according to two typologies:

- On bar, in which the various parts are mounted on a support bar and the movement of the moving contacts is of the rotary type; used for high currents and operating voltages (about > 1000 A and 1000 V), in specific fields such as traction, lifting, DC circuits;
- Compact, in which the various parts are integrated in a single insulating box, with rectilinear translational movement of the contacts; currently the most commonly used.





Contactors

Contactors are classified into *categories of use* to take into account in their construction the different working conditions to which they may be subjected (for example, the operation of resistive loads is not very burdensome, while the operation of starting an asynchronous motor is burdensome, and even more burdensome is the use for reversing the direction of rotation of the motor).

The categories of use are distinguished by an acronym, which has as its first part the wording AC or DC, depending on whether the contactor is designed to operate with alternating or direct currents, and the second part consists of a number that specifies the individual application.

Contactors

Characteristics and selection criteria

In addition to the category of use, contactors are defined by numerous other characteristic quantities:

- *Rated insulation voltage*;
- *Rated operational voltage* and *rated operational current*, to which the making and breaking capacities refer. A contactor can have various voltage and current pairs (P ≈ cost);
- *Conventional thermal rated current* and *rated thermal current in casing* relating to service of up to 8 hours at a specified ambient temperature;
- *Admissible short-time current* under fault conditions for a specified duration (1 s, 30 s);
- *Type of service*, in addition to the 8-hour and uninterrupted service, also periodic intermittent service (intermittency 15, 25, 40, 60%) and limited duration service (contacts closed for 10, 30, 60, 90 min) are considered;
- *Rated breaking capacity*, usually quite low since the contactor can interrupt overloads but not short circuits (must be combined with protection);

Contactors

- *Rated making capacity*;
- *Rated frequency*;
- *Operating ambient temperature range*;
- *Reference ambient temperature*;
- *Degree of protection of the casing*.

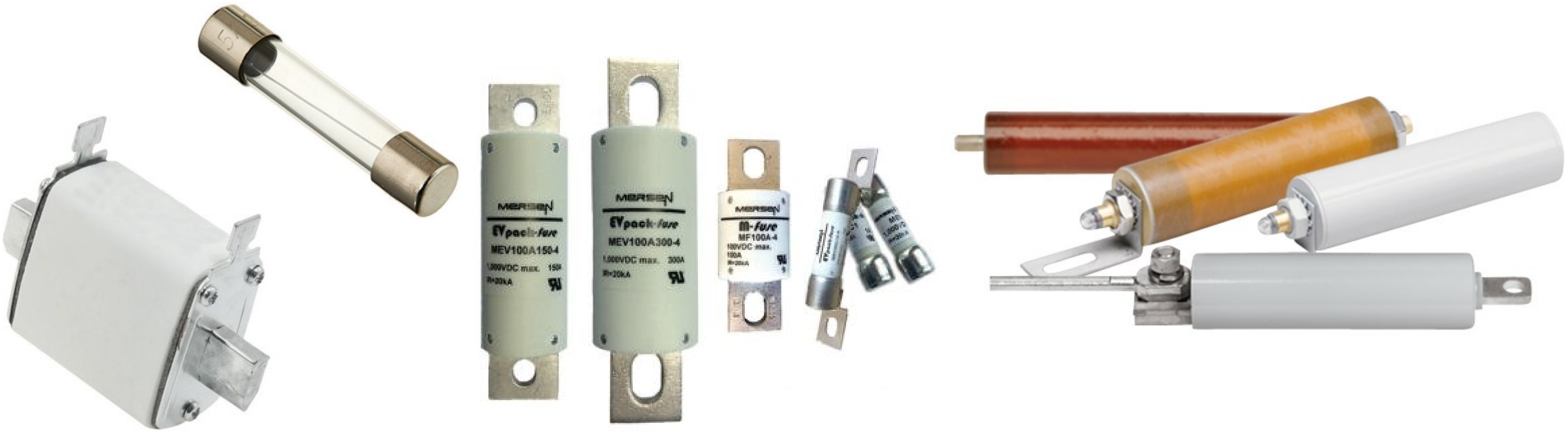
The choice of the contactor must primarily take into account the category of use, the power and the current of the load.

If the load presents overcurrents at insertion (e.g. asynchronous motor inrush), the ratio between the closing (or opening) current and the rated operating current must be evaluated. The standards establish standardized values for this ratio, which all contactors must comply with. In the case of occasional operation (less than 50 operations during the life of the contactor) the regulation allows these values to be increased.

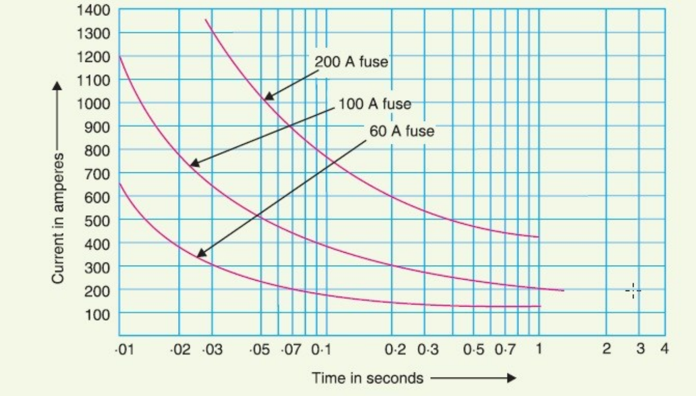
Fuses and their characteristics

Fuses are overcurrent protection devices, suitable for both overload and short circuit (although they are more frequently used for the latter).

They are connected in series to the element to be protected and their intervention occurs when the current, exceeding the rated value, causes the fuse element to melt, interrupting the circuit. For high currents, HRC (high rupturing capacity) fuses are used, which are filled inside with powder designed to react with the fusible element's vapors and form a compound with high electrical resistance.



Fuses and their characteristics

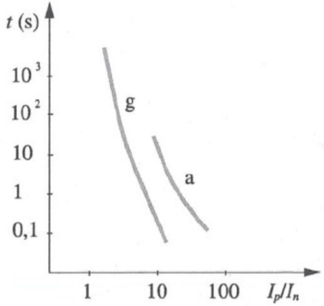


Tripping characteristic

Typically inverse time, being thermal devices.

Category of use and tripping range

Based on their category of use and tripping range, fuses are classified as follows:



Tripping range \ Category of use	G (general purpose)	M (motor supply)
g (full range)	gG	gM
a (reduced range)	/	aM

The difference between full-range and reduced-range fuses is the current I_p from which the fuse begins to trip. Full-range fuses begin to trip at $I_p = I_n$, while reduced-field fuses begin to trip at a higher current value (useful for avoiding their tripping during motor start-up).

Fuses and their characteristics

Conventional tripping and non-tripping currents

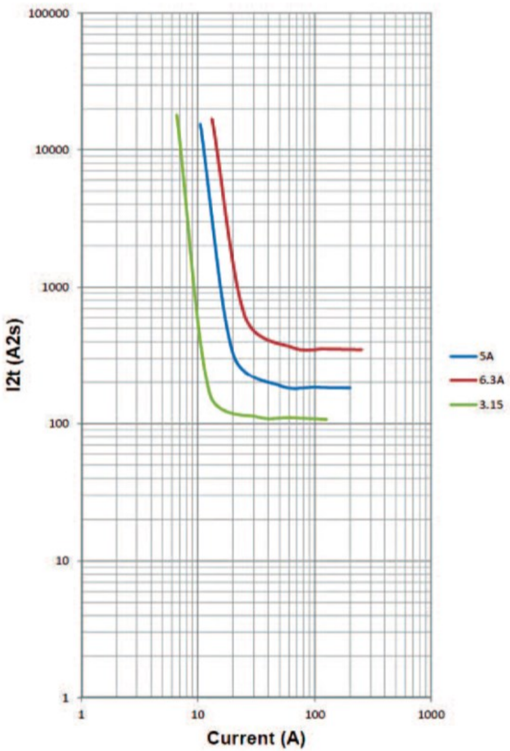
Defined in a similar way to breakers, they assume the values shown in the table (for gG and aM fuses).

Rated current I_n (A)	Conventional currents		Conventional time t_c (h)
	I_{nf}/I_n	I_f/I_n	
$I_n < 4$ (only for gG)	1.5	2.1	1
$4 < I_n \leq 16$ (only for gG)	1.5	1.9	1
$16 < I_n \leq 63$	1.25	1.6	1
$63 < I_n \leq 160$	1.25	1.6	2
$160 < I_n \leq 400$	1.25	1.6	3
$400 < I_n$	1.25	1.6	4

Fuses and their characteristics

Specific let-through energy

The specific thermal energy flowing through a fuse before the overcurrent is interrupted starts from a maximum value (called *maximum thermal impulse*) and decreases as the short-circuit current increases, tending to a nearly constant value.



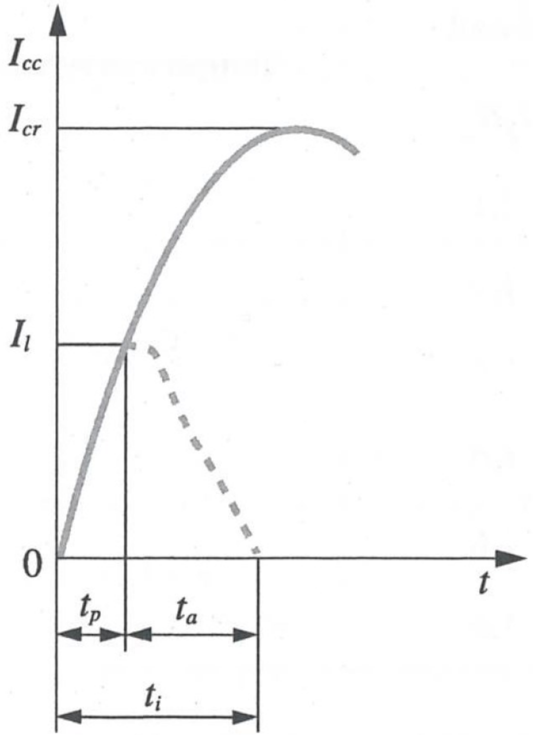
Fuses and their characteristics

Limitation characteristic

Fuses are by nature short-circuit current limiters, since, if correctly chosen, they intervene before the current reaches its peak value.

After the *pre-arc time* t_p during which the fuse heats up to the melting temperature, the electric arc develops and extinguishes after the *arc time* t_a. In this interval, the significant increase in resistance of the fuse causes a decrease in the current from the value Il (*limited current*) to zero.

The limiting factor is defined as the ratio $K_l = I_l / I_{cr}$ (between 0.15 and 0.30)



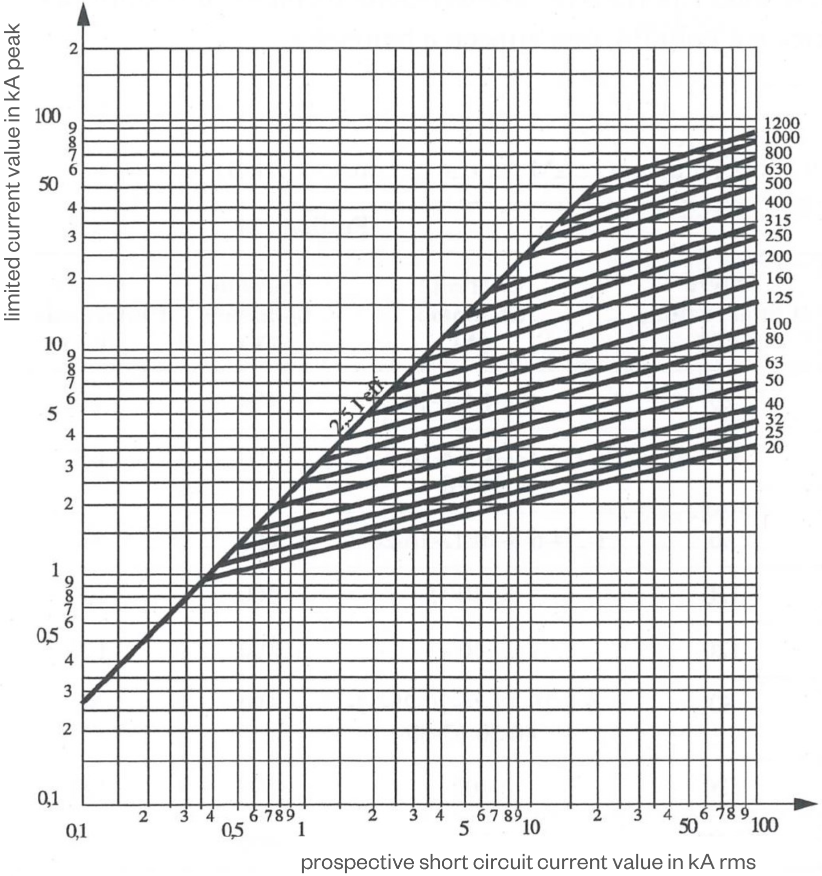
Fuses and their characteristics

Due to the limitation, the peak value of the short-circuit current is lower than expected.

The **limitation characteristic** is defined as the graph that links the peak value I_p of the limited current to the effective value I_S of the symmetrical component of the prospective short-circuit current.

The figure shows the limitation characteristic of knife-edge fuses class gG for $\cos\varphi_{cc} = 0.1$ ($K_{cr} = 2.5$).

A similar result can also be obtained in automatic switches by means of appropriate construction measures (*current limiting automatic circuit breaker*), with a limitation factor between 0.3 and 0.4.



Fuses and their characteristics

Rated breaking capacity

Like breakers, fuses are also characterized by their rated short-circuit breaking capacity, equal to the maximum rms value of the symmetrical short-circuit current that they are able to interrupt under specified conditions.

This is generally a very high value, and must not be less than the values specified by the reference standards.

Applications	Rated voltage (V)	Minimum breaking capacity (kA)
Home and similar	$V_n < 240$	6
	$240 < V_n \leq 500$	20
Industrial	$V_n < 660$	50
	$V_n < 750$	25

Protection of cables against overloads and short-circuits

Protection of circuits against overloads

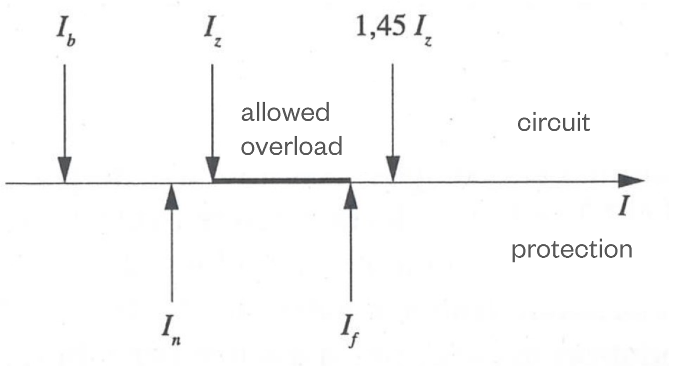
Carried out with automatic breakers, fuses, thermal relays coupled with contactors (no short circuit currents).

The purpose is to interrupt overload currents in the conductors before they can reach temperatures that are harmful to insulation, connections, terminals, or other parts, while still allowing the conduction of short-term overloads that occur during normal operation.

For low voltage systems, the standards (in Italy CEI 64-8/4) require compliance with the following conditions:

$I_b \leq I_n \leq I_z$ $\qquad$ $I_f \leq 1.45 I_z$

where I_b operating current; I_z ampacity; I_n rated protection's intervention current (or calibration current for adjustable devices); I_f conventional tripping current of the protection



Protection of circuits against overloads

By introducing the ratio $k_f = I_f / I_n$, the coordination relations become:

$$I_b \leq I_n \leq I_z \qquad\qquad I_n \leq \frac{1.45}{k_f} I_z$$

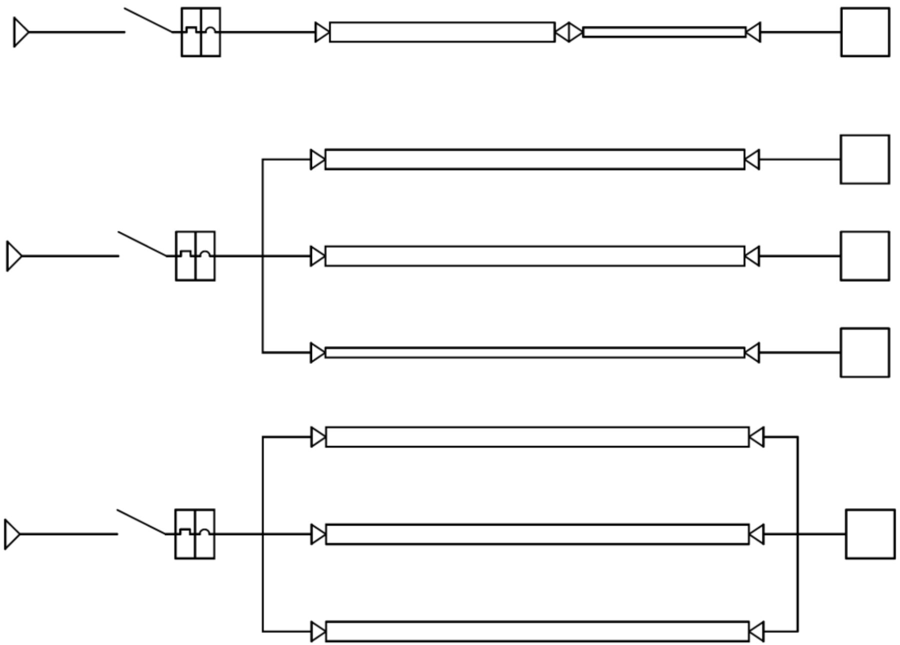
Depending on the type of device used, the k_f ratio varies, so there can be two conditions:

- devices with $k_f \leq 1.45$, , it is enough to satisfy the first relation (the second is automatically satisfied);
- devices with $k_f > 1.45$, the two relations can be summarized in the following: $I_b \leq I_n \leq \frac{1.45}{k_f} I_z$

Device		$k_f = I_f / I_n$
Termal relays (coupled with contactors)		1.2
Adjustable automatic circuit breakers (industrial LV)		1.3
Non-adjustable automatic circuit breakers (residential and similar uses LV)		1.45
Fuses	$I_n > 16$ A	1.6
	4 A $< I_n \leq 16$ A	1.9
	$I_n \leq 4$ A	2.1

Protection of circuits against overloads

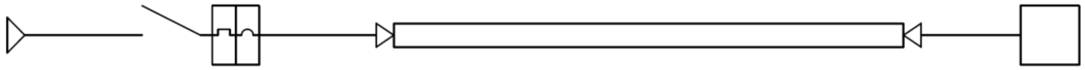
- If the circuit is composed of sections with different ampacities, the protection conditions must be respected for the lowest one;
- If the device is placed upstream of several branch lines, it protects from overload all the lines in which the protection conditions are satisfied;
- If the protected circuit is formed by several conductors in parallel, the aggregate ampacity I_z is assumed to be the sum of the ampacities of the individual conductors (provided that they are substantially equal).



Installation of overload protection devices

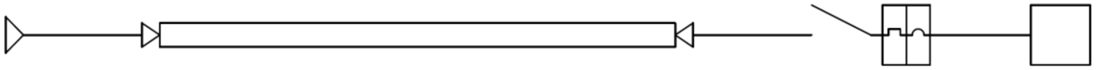
Installation point of the overload protection device

In general, it is commonly installed at the beginning of the circuit to be protected.



This installation point is mandatory for the protection of circuits that enter or pass through special places (for example, environments with a higher risk of fire).

In ordinary environments, the device can also be installed along the circuit or at the arrival, provided that there are no branches or plug sockets on it (in the absence of these, the overload current is the same in all positions, so the protection intervenes anyway).



Installation of overload protection devices

Mandatory installation and optional/mandatory omission of overload protection

Overload protection is mandatory for all circuits in the following cases:

- Places with increased risk of fire or explosion;
- Special environments and applications (bathrooms, swimming pools, medical clinics, etc.);
- Conductors that supply branches or loads for which, at the design stage, a coefficient of use or contemporaneity lower than 1 has been assumed;
- Conductors that supply plug sockets.

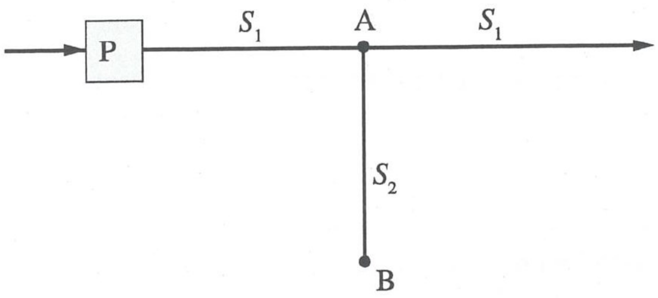
The basic concept is to require the installation of overload protection when the overtemperature caused by an overload can have significant consequences, or in cases in which there is no certainty of the amount of current absorbed by the load.

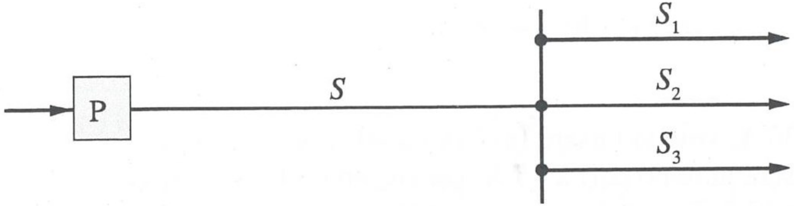
Installation of overload protection devices

Overload protection may be omitted in the following cases:

- *Circuits connected downstream of points where there are variations in section, nature, method of installation or construction, provided that they are correctly protected by upstream devices.*

If the upstream device is suitable for the protection of both the main line and the branch(es), the upstream protection is considered sufficient.





Installation of overload protection devices

- *Conduits that supply power to devices that cannot cause overload, provided that there is effective short-circuit protection and they are free of branches and plug sockets.*

This includes many practical cases:

- Circuits that supply lighting equipment;
- Circuits that supply thermal users (e.g. heating resistors, like boilers);
- Circuits that supply motors with a locked rotor current (maximum current absorbed by the motor in normal conditions) lower than the circuit ampacity;
- Circuits that supply users equipped with their own protection device, provided that it is also suitable for protecting the supply line;
- Circuits that supply multiple branches, each protected by its own device, such that the sum of the nominal currents of the downstream protections is lower than or equal to the ampacity of the upstream line.
- Telecommunications, control, signaling and similar systems, for which specific protection conditions apply.

Installation of overload protection devices

There are cases in which the standards set a *mandatory omission of the overload protection for safety reasons*. These are all cases in which the interrupting the circuit can cause a condition of greater danger than the overload itself.

Significant examples are:

- Excitation circuits of rotating machines;
- Power circuits of lifting electromagnets;
- Secondary circuits of current transformers (CT);
- Circuits that power fire-fighting devices.

In such cases, it is recommended to install an alarm device that signals the overload, but leaves the decision of intervention to the user.

Protection against short circuits

Short circuit protection can be performed with automatic breakers or fuses.

For LV user systems, the conditions that must be met for protection are reported in the standards (in Italy, CEI 64-8). *The standard does not indicate specific circuits to be protected, therefore short circuit protection must be performed on all circuits*, except those where it is specifically permitted to omit it:

- Connection lines between specific types of equipment (batteries, generators, transformers, rectifiers) and the respective electrical panels, when the latter contain the protection devices;
- Circuits whose interruption can give rise to situations of greater danger than the short circuit itself (e.g. lifting electromagnets);
- Some measuring circuits (e.g. secondary circuits of CTs), when the interruption of the circuit conflicts with the operating principle of the equipment.

When the protection is not installed, it must be verified (and enforced, if necessary) that the danger of a short circuit is minimal and that the line is not close to combustible materials.

Protection against short circuits

General criterion

Protective devices shall be provided, to interrupt short-circuit currents in the circuit before such currents can become dangerous due to thermal and mechanical effects produced in conductors and connections.

Installation point

The protection devices must be installed at the beginning of the circuit to be protected and at the points where there is a reduction in the section or another variation such as to reduce the K coefficient relating to the verification of the Joule integral (the relationship $I^2t \leq K^2S^2$ must always be verified).

The position of the device must be such as to interrupt the short-circuit currents at any point in the circuit, within a time such that the circuits do not exceed their permissible limit temperature.

In systems with a higher risk of fire or with danger of explosion, it is permitted to place the device up to 3 meters from the point of the variation, if the section is made appropriately and far from combustible material.

Protection against short circuits

Rated current and tripping characteristic

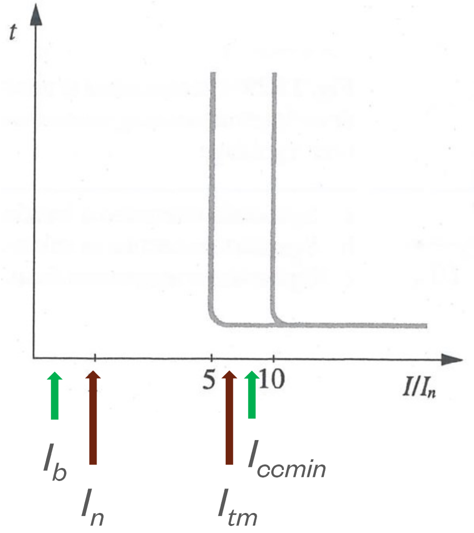
The rated current (or the calibration current for adjustable breakers/relays) must not be lower than the circuit's operating current, to allow it to function correctly:

$$I_n \geq I_b$$

The I_{tm} calibration current of the magnetic relay (or of the maximum current relay used for short-circuit protection, if it is a programmable electronic switch) must not exceed the minimum short-circuit current at the end of the line, to allow it to intervene in the event of faults at any point:

$$I_{tm} \leq I_{ccmin}$$

Adjustable magnetic breaker



Protection against short circuits

Breaking capacity

The breaking capacity must not be less than the maximum prospective short-circuit current value, i.e. the current that can be produced by a short circuit at the point of installation of the device and considering the type of fault that produces the maximum current, to allow the protection device to intervene safely:

$$I_{cn} \geq I_{ccmax}$$

The use of a device with a lower breaking capacity is allowed, provided that a device with a suitable breaking capacity is installed upstream (*series* or *back-up protection*, discussed later).

Protection against short circuits

Verification of specific let-through energy

As discussed previously, the specific thermal energy that is let through by the protection device during the short circuit must not exceed the one admissible by the downstream components, to avoid excessive overtemperature of the insulation. This is achieved by satisfying the condition (for cables):

$$\int_0^{t_i} i^2 dt \leq K^2 S^2$$

The values of *K* are those reported in the first section of this presentation, valid for short circuits lasting less than 5 s.

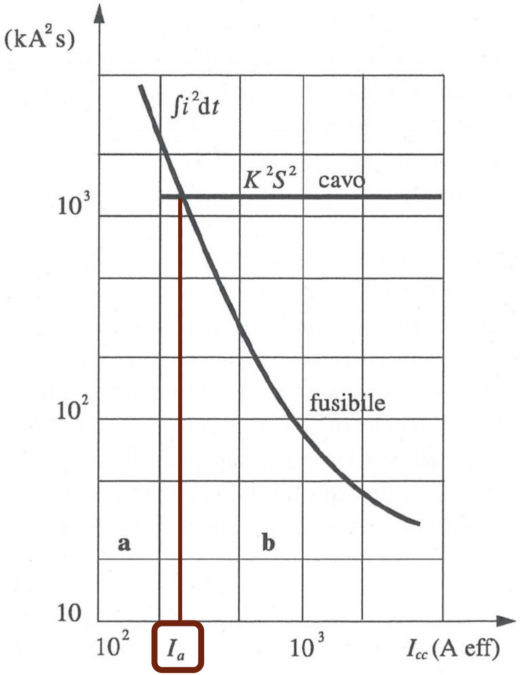
The verification is different depending on the type of device used for protection.

Protection against short circuits

Protection of a cable with a fuse

The comparison between the specific energy of a cable and a fuse is shown in the figure. The verification is satisfied in zone *b*, i.e. for all currents not lower than the value I_a, determined by the intersection of the two characteristics. This means that for the verification it is necessary to calculate the minimum short-circuit current at the end of the line, determine I_a graphically, and check that it is:

$$I_{ccmin} \geq I_a$$

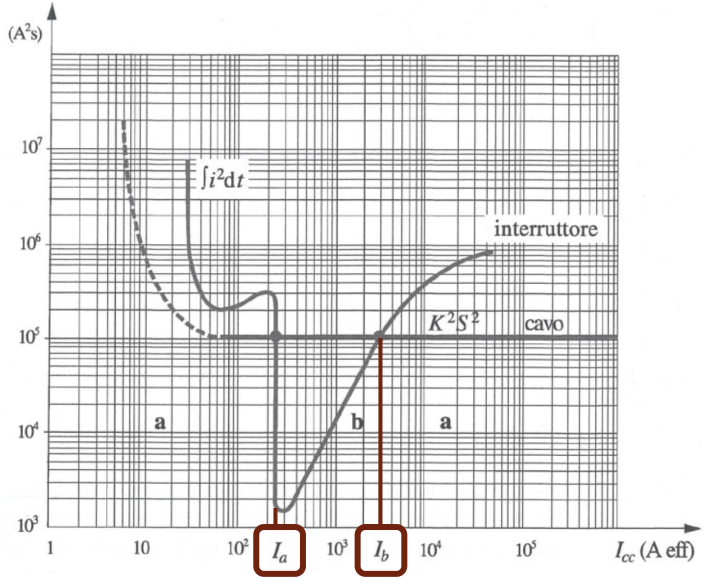


Protection against short circuits

Protection of a cable with an automatic breaker

The comparison between the specific energy of a cable and of an automatic switch is shown in the figure. The verification is satisfied in zone *b*, i.e. for all the currents included between the values I_a and I_b determined by the intersection of the two characteristics. This means that for the verification it is necessary to calculate the minimum short-circuit current at the end of the line and the maximum at the beginning of the line, determine I_a and I_b graphically, and check that it is

$$I_{ccmin} \geq I_a \qquad\qquad I_{ccmax} \leq I_b$$



Protection against short circuits

Series (or back-up) protections

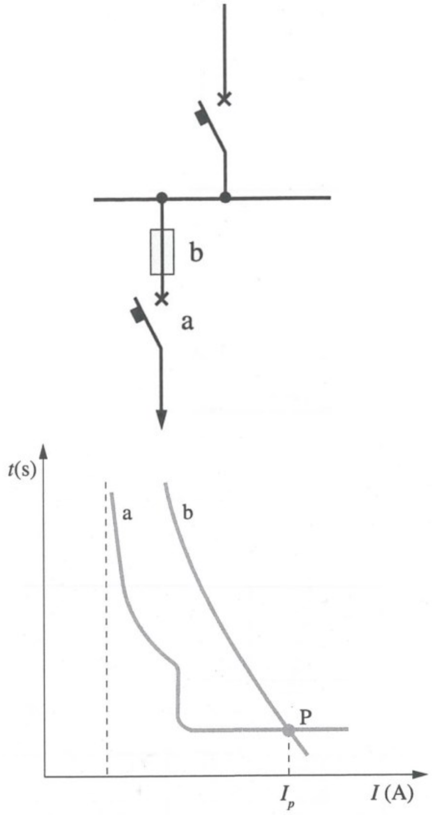
The standards allow the use of a protection device with a breaking capacity lower than the prospective short-circuit current at the point of installation, provided that there is another device with the necessary breaking capacity upstream.

The upstream protection must have I^2t not higher than the value tolerable by the downstream protection and the protected conduit, so as not to allow excessive thermal energy to flow.

Example: line protected by a low-breaking-capacity automatic circuit breaker, in series with a fuse with a breaking capacity not lower than the prospective short-circuit current at the point of installation.

The two tripping characteristics intersect at the I_p current (*exchange current*), which must not be higher than the breaking capacity of the circuit breaker.

For currents < I_p the circuit breaker intervenes, also protecting the fuse, for currents ≥ I_p the fuse intervenes (shorter intervention time and suitable breaking capacity).



Protection against short circuits

This solution is suitable when using *aM* type fuses, which are not very effective in protecting against small-intensity overcurrents due to their limited intervention range.

Often this type of solution is implemented using automatic breakers with different breaking capacity. For the correct choice of switches, manufacturers provide indications for coordination, both in tabular form and with software, which also allow the value of the interrupting capacity of the combination to be determined.

Combined or separate overload and short circuit protection

Protection against overload and short-circuit currents can be performed with a single device (*combined protection*) or with separate devices.

The standards allow the use of a single LV device (i.e., automatic thermos-magnetic breaker), provided that it simultaneously satisfies the requirements for both functions.

In particular, by choosing a device that satisfies the relationships for overload:

$$I_b \leq I_n \leq I_z \qquad\qquad I_f \leq 1.45 I_z$$

the standard considers that it is also adequate for short-circuit protection, provided that:

- **it has sufficient breaking capacity;**
- **it is installed as prescribed for short-circuit.**

The use of separate devices for overload and short-circuit protection requires that the single device satisfies the requirements for its specific function. The short circuit protection device must be installed at the beginning of the line, upstream of the overload protection, and in practice falls within the case of series protections (back-up), seen previously.

Protection of phase and neutral conductors

In a three-phase line with neutral, it must be decided whether a hypothetical four-pole breaker (which interrupts all four poles) must have overcurrent protections on the phases only (type 3P+N) or on all poles (type 4P).

To decide whether the overcurrent protection must also concern the neutral conductor, the following must be considered:

- the type of distribution (TT, TN, IT);
- the cross-section of the neutral conductor (it can be different than that of the phases);
- the maximum current that affects the neutral conductor in relation to its ampacity, in ordinary conditions.

The criteria established by the standards are reported below, divided by distribution system.

Protection of phase and neutral conductors

Phase conductors

Except in special cases, overcurrent protection must concern all phase conductors.

TN-C system

The neutral conductor also has a protective function (PEN), therefore it must not be protected or interrupted. Three-pole or single-pole devices must therefore be used, depending on the circuit.

TT and TN-S systems

The neutral is an active conductor and as such can be interrupted. If the neutral cross-section is greater than or equal to the phase cross-section, the neutral conductor may be unprotected. If the neutral cross-section is smaller, protection is not required if there is short-circuit protection on the phases and the maximum current flowing in the neutral in ordinary conditions is much lower than its capacity.

In phase-neutral circuits, protection is neither required nor prohibited, but interruption is appropriate. In three-phase circuits without neutral or phase-phase, all phases are normally protected.

Protection of phase and neutral conductors

IT system

The neutral is not directly connected to earth, and it is good practice not to distribute it in the system unless strictly necessary.

Phase protection is always required.

Neutral protection, when used as an active conductor, can be omitted if:

- there is already upstream protection against short circuit;
- or if the phase short circuit protection is also suitable for the neutral (let-through energy check) and the circuit is protected by a differential switch that interrupts all conductors, including the neutral.

Selectivity of overcurrent protection

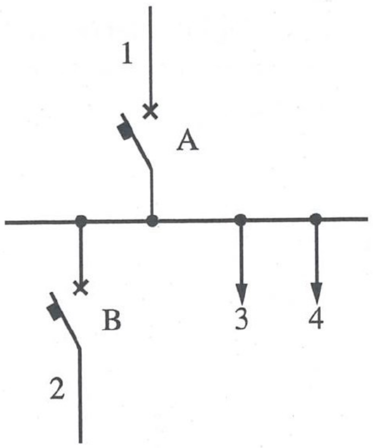
Consider a system in which lines 2, 3, 4 are derived from a main line 1.

The protection is defined as *selective* when a fault on line 2 causes only its protection (breaker B) to trip, so that the remaining part of the system remains powered.

In general, the protections are coordinated selectively when a fault at one point of the system causes only the protection immediately upstream of the fault point to trip.

Selectivity is:

- *total*, when only the affected device intervenes for values up to the maximum prospective short-circuit current at the point of installation;
- *partial*, when the previous condition is not satisfied, therefore once a certain short-circuit current value is exceeded, the upstream switch also intervenes.

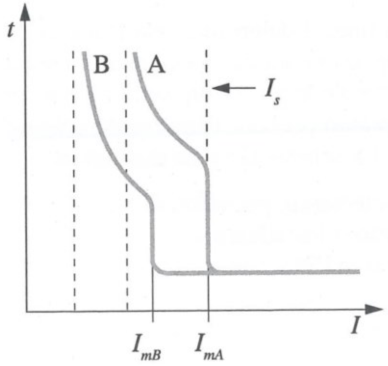


Selectivity with automatic breakers

Selectivity can be achieved with common circuit breakers in two ways:

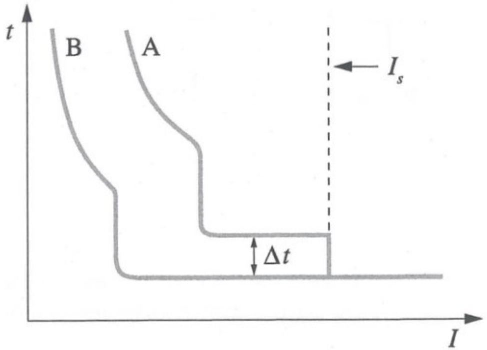
- **Current selectivity**

  Achieved by acting on the tripping currents of the circuit breakers: the upstream protection has a higher tripping current than the downstream one.



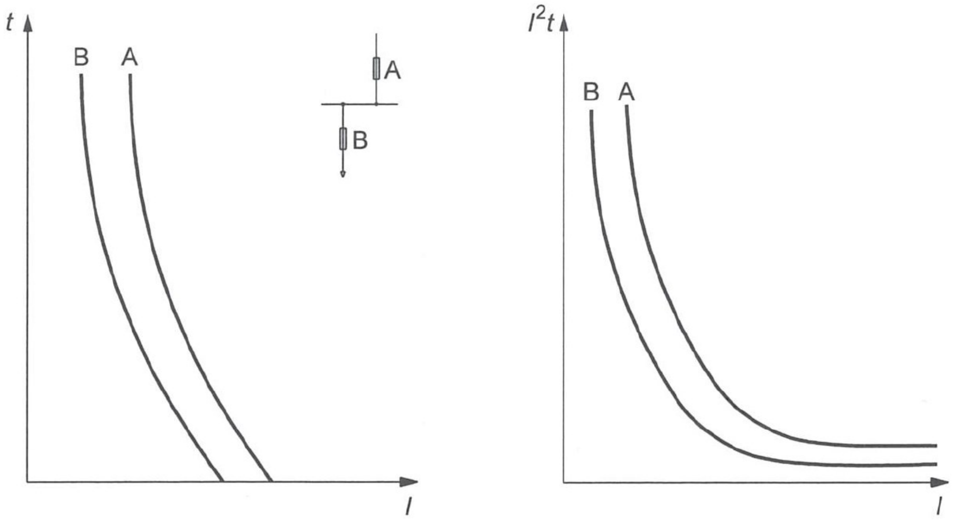
- **Time selectivity**

  Achieved by acting on the tripping times of the devices: the upstream protection intervenes with a given delay compared to the downstream one. The delay time is generally not less than 0.1 s, leading to excessive tripping times in the case of more than 4-5 circuit breakers in cascade.



Selectivity with fuses

Selectivity between fuses is not a problem, and is always total, provided that the ratio between the currents of two fuses in series is at least 1,6.



Overcurrent protection design examples

Application example 1

Overcurrent protection of a consumer electrical system

The electrical system in question serves a building used as a workshop for vehicles tires' repair, consisting of a work room which also contains a box used as an office, an adjacent courtyard, and two toilets.

The electrical system is powered at 230/400 V from the low voltage public distribution network, with a three-phase electric meter installed in the workshop, near the entrance door. The power of the contract is 20 kW.

The system is of the ordinary type, therefore it is not subject to particular regulations.

The control and protection equipment of the various circuits of the system will be grouped in a general electrical panel, to be placed in the immediate vicinity of the electric meter, at a distance of no more than 1 m.

The general characteristics of the protection system, those of the devices to be used, and the verification of the Joule integral for at least one line are to be determined.

Application example 1

Circuit	N° phases	V_n (V)	I_b (A)	Cable	S (mm^2)	I_Z (A)
Meter-general panel line	3 + N	400	35	EPR	16	54
Interlocked CEE sockets	3 + N	400	22	PVC	6	27
Single-phase office sockets	1 + N	230	8,5	PVC	2,5	16
Toilets	1 + N	230	2,5	PVC	1,5	11,5
Air extractors	3	400	1,2	PVC	1,5	10,5
Convector heaters	3	400	1,3	PVC	1,5	10,5
Air compressor	3	400	7,5	PVC	4	19
External lights	1 + N	230	0,7	PVC	1,5	11,5
Workshop lights	1 + N	230	3,4	PVC	1,5	11,5
Switchboards (telephone + entryphone)	1 + N	230	0,9	PVC	1,5	11,5
Water heater	1 + N	230	1,1	PVC	1,5	11,5

Application example 1

General characteristics of the protection system

Since it is planned to place the overcurrent protection devices in the general electrical panel, it is possible to use the combined protection against overload and short circuit by means of automatic switches with thermomagnetic relays, to be installed at the start of the circuits. This also allows for a smaller footprint compared to separate protection solutions.

It remains to evaluate the protection of the line between the meter and the general panel. This line has a circuit breaker at the arrival (the general breaker of the panel), which ensures protection against overload but not against short circuit on the cable. This solution is however acceptable, given that the line is less than 3 meters long, is made in such a way as to minimize the risk of short circuit (insulated cable with external sheath), and is not placed near combustible material.

The short circuit protection must be installed for all the circuits starting from the panel, while the overload protection could be omitted for the lighting circuits. In practice, given the reduced operating currents, it is simple to obtain coordination of the overload protection also for the latter, therefore for uniformity thermomagnetic automatic breakers are used also for these circuits.

Application example 1

The requirements for the protection system are:

- Rated currents that satisfy the relationship $I_b \leq I_n \leq I_z$ (these are automatic breakers, which have $k_f \leq 1.45$, therefore the condition is sufficient for overload protection; furthermore, the condition $I_n \geq I_b$ foreseen for short-circuit protection is also included);
- Breaking capacity I_{cn} of the switches not less than the prospective short-circuit current at the point of installation;
- Verification of the Joule integral for the circuits protected from the short circuit.

Rated currents selection

The choice of the rated current value of the protection devices is made based on the operating currents and the ampacities of the various circuits.

The number of poles of the breaker depends on the number of phases of the circuit.

Application example 1

Circuit	N° poles	I_b (A)	I_n (A)	I_z (A)	$I_b \leq I_n \leq I_z$
Meter-general panel line	4P	35	50	54	Y
Interlocked CEE sockets	4P	22	25	27	Y
Single-phase office sockets	1P + N	8,5	10	16	Y
Toilets	1 P+ N	2,5	6	11,5	Y
Air extractors	3P	1,2	6	10,5	Y
Convector heaters	3P	1,3	6	10,5	Y
Air compressor	3P	7,5	16	19	Y
External lights	1P + N	0,7	6	11,5	Y
Workshop lights	1P + N	3,4	6	11,5	Y
Switchboards (telephone + entryphone)	1P + N	0,9	6	11,5	Y
Water heater	1P + N	1,1	6	11,5	Y

Application example 1

Breaking capacity

The short circuit current to be considered for determining the breaking capacity is the three-phase one, calculated at the installation point of each breaker (in the general electrical panel in this case). Given the short length of the connection line between the meter and the general panel, it is possible to use the value of the short circuit current immediately downstream of the electricity meter.

This value is provided by the distribution system operator. In the case in question, the value I_{cc} = 10 kA is assumed, a value indicated by the Italian standard CEI 0-21 as the maximum value for the three-phase supply of users with available power up to 33 kW.

Consequently, all the breakers in the panel can be chosen with a nominal breaking capacity I_{cn} = 10 kA, which is a standardized value for commercial appliances (having chosen the worst case foreseen by the standard, the choice is precautionary).

Application example 1

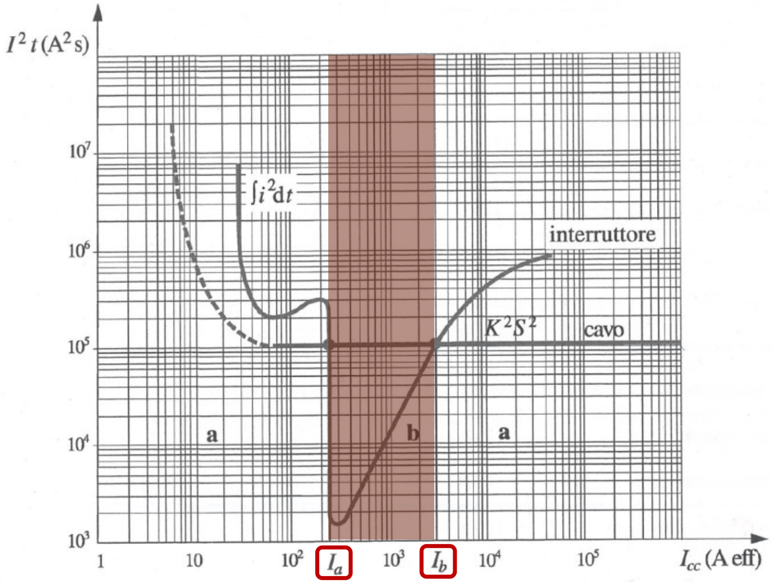
Specific let-through energy

The verification is carried out by comparing the curves of the specific let-through energy of the protection device and the circuit cable.

The cable is protected against the thermal effects of the short circuit in the current range in which the ordinates of the circuit breaker curve are not greater than those relating to the line. All possible values of the short circuit current in the line must therefore be between I_a and I_b.

The following must therefore occur:

- Short circuit current at the start of the line not greater than I_b;
- Short circuit current at the end of the line not less than I_a.



Application example 1

The calculation of the minimum short circuit current at the end of a line can be done using conventional formulae, using the relations indicated by the standards (not shown here).

As an example of verification of the Joule integral, the method is applied to line 1, which supplies the CEE sockets, for which the following characteristics are considered:

- Three-phase line with distributed neutral, S = 6 mm^2, neutral and phase with the same section, both in copper;
- $E_0 = 230$ V;
- $l = 25$ m;
- $K = 115$ (PVC insulated copper);
- Protection with a magnetothermal switch $I_n = 25$ A;
- Maximum short circuit current of 10 kA;
- Minimum short circuit current calculated as $I_{ccmin} = \frac{0{,}8 * E_0}{1{,}5\ \rho_{20°}(1+m)\,\frac{l}{S}} = \frac{0{,}8 * 230}{1{,}5 * 0{,}018\ (1+1)\,\frac{25}{6}} = 1636\ A$

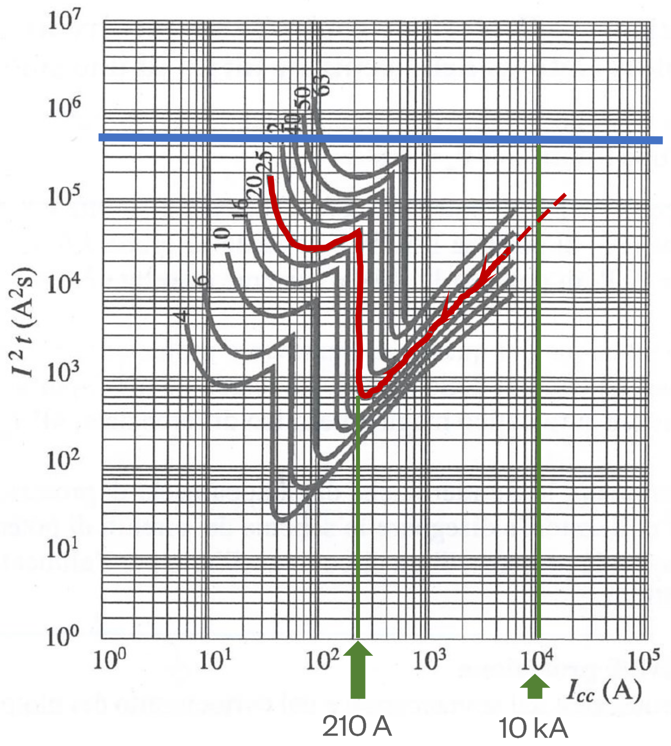
Application example 1

The specific let-through energy tolerable by the line is:

$$K^2S^2 = 115^2 * 6^2 = 4{,}76 * 10^5 A^2s$$

From the figure it can be seen that this value never intersects the curve of the breaker. This means that for short-circuit currents greater than approximately 210 A (trigger threshold of the magnetic relay) up to current values much higher than 10 kA, the energy let through by the breaker is certainly lower than that tolerable by the cable. Given the values of the minimum (1636 A) and maximum (10 kA) short-circuit currents, the verification of the Joule integral is positive.

In practice this almost always happens, especially if the short-circuit protection switch is chosen so that it also satisfies the requirements for overload (combined protection). For this reason the standard generally considers the verification satisfied, especially in the case of using current limiting breakers.



Application example 2

Overcurrent protection for electric motors of a building's water supply plant

The water plant for lifting drinking water for a building includes the following three-phase users, with V_n = 400 V:

- n° 2 electric pumps (P1 and P2) with 3 kW power and absorbed current 6,8 A;
- n° 1 electric pump (P3) with 1,5 kW power and absorbed current 3,6 A;
- n° 1 compressor (CP) with 1,1 kW power and absorbed current 2,8 A.

The line that supplies the control and protection panel starts from the general electrical panel of the building's common services, has a section of 6 mm^2, ampacity 31 A, and is protected by an automatic differential thermo-magnetic breaker, 4P, I_n = 25 A, I_{cn} = 6 kA, I_{dn} = 0,5 A.

We want to determine the characteristics of the protection devices against overcurrents of the four users and draw the diagram of the electrical panel power circuits, considering also the presence of an auxiliary circuit for the power supply of the 24 V controls, with 50 VA power .

Application example 2

Choice of protective devices

The aim is to protect asynchronous motors from overload and short circuit. Therefore, it is possible to choose between the solution with fuses and thermal relays coupled to contactors (separate protection), and the solution with automatic breakers (combined protection). It is decided to adopt the first solution.

The choice must therefore be made on the basis of the nameplate data of the machines, and leads to the following results:

User	Rated current (A)	Rated current of the fuse aM (A)	Calibration range of the thermal relay (A)
Pump P1	6,8	8	6 – 8,5
Pump P2	6,8	8	6 – 8,5
Pump P3	3,6	6	2,8 – 4
Compressor CP	2,8	4	2,2 – 3,1

Application example 2

The choice of the nominal breaking capacity of the fuses is easy. Since the breaker that protects from the short circuit the line coming from the building's common services panel (upstream) has I_{cn} = 6 kA, it can be deduced that the short circuit current on this panel is lower. Consequently, the short circuit current on the panel in question can only be further lower, due to the impedance of the supply line. Since the fuses on the market for 400 V systems have breaking capacities greater than 6 kA, no problems arise in this sense.

As regards the choice of contactors (to be combined with the thermal relays), they must have a category suitable for starting and stopping asynchronous motors and operating currents at 400 V not lower than the rated ones of the single users. The choice of individual contactors, based on manuals or commercial catalogues of the manufacturing companies, is not described here.

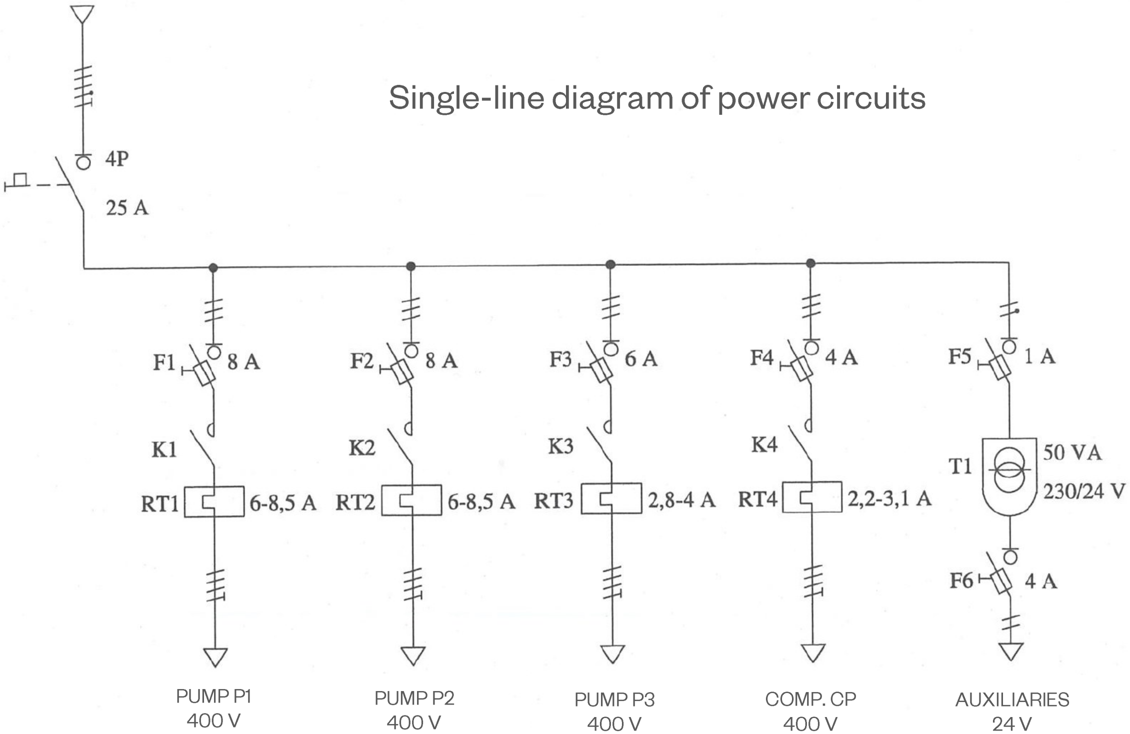
The 24 V auxiliary services can be powered by a 230/24 V isolation transformer, with a power of 50 VA. Since the nominal currents at the primary and secondary are 0,22 A and 2,1 A respectively, it is possible to use gG type fuses with nominal currents of 1 A and 4 A respectively as short-circuit protection.

Application example 2

The fuses are mounted on removable fuse holder bases, which allow the circuit to be sectioned under load.

A general switch is provided at the arrival of the power line, equipped with a door lock, to prevent access to the inside of the panel with the circuits powered.

Single-line diagram of power circuits



Overvoltages in electrical systems

Classification of overvoltages

***Overvoltage* is any voltage with a peak value higher than the highest voltage in the system**. (If the overvoltage affects a phase conductor and the earth, the peak value of the phase voltage is considered.)

In a system, overvoltages can be:

- *of internal origin*, due to the electrical system operation;
- *of external origin*, resulting from electrical phenomena that develop outside the system but that have an effect on it (for example, atmospheric lightning).

Overvoltages of internal origin can in turn be classified according to their waveform:

- at mains(operating) frequency;
- composed of oscillations at higher frequencies;
- impulsive with a steep front.

Internal overvoltages at operating frequency

They are overvoltages with a sinusoidal waveform and a frequency equal to the electrical system one, therefore they are a simple variation of the peak value. They can be caused by various phenomena.

Overvoltage due to permanent earthing of a phase

In a three-phase system with an isolated star center, if the insulation of the three phases is symmetrical (same impedance to earth), the voltage to earth of the three phases is equal to the phase voltage E. In the case of a fault to earth of a phase, its voltage to earth becomes zero, while the voltage to earth of the other phases assumes, after a transient, a value equal to the phase-to-phase voltage $V = \sqrt{3}E$. The resulting overvoltage is equal to 73% and is normally supported without damage by the components' insulation, if the latter has been chosen following the standards requirements.

The loads are not affected by this fault (provided that the choice of their insulation has been made appropriately) since the voltages between the phase conductors do not vary.

A fault warning is therefore sufficient.

Internal overvoltages at operating frequency

Overvoltage due to sudden load shedding

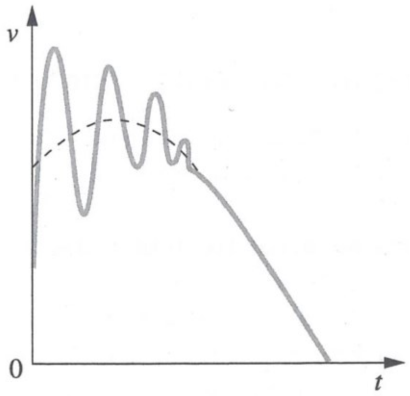
The sudden disconnection of a load from the network causes a sudden increase in voltage at the disconnection point, due to the cancellation of part of the voltage drop on the network impedances. The more significant the power of the disconnected load is compared to the short-circuit power at the connection point, the more significant the overvoltage. For high-power machines connected at the end of long lines, values of up to 50% can be reached, in the case of long lines with non-negligible capacitive component that add to the effect of the load disconnection also the overvoltage due to the Ferranti effect. The overvoltage can be harmful to the machines and equipment that remain connected to the line.

Protection is implemented by means of the control systems of the alternators, or by other devices used for voltage regulation, which must react promptly to load disconnections.

Load shedding is particularly dangerous for generators, as the resisting torque is suddenly missing and could cause the machine to run away.

Internal overvoltages of oscillatory nature

This type of overvoltage is characterized by a waveform composed of the superposition of the mains frequency sinusoid and one or more damped oscillatory components at high frequency.



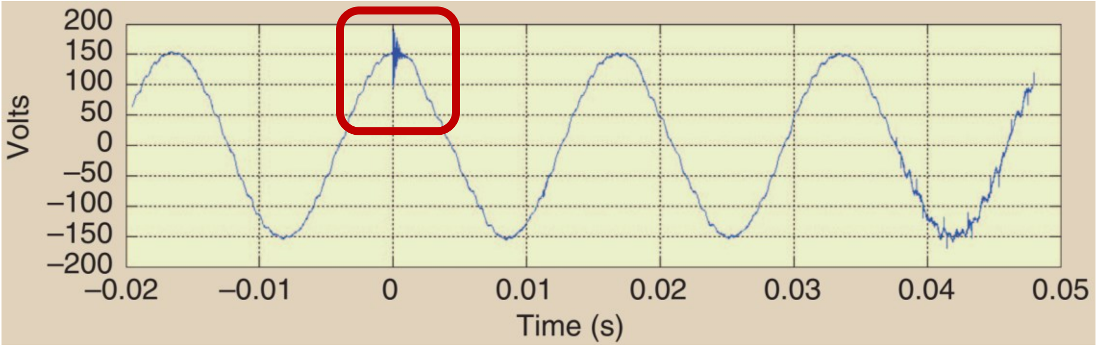


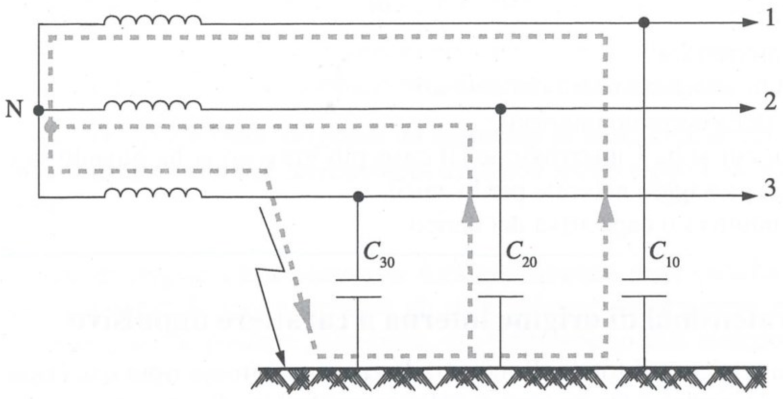
Figure from attached paper on overvoltages in the railway sector

Internal overvoltages of oscillatory nature

Ground arc overvoltages

Along overhead power lines, an accidental arc to ground may occur due to the failure of an insulator or transient phenomena (e.g., tree branch due to wind). This then creates an arc current that closes through the earth capacitances of the conductors (assuming that the neutral is insulated). Since the fault impedance is small, the faulty phase tends to assume the earth voltage, while the other phases tend to reach the value of the concatenated phase, similarly to what happens in the permanent earthing of a phase.

However, given the presence of the capacitances to ground, a transient charge and discharge of these capacitors is generated, which causes an oscillatory trend of the overvoltage due to the exchange of energy with the inductances of the line. The resistance of the line dampens these oscillations over time, leading to the waveforms seen previously.



Internal overvoltages of oscillatory nature

Without analyzing the phenomenon in detail, it can be noted that the first oscillation can reach a peak value of up to 2,5 times the maximum value of the operating voltage.

The situation worsens in the case of *intermittent arcs*, i.e., a rapid succession of arc's ignition and exstinguishing, as there is the superposition of numerous oscillatory overvoltages, reaching values even 4 times higher than the rated voltage.

The phenomenon can be avoided by operating the line with a grounded neutral. In this case the fault current becomes high, since each arc to ground is like a phase-ground short circuit, causing the intervention of the maximum current protections of the line. In this case, the overvoltage protection is in fact an overcurrent protection, which has the disadvantage of decreasing continuity of operation.

Internal overvoltages of oscillatory nature

Overvoltages due to breakers' opening

Opening a breaker under load, with consequent abrupt interruption of the current, causes an electric arc due to the inductive elements of the system (as previously mentioned). In circuits with non-negligible capacitive effects, this operation triggers energy exchanges between inductances and capacitances, dampened by the resistances.

The maximum amplitude of the overvoltages can reach even 3-4 times the operating voltage, even if normally we see values up to 20-30% of the nominal voltage. The amplitude depends on various factors.

A similar effect can be caused by the switching of high-power static conversion systems (power electronics converters), since from the point of view of the upstream system the static switches (used to build the converters) operate by opening and closing the circuit multiple times per second **(it is a present problem!).**

Impulsive internal overvoltages

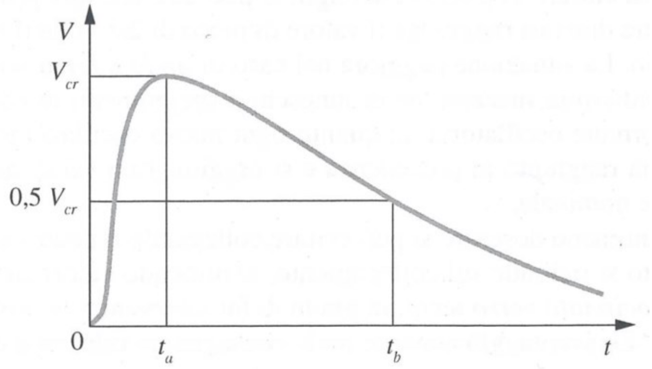
These are overvoltages with a steep front unidirectional waveform. The surge rises rapidly to the peak value, and then dies out much more slowly. The waveform is characterized by three values:

- V_{cr} peak value in kV (or kA if it is a current pulse);
- t_a time to reach the peak value in microseconds;
- t_b half-time of the peak value (time to half-value), expressed in microseconds.

For example, the term 10 kV (8/20 µs) indicates a voltage pulse that reaches 10 kV of peak value in 8 µs and halves in 20 µs.

Overvoltages of this type occur when a switch closes on an empty line.

They are generally less dangerous than the other overvoltages, since they reach values that are only slightly higher than double the nominal voltage.



External overvoltages

External overvoltages are due to electrical phenomena that develop in the atmosphere and affect electrical systems; they are divided into two categories:

- *slow-forming overvoltages*, originating from electrostatic induction phenomena;
- *impulse overvoltages*, originating from very rapid and short-lived transient phenomena, typical of lightning.

Electrostatic overvoltages are formed when clouds charged with static electricity pass by power lines. The lower layers of the clouds, negatively charged, behave like a capacitor plate, attracting positive charges onto the lines. Under normal conditions, the two charges are in equilibrium; however, when a cloud discharges to the ground or onto another cloud, the charge on the line is released, and originates an impulsive overvoltage that propagates in both directions on the line.

These overvoltages cannot occur in systems with a point connected to the ground (for example, the neutral), as the latter provides a path for the charges to discharge to the ground. It is a type of overvoltage that is generally harmless for high voltage lines but can become dangerous for systems with low operating voltage.

External overvoltages

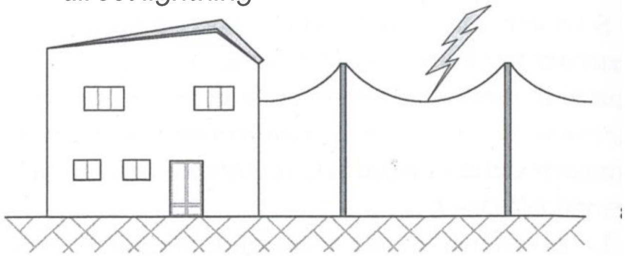
Overvoltages due to *atmospheric lightning* are much more dangerous and can affect lines and system components both through *direct lightning* (lightning on a part of the system) and *indirect lightning* (lightning near the system).

Lightning current causes overvoltages on circuits and equipment, due to resistive and inductive couplings.

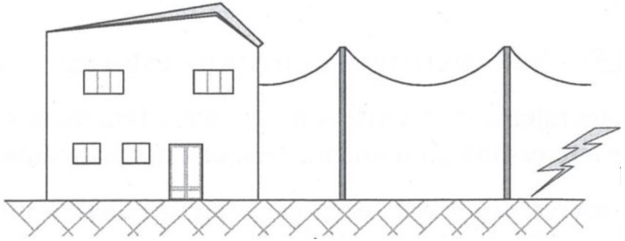
Resistive coupling occurs in the case of direct lightning, when the current is discharged to earth through the dispersing system of a building or line. The masses of the system assume the total earth voltage $U_E = ZI$, which depends on the magnitude of the current and its path. Voltage can reach hundreds of kV and damage the insulation towards earth of the equipment.

Overvoltages due to resistive coupling have the same waveform as the current originating them. In conventional tests, the standard impulse 10÷50 kA (10/350 μs) is used.

direct lightning



indirect lightning



External overvoltages

Inductive coupling occurs in both direct and indirect lightning strikes. The lightning current generates a rapidly varying magnetic field, which induces overvoltages in the closed loops formed by the internal circuits of a building, and in the loops formed by the conductors of the lines and the ground (any possible closed path formed by conductors). The overvoltage depends on the product of the inductance of the circuit and the rate of change of the current, which can reach up to 200 kA/µs.

For this type of overvoltage, the standard impulsive waveform with values 1÷5 kA (8/20 µs) is considered.

Given the magnitude of overvoltages of external origin, it is not convenient to carry out protection solely by increasing the insulation level of the equipment, but it will be necessary to use surge arresters (examined later).

In addition to the damage to the insulation due to the high voltage, atmospheric lightning also causes electrodynamic stresses and thermal effects.

Overvoltage (surge) protection

External overvoltage protection of structures is carried out by means of lightning rod systems, technically defined as LPS (*Lightning Protection System*).

The protection of electrical systems and equipment is carried out by correctly selecting their insulation levels (i.e., *insulation coordination*), which must be sized in such a way as to resist up to a certain voltage value, and by means of the use of surge arresters, for higher voltage values or specific needs.

Insulation coordination

LV systems

Insulation coordination and limitation of overvoltages are addressed by the standards regarding LV installations (in Italy, CEI 64-8, parts 4 and 5).

Regarding insulation, components are classified into categories based on their *impulse withstand voltage* U_w. This voltage is set by the manufacturer for the component or its part and characterizes the insulation's ability to withstand overvoltages. The categories range from I to IV, with increasing impulse withstand values.

The standards enforce that electrical components must be chosen so that the nominal value of their impulse withstand voltage is not lower than the value required by the standard itself.

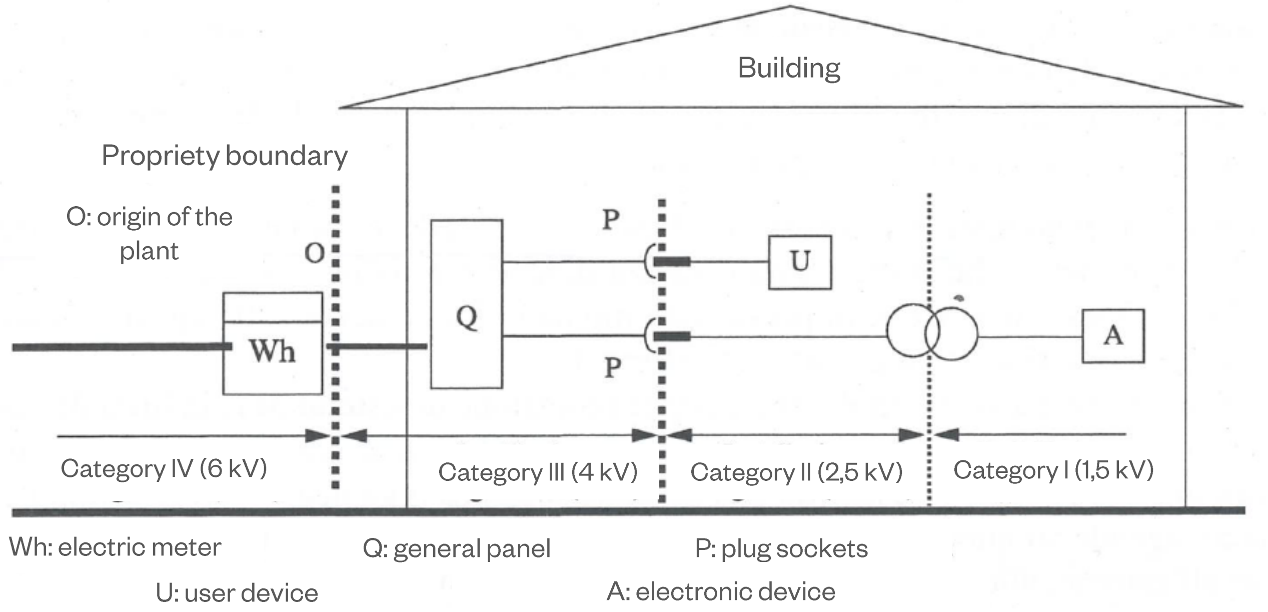
Insulation coordination

- *Category I* (*component with low impulse withstand*): equipment with electronic circuits (computers, audio/video equipment, etc.);
- *Category II* (*component with normal impulse withstand*): components suitable for direct connection to the fixed electrical system of a building (household appliances, air conditioners, mobile tools, etc.);
- *Category III* (*component with high impulse withstand*): components that are part of the fixed electrical systems of buildings (distribution panels, automatic breakers, electrical conduits, etc.);
- *Category IV* (*component with very high impulse withstand*): components intended for installation at the point of common coupling or in its vicinity, upstream of the main distribution panel (for example meters).

Rated voltage of the electric system (V)	Rated impulse withstand voltage required for electrical components (kV)			
	Category IV	Category III	Category II	Category I
230/400 277/480	6	4	2,5	1,5
400/690	8	6	4	2,5

Insulation coordination

Example of choice of impulse withstand categories for electrical user systems
with rated voltages of 230 V phase and 400 V phase-to-phase (from CEI 64-8/4 standard)



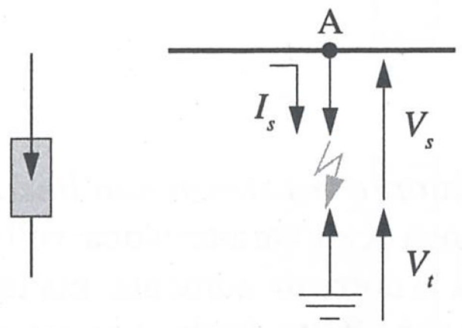
Surge arresters

Also called *surge protectors* and indicated by the acronym SPD (*Surge Protective Device*).

To fix the ideas, reference is made to a generic spark gap arrester.

When the voltage to earth of the point where the arrester is installed (point A in the figure) remains at normal operating levels, or when an overvoltage compatible with the system insulation levels occurs, the arrester keeps the line isolated from earth. If the voltage between point A and earth exceeds the device's trigger voltage, a discharge is generated between the two electrodes of the device, which conveys the overvoltage wave to earth, protecting the downstream equipment. When the voltage returns to normal values, the arrester restores the insulation to earth.

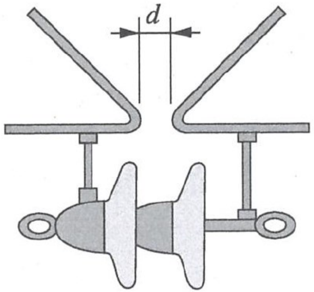
During the passage of the discharge current I_S, the voltage to earth of point A is given by the sum $V_A = V_S + V_t$, which is the sum between the arrester's own voltage corresponding to the current I_S and the earth voltage. Since V_A is applied to the downstream equipment, the insulation of the latter must be sized to withstand it.

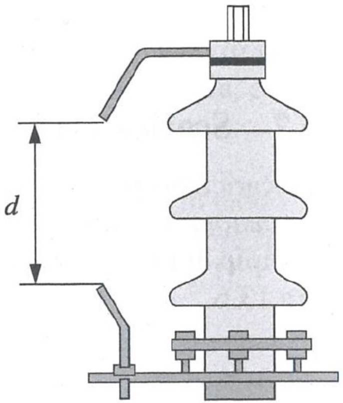


Surge arresters

Spark gap arresters

Horn or rod type, consisting of an insulator on which two metal rods are mounted, placed at a distance depending on the ignition voltage. It is mainly mounted directly on the equipment to be protected (brealers, disconnectors, transformers).





Surge arresters

Expulsion type arresters

Widely used for the protection of MV systems. In general, they consist of the series connection of an external spark gap arrester and an internal one placed in an insulating tube coated with a special organic substance. The heat developed by the arc, acting on this coating, generates a notable quantity of gas which, discharging to the outside, lengthens the arc, cools it and extinguishes it.

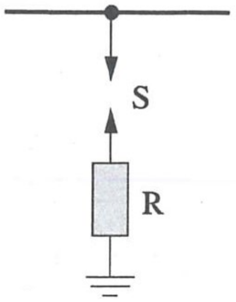
Surge arresters

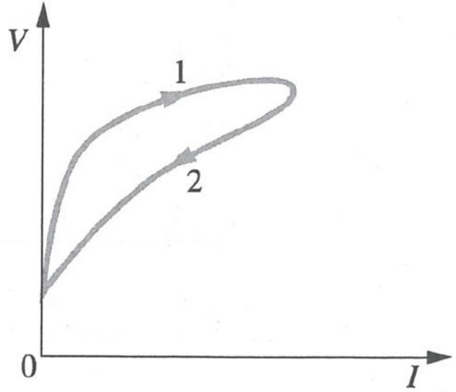
Non-linear resistance arresters

Consisting of the series of a spark gap S and a resistor R with a non-linear V-I characteristic.

During the discharge the current increases, but the voltage remains almost constant (curve 1); due to the Joule effect the resistor, composed of ceramic material with a negative temperature coefficient, heats up but its resistance decreases, leading to lower voltage values in the section of the curve relating to the phase of current cancellation (curve 2).

This feature separates the voltage on the arrester from the current flowing through it, making it easier to size the insulation (sizing for a known voltage, which depends only on the characteristic of the arrester).

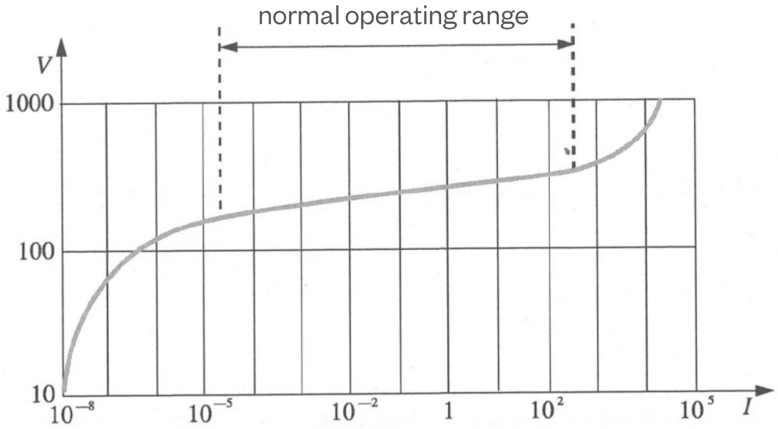




Surge arresters

For the protection of LV systems and equipment, non-linear resistance arresters based on the use of MOV (*Metal Oxide Varistors*) are widely used.

By presenting a V-I curve with an almost horizontal section (V = const.), these components can ensure that during the discharge the voltage on the component to be protected does not exceed a certain value (called *residual voltage*).



SPD Features and Installation – base concepts

In LV electrical systems, SPD voltage limiters are divided into classes that define where they are suitable to be installed:

- *Class I* - SPDs to be installed at the connection with lines that are highly exposed to direct lightning (10/350 μs impulse, typical of resistive coupling);
- *Class II* - SPDs to be installed at the connection with lines in buildings not subject to direct lightning or with lines subject to a minimal fraction of the lightning current (8/20 μs impulse, typical of inductive coupling);
- *Class III* - SPDs to be installed in proximity to individual equipment, to protect them from residual voltage from previous SPDs, or against the effects of excessive distance from these (combined wave 1/50 μs open circuit, 8/20 μs short circuit);

SPD Features and Installation – base concepts

SPD installation

The choice of whether to install SPD systems is based on a detailed study, which must be conducted according to the IEC 62305 standard.

The standard proposes a method of analysis of the risk due to lightning, with the aim of quantifying it analytically in terms of:

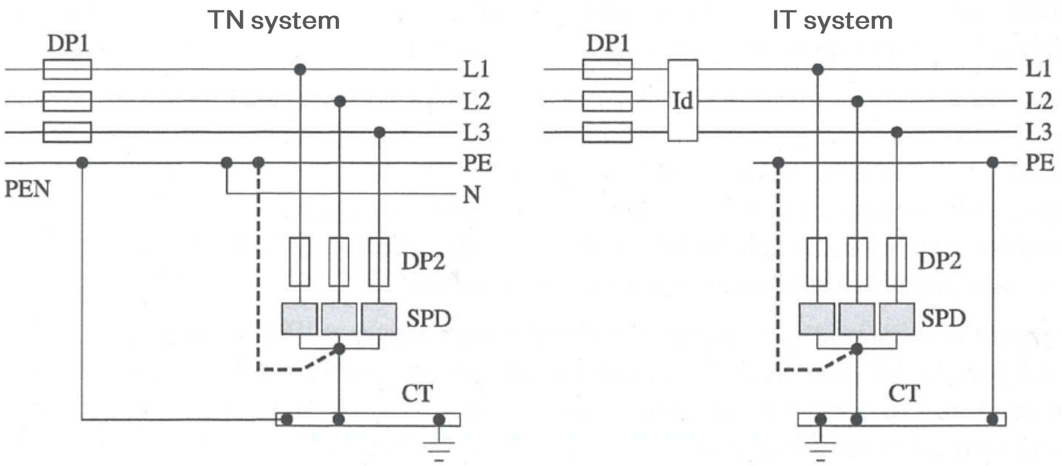
- Loss of Human Life
- Loss of Public Services
- Loss of Cultural Heritage
- Economic Loss

This risk can then be weighted with respect to the value of the tolerable risk (defined by each European country independently), to decide whether it is appropriate to adopt suitable protection measures.

SPD Features and Installation – base concepts

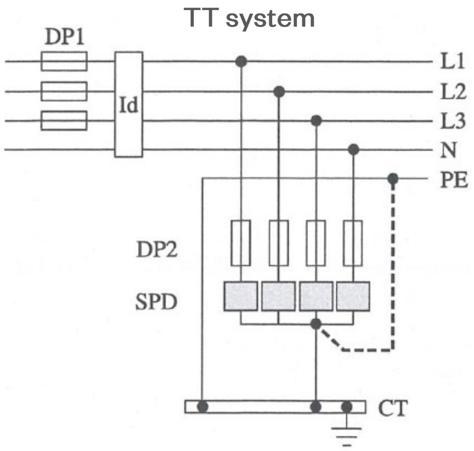
Limiting the discussion to small-scale LV electrical systems, the regulations require the installation of SPDs at the entrance of the electrical line into the building, according to three types of connections:

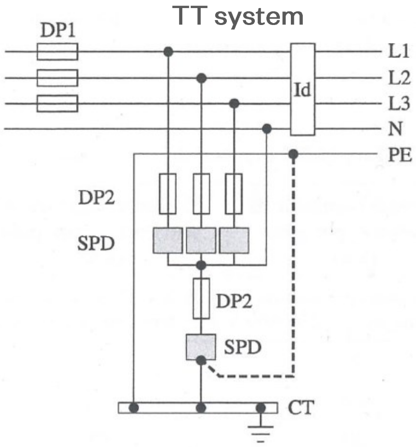
- *Type A connection*. Used in TN and IT systems by connecting three SPDs (one per phase) between the phase conductors and the main grounding bar or to the PE conductor (if the connection is shorter or gives rise to a lower voltage drop).



SPD Features and Installation – base concepts

- *Type B connection*. Used in the TT system by connecting four SPDs (one per phase, and one for the neutral) to the main grounding bar or to the PE protective conductor (if the connection is shorter or results in a lower voltage drop).
- *Type C connection*. Used in the TT system by connecting, upstream of the differential protection device, three SPDs (one per phase) between the phase conductors and the neutral; in addition, an additional SPD connects the neutral to the main grounding bar or to the PE protective conductor (if the connection is shorter or results in a lower voltage drop).



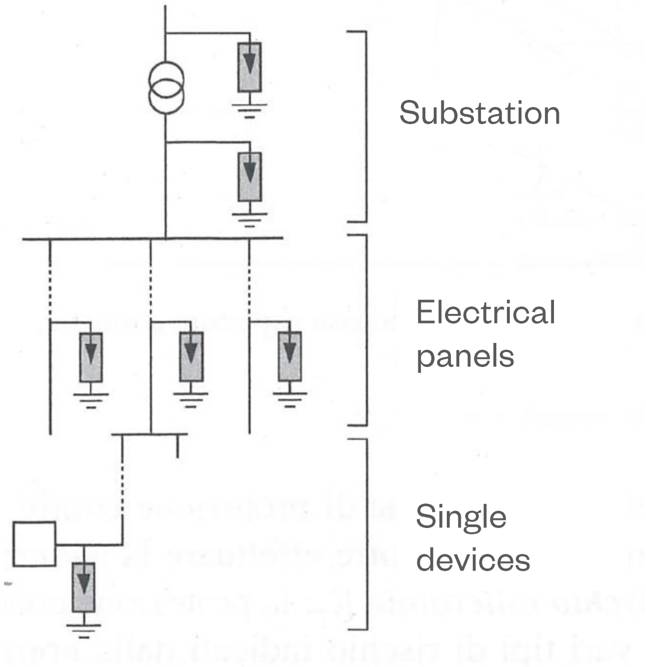


SPD Features and Installation – base concepts

For more complex systems, where the extension of the system becomes relevant, it is not possible to assume that the only entry point for overvoltages of atmospheric origin is the power supply network upstream of the delivery point (origin of the system).

Instead, it is necessary to consider the possibility of overvoltages of atmospheric origin coming from inside the system.

It may therefore be necessary to install multiple SPDs in cascade, to protect the various areas of the system, which must be appropriately coordinated.



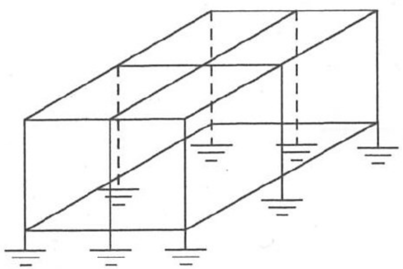
Protection of buildings against atmospheric lightning

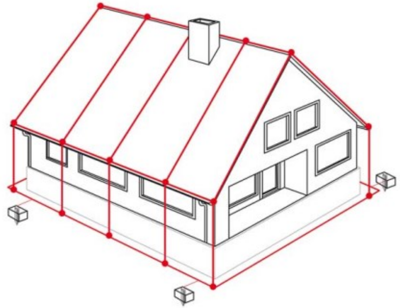
The protection of buildings and the systems contained therein from atmospheric discharges is also subject to the technical standards previously mentioned, according to the same analytical approach.

The topic is very complex, so it will not be treated in depth.

The complete protection system of a structure against lightning is called LPS (*Lightningh Protection System*) and has the purpose of reducing the material damage due to direct lightning strikes of the structure. It consists of an external protection system (*external LPS*) and an internal one (*internal LPS*).

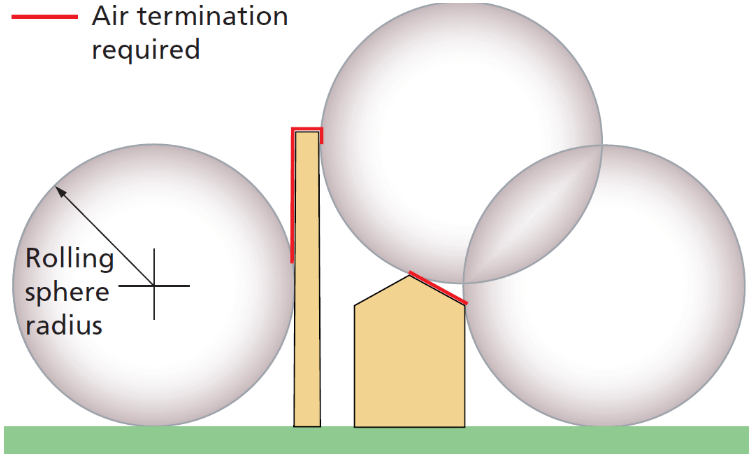
The *external system* serves to intercept lightning so that it does not strike the protected structure and to disperse the lightning current into the ground. It is made up of the *lightning rods (air-termination system)*, the *down conductor system* having the function of conducting the lightning current to the ground, and the part used to conduct and disperse the lightning current in the ground (*earth-termination systems*).

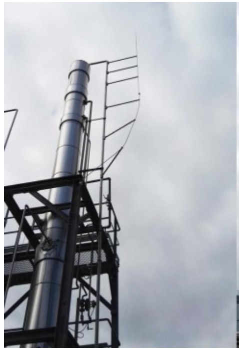


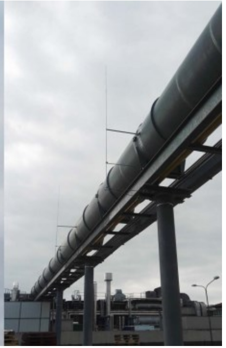


Protection of buildings against atmospheric lightning

The external protection system can have various forms, depending on the type of structure to be protected, and can be made with mesh, rod, or rope collectors, or even with a combination of these. The choice of installation points for the collectors is made using the rolling sphere method. At all points where the sphere can come into contact with the building, the triggering of an atmospheric lightning strike is possible. There is a correlation between the radius of the sphere and the presumed lightning current: $r = 10\ I^{0.65}$.







Protection of buildings against atmospheric lightning

The *internal protection system* includes all devices (e.g., SPD) and protection measures (insulation coordination, mechanical anchors, etc.) designed to reduce the effects (overvoltages, electrodynamic stresses, thermal stresses) of the lightning current within the structure to be protected, both for direct and indirect lightning strikes.

As already mentioned, the decision whether or not to install a lightning protection system for the structure in question and for the services connected to it passes through a risk assessment procedure.

UNIVERSITÀ DEGLI STUDI DI TRIESTE

dipartimento di ingegneria e architettura

Abnormal operations, switching devices, safety and protections

Fundamentals of Modern Power Systems

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