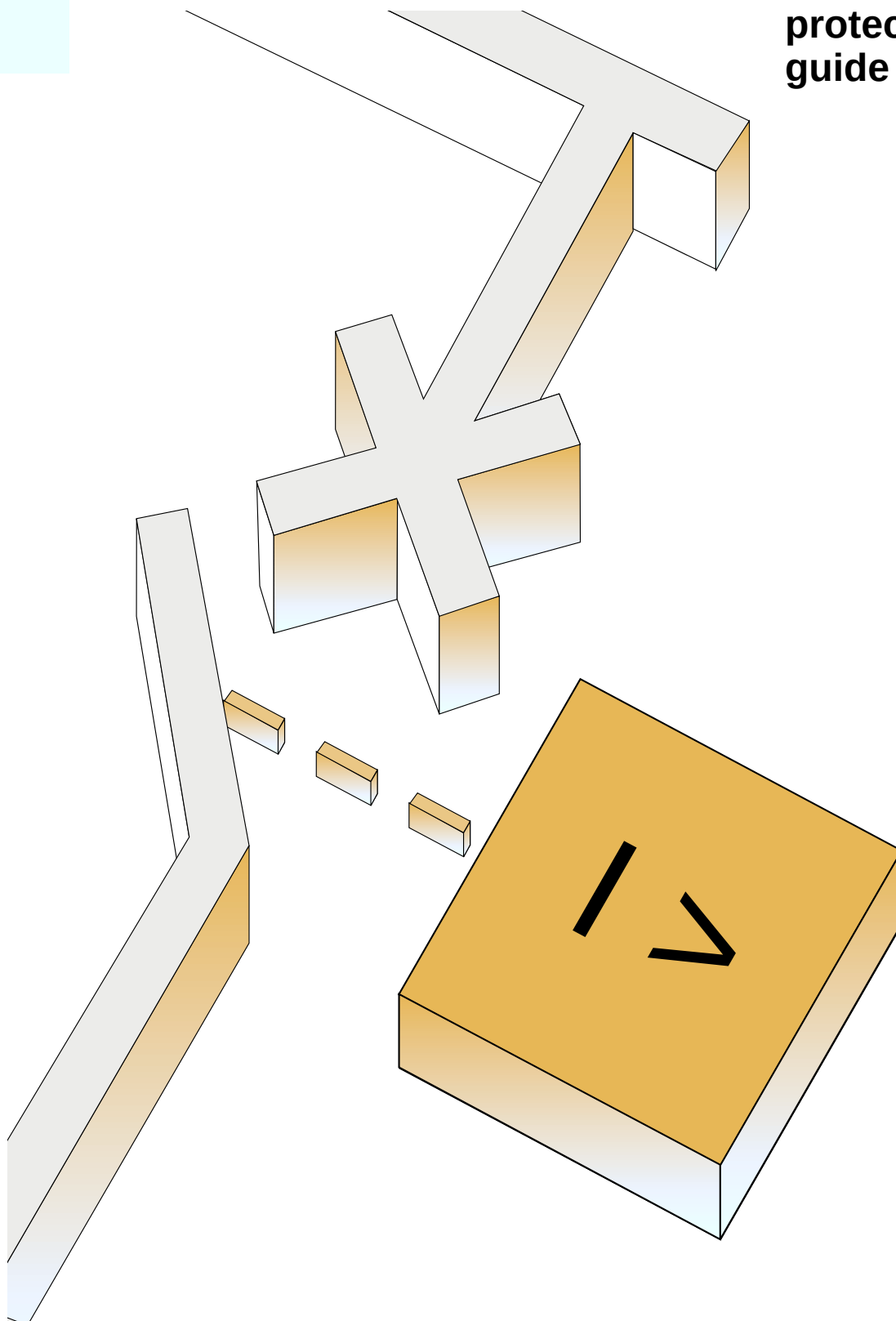


protection
guide



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lexicon

	overcurrent protection		undervoltage protection
	directional overcurrent protection		over and underfrequency protection
	earth fault protection		overvoltage protection
	negative sequence unbalance protection		real reverse power protection
	thermal overload protection		reactive reverse power protection
	differential protection		neutral voltage displacement protection
	voltage restrained overcurrent protection		Buchholz

generalities

Protection devices continuously monitor the electrical status of system units and cause them to be de-energized (e.g. tripped by a circuit breaker) when they are the site of a disturbance: short-circuit, insulation fault...

The objectives are:

- to contribute to protecting people against electrical hazards,
- to prevent equipment damage (the power produced by a three-phase short-circuit on a MV busbar can melt up to 50 kg of copper within 1 second, the temperature at the centre of the arc can exceed 10,000°C),
- to limit thermal, dielectric and mechanical stress on equipment,
- to maintain stability and service continuity in the system,
- to protect adjacent installations (for example, by reducing induced voltage in adjacent circuits).

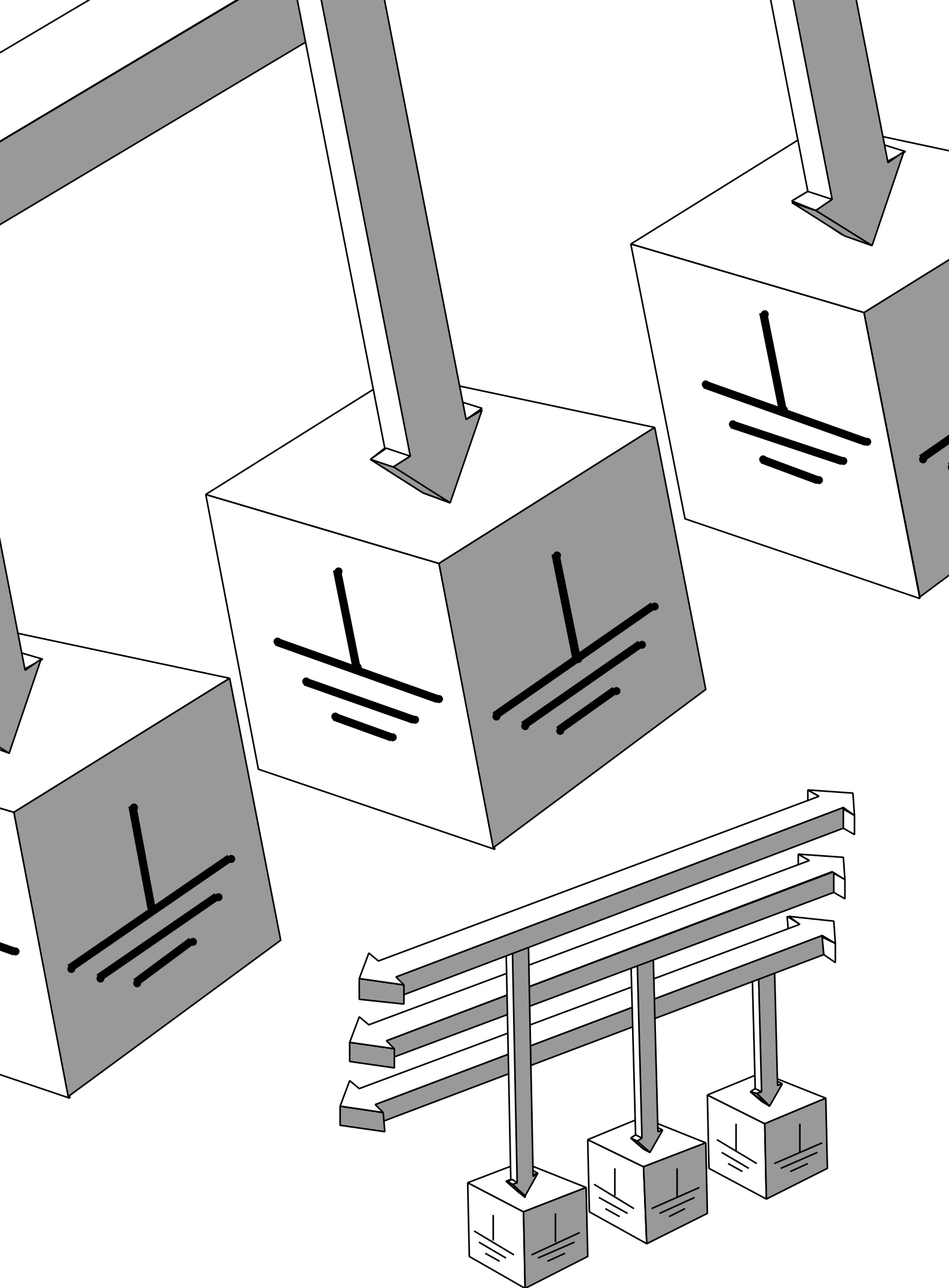
In order to attain these objectives, a protection system should have the following features:

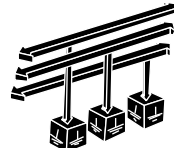
- speed,
- discrimination,
- reliability.

Protection, however, has its limits: faults have to actually occur in order for it to take effect. Protection cannot therefore prevent disturbances; it can only limit their duration. Furthermore, the choice of a protection system is often a technical and economic compromise between the availability and safety of the electrical power supply.

The choice of a protective device is not the result of isolated study, but rather one of the most important steps in the design of the electrical system.

Based on an analysis of the behaviour of electrical equipment (motors, transformers...) during faults and the phenomena produced, this guide is intended to facilitate your choice of the most suitable protective devices.





introduction

The choice of MV and HV grounding systems has long been a topic of heated controversy due to the impossibility of finding a single compromise for the various types of electrical systems. Experience acquired today enables a pertinent choice to be made according to the specific constraints of each system.

five grounding systems

Neutral potential can be grounded using five methods that differ according to the kind (capacitive, resistive, inductive) and value (zero to infinity) of the Z_n impedance connection made between the neutral and earth:

- $Z_n = \infty$ **ungrounded**, no deliberate connection,
- Z_n is a **resistance** with a fairly high value,
- Z_n is a **reactance** with a generally low value,
- Z_n is a **reactance** designed to compensate for the system capacity,
- $Z_n = 0$ - the neutral is directly **grounded**.

difficulties and selection criteria

The selection criteria involve many aspects:

- technical characteristics (system function, overvoltage, fault current, etc...),
- operation (service continuity, maintenance),
- safety,
- cost (investment and operating expenses),
- local and national customs.

In particular, there are two major technical considerations which are, in fact, contradictory:

Reducing the level of overvoltage

Overvoltage is of several origins:

- lightning overvoltage, which all overhead systems are exposed to, up to the user supply point,
- internal system overvoltage caused by operations and certain critical situations (resonance),
- overvoltage resulting from an earth fault itself and its clearance.

Reducing earth fault current (I_f).

Fault current that is too high produces a whole series of consequences:

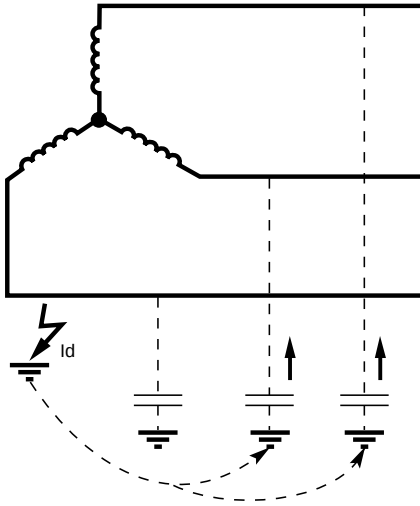
- damage caused by the arc at the fault point; particularly the melting of magnetic circuits in rotary machines,
- thermal withstand of cable shields,
- size and cost of earthing resistance,
- induction into adjacent telecommunication systems,
- danger for people created by raised frame potential.

Unfortunately, optimizing one of these requirements is automatically to the disadvantage of the other. Two typical grounding methods accentuate this contrast:

- the ungrounded neutral system, which eliminates the flow of earth fault current through the neutral but causes the most overvoltage,
- the directly grounded neutral system, which reduces overvoltage to a minimum, but causes high fault current.

An intermediate solution is therefore often chosen: the impedance grounded neutral system.

ungrounded



In this type of system, a phase-to-earth fault only produces a weak current through the phase-to-earth capacity of the fault-free phases.

It can be shown that $I_d = 3 C \omega V$

- V being the simple voltage,
- C the phase-to-earth capacity of a phase,
- ω the frequency of the system ($\omega = 2\pi f$).

The I_d current can remain for a long time, in principle, without causing any damage since it does not exceed a few amperes

(approximately 2 A per km for a 6 kV single-pole cable, with a 150 mm² cross-section, PRC insulated, with a capacity of 0.63 μ F/km). Action does not need to be taken to clear this 1st fault, making this solution advantageous in terms of maintaining service continuity.

However, this brings about the following consequences:

- if not cleared, the insulation fault must be signalled by a **permanent insulation monitor**,
- subsequent fault tracking requires device made all the more complex by the fact that it is automatic, for quick identification of the faulty feeder, and also maintenance personnel qualified to operate it,
- if the 1st fault is not cleared, a second fault occurring on another phase will cause a real two-phase short circuit through the earth, which will be cleared by the phase protections.

Advantage

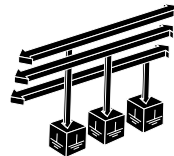
The basic advantage is **service continuity** since the very weak fault current prevents automatic tripping.

Drawbacks

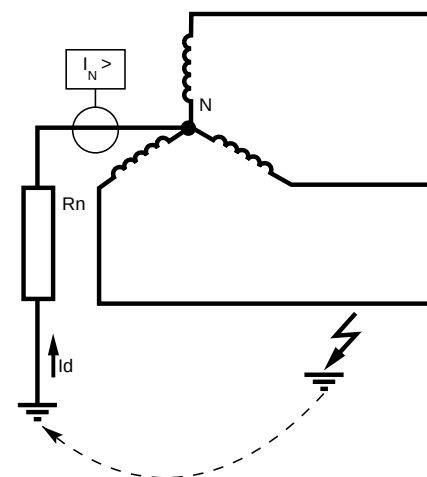
The **failure to eliminate overvoltage** through the earth can be a major handicap if overvoltage is high. Also, when one phase is earthed, the others are at delta voltage ($U = V \cdot \sqrt{3}$) in relation to the earth increasing the probability of a 2nd fault. Insulation costs are therefore higher since the delta voltage may remain between the phase and earth for a long period as there is no automatic tripping. A maintenance department with the equipment to quickly track the 1st insulation fault is also required.

Applications

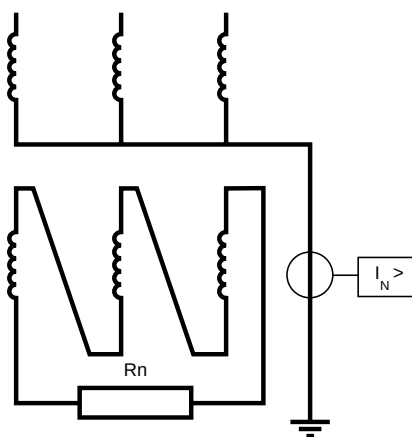
This solution is often used for industrial systems (≤ 15 kV) requiring service continuity.



resistance grounding



accessible neutral



non accessible neutral

In this type of system, a resistive impedance limits earth fault current I_d , while still allowing proper evacuation of overvoltage. Protections must however intervene automatically **to clear the first fault**. In systems that feed rotating machines, the resistance is calculated so as to obtain an I_d current of 15 to 50 A.

This weak current must however be $I_d \geq 2 I_c$ (I_c : total capacitive current in the system) in order to reduce operation overvoltage and to enable simple detection.

Distribution systems use higher ratings (100 to 1000 A) that are easier to detect and allow evacuation of lightning overvoltage.

Advantages

This system is a good compromise between weak fault current and good overvoltage evacuation. The protection devices are fairly simple and discriminating and the current is limited.

Drawbacks

- no service continuity; earth faults must be cleared as soon as they occur,
- the higher the voltage and level of current limitation, the higher the cost of the earthing resistance.

Applications

Public and industrial MV distribution systems.

Earthing resistance

If the neutral is accessible (star-connected transformer), the earthing resistance is inserted between the neutral and earth.

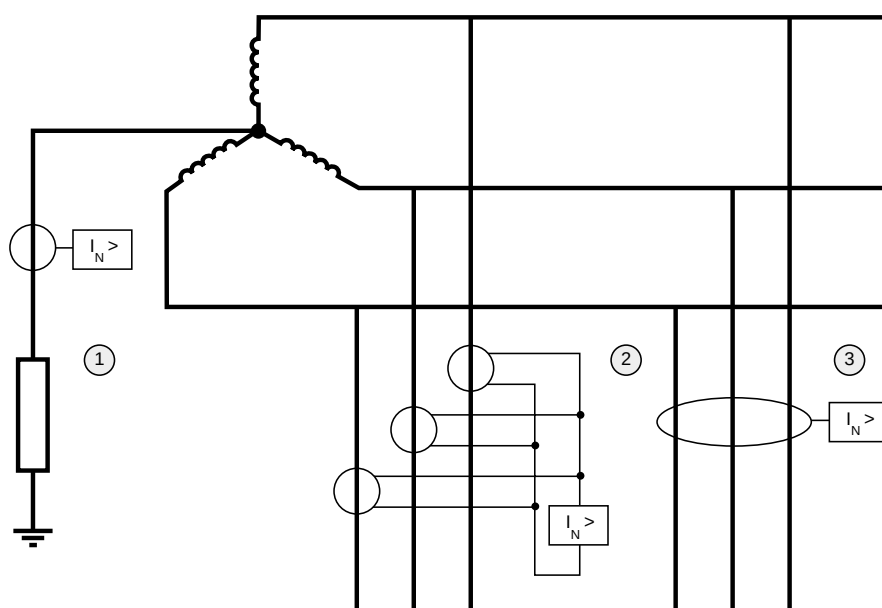
When the neutral is not accessible or when determined by the discrimination study, an artificial neutral point is established (zero sequence generator) using a coil or a special transformer with a very low zero sequence reactance.

Protections

The detection of weak fault current I_d requires protections other than overcurrent phase relays.

These "earth fault" protections detect fault current:

- directly in the neutral earthing connection ①,
- or within the system by measuring the vectorial sum of the 3 currents using:
 - 3 CTs feeding the phase overcurrent protections ②,
 - a core balance CT - (accurate solution - to be used preferably) ③.



The relay is set according to the fault current I_d that is calculated leaving out the zero sequence impedance of the source and of the connection in relation to impedance R_n and taking the following 2 rules into account:

- setting > 1.3 times system capacitive current downstream from the protection,
- setting at approximately 20 % of maximum earth fault current.

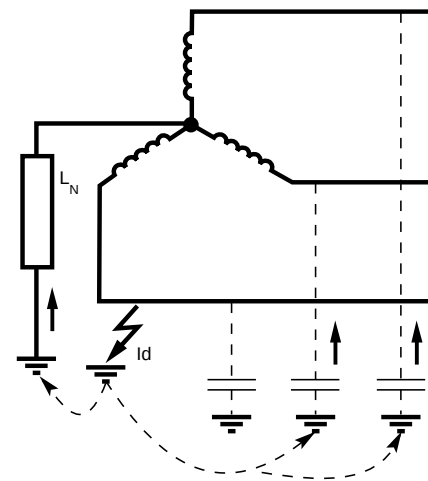
Also, if 3 CTs are used for detection, the setting must not be less than 10% of the CT rating to take into consideration the uncertainty linked to:

- asymmetry of transient currents,
- differences in performance level.

reactance grounding

For system voltage above 40 kV, it is preferable to use reactance rather than a resistance because of the difficulties arising from heat emission in the event of a fault.

compensation reactance grounding



This system is used to compensate for capacitive current in the system. Fault current is the sum of the currents which flow through the following circuits:

- reactance grounding,
- fault-free phase capacitance with respect to earth.

The currents may compensate for each other since:

- one is inductive (in the grounding),
- the other one is capacitive (in the fault-free phase capacitances).

They are therefore opposite in phase.

Advantage

The system reduces fault current, even if the phase-to-earth capacitance is high.

Drawback

The cost of reactance grounding may be high due to the need to modify the reactance value in order to adapt compensation.

Protection

Fault detection is based on the active component of the residual current. The fault causes residual currents to flow throughout the system, but the faulty circuit is the only one through which resistive residual current flows. In addition, the protective devices take into account repetitive self-extinguishing faults (recurring faults).

When the earthing reactance and system capacitance are compensated ($3L_N C_w^2 = 1$)

- fault current is minimal,
- it is resistive current,
- faults are self-extinguishing.

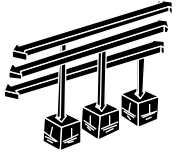
The compensation reactance is called an **extinction coil** or **Petersen coil**.

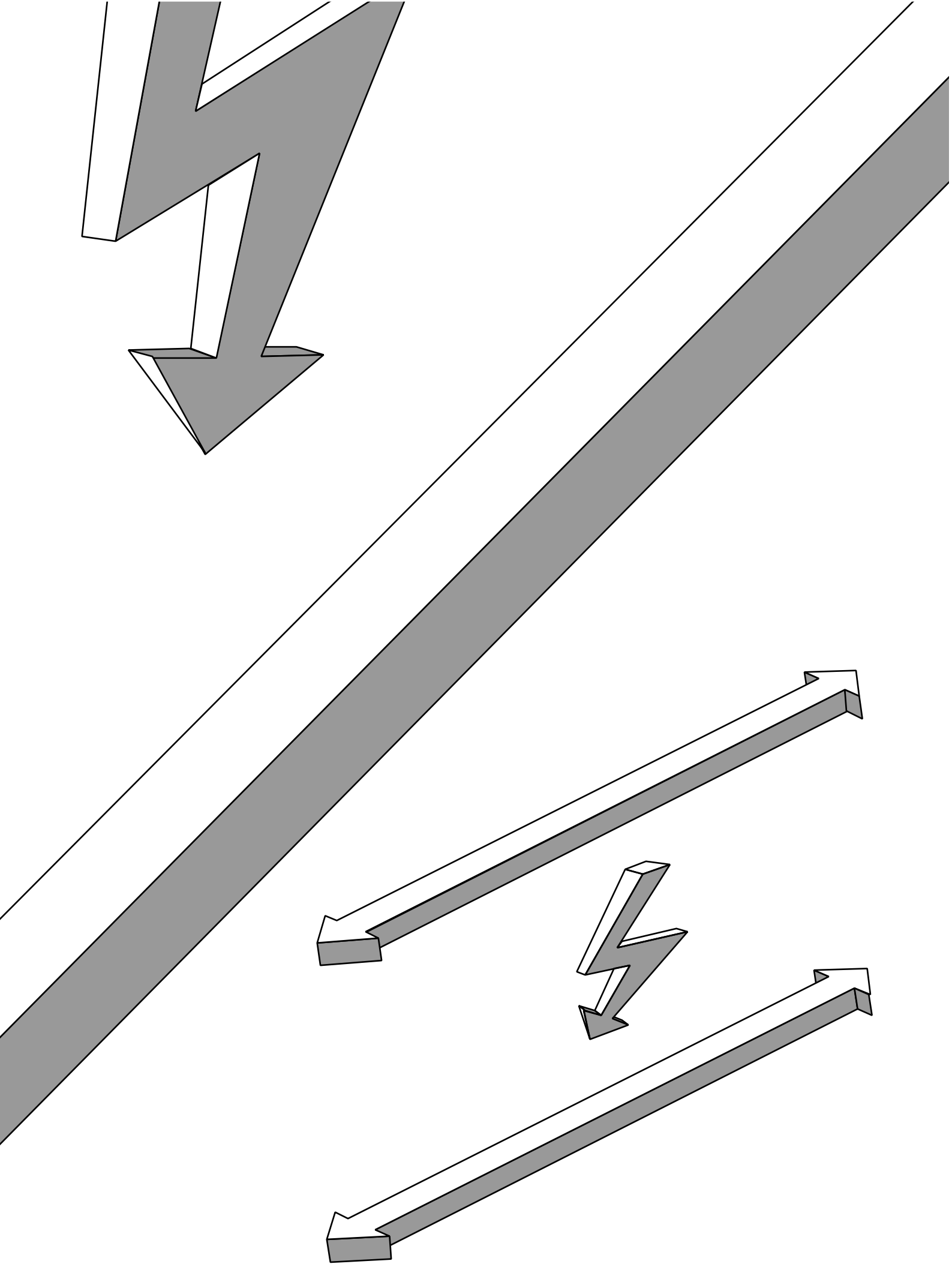
direct grounding

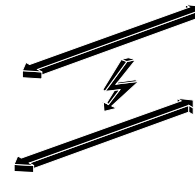
When the neutral is directly grounded without any coupling impedance, fault current I_d between the phase and earth is practically a phase-to-neutral short-circuit, with a high value. This system, ideal for overvoltage evacuation, involves all the drawbacks and hazards of strong earth fault current. There is **no continuity of service**, but there are no specific protections: the **regular phase overcurrent protections** clear the fault.

Applications

- this type of system is not used in European overhead or underground MV systems, but is prevalent in North American distribution systems. In these (overhead) systems, other features come into play to justify the choice:
 - the existence of a distributed neutral conductor,
 - 3 ph or 2 ph/N or ph/N distribution,
 - use of the neutral conductor as a protective conductor with systematic earthing of each electrical cable pole.
- this type of system may be used when the short-circuit power of the source is low.







introduction

A short circuit is one of the major incidents affecting electrical systems.

The consequences are often serious, if not dramatic:

- a short circuit disturbs the system environment around the fault point by causing a sudden **drop in voltage**,
- it requires a part of the system (often a large part) to be **disconnected** through the operation of the protection devices,
- all equipment and connections (cables, lines) subjected to a short circuit undergo strong **mechanical stress** (electrodynamic forces) which can cause breaks, and **thermal stress** which can melt conductors and destroy insulation,
- at the fault point, there is often a **high power electrical arc**, causing very heavy damage that can quickly spread all around.

Although short circuits are less and less likely to occur in modern well-designed, well-operating installations, the serious consequences they can cause are an incentive to implement all possible means to swiftly detect and attenuate them.

The short circuit value at different points in the system is essential data in defining the cables, busbars and all breaking and protection devices as well as their settings.

definitions

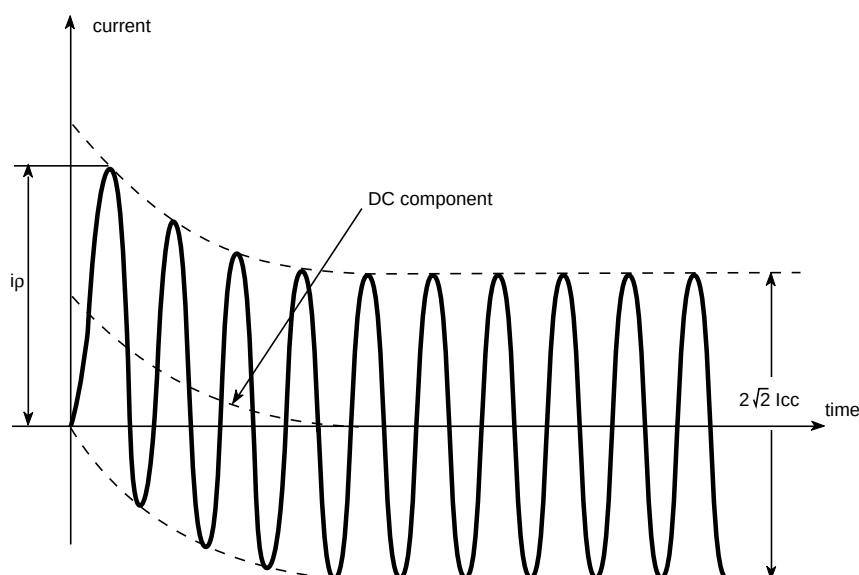
Short-circuit current at a given point in the system is expressed as the **rms value I_{sc}** (in kA) of its AC component.

The maximum **instantaneous value** that short-circuit current can reach is the **peak value i_p** of the first half cycle.

This peak value can be much higher than $\sqrt{2} \cdot I_{sc}$ because of the **damped DC component** that can be superimposed on the AC component. This random DC component depends on the instantaneous value of voltage at the start of the short-circuit and on the system characteristics.

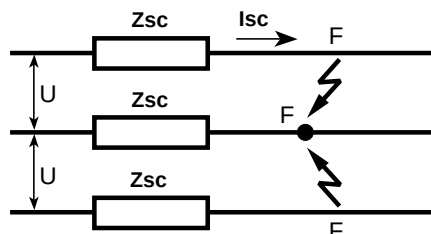
Short-circuit power is defined by the formula $S_{sc} = \sqrt{3} U_n \cdot I_{sc}$ (in MVA).

This theoretical value has no physical reality; it is a **practical conventional value** comparable to an apparent power rating.



short-circuit currents (cont.)

phase-to-phase short-circuit



The I_{sc} value of three-phase short circuit current at a point F within the system is:

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

in which U refers to the phase-to-phase voltage at point F before the fault occurs and Z_{sc} is the equivalent upstream system impedance as seen from the fault point.

■ in theory, this is a simple calculation; in practice, it is complicated due to the difficulty of calculating Z_{sc} , an impedance equivalent to all the unitary impedances of series- and parallel-connected units located upstream from the fault. These impedances are themselves the quadratic sum of reactances and resistances.

$$Z_{sc} = \sqrt{R^2 + X^2}$$

Calculations can be made much simpler by knowing the short-circuit power S_{sc} at the point that joins the distribution system.

Knowing S_{sc} at this point, the equivalent Z_a impedance upstream from this point can be calculated using the formula:

$$Z_a = \frac{U^2}{S_{sc}}, \quad I_{sc} = \frac{U}{\sqrt{3} Z_a}$$

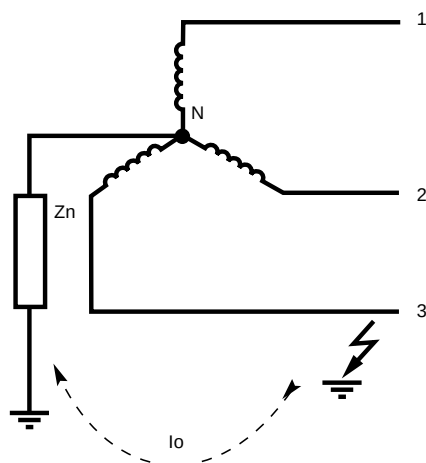
There may not be a single source of voltage, but rather several sources in parallel, in particular, synchronous and asynchronous motors, reacting like generators upon the occurrence of short circuits.

Three-phase short circuit current is generally the strongest current that can flow in the system.

Two-phase short circuit current is always weaker (by a ratio of $\sqrt{3}/2$, i.e. approximately 87%).

$$\text{2-phase } I_{sc} = \frac{U}{2 Z_{sc}}$$

phase-to-earth short circuit current (single-phase)



The value of this current depends on Z_n impedance between the neutral and earth. This impedance can be virtually nil if the neutral is directly grounded (in series with the earthing connection resistance) or, on the contrary, almost infinite if the neutral is ungrounded (in parallel with the system's phase to earth capacitance).

Calculation of this unbalanced short-circuit current requires the use of the symmetrical components method.

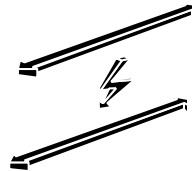
This method replaces the real system by superimposing 3 systems: positive Z_1 , negative Z_2 , zero sequence Z_0 . The value of the phase-to-earth fault current I_0 is:

$$I_0 = \frac{U \sqrt{3}}{Z_1 + Z_2 + Z_0 + 3 Z_n}$$

This calculation is required for systems in which the neutral is earthed by a Z_n impedance. It is used to determine the setting of the "earth fault" protection devices which are to intervene to break the earth fault current.

In practice :

$$I_0 \approx \frac{U}{\sqrt{3} Z_n}$$



short circuit currents at generator terminals

It is more complicated to calculate short-circuit current at a synchronous generator's terminals than at the terminals of a transformer connected to the system. This is because the internal impedance of the machine cannot be considered constant after the start of the fault. It increases progressively and the current becomes weaker, passing through three characteristic stages:

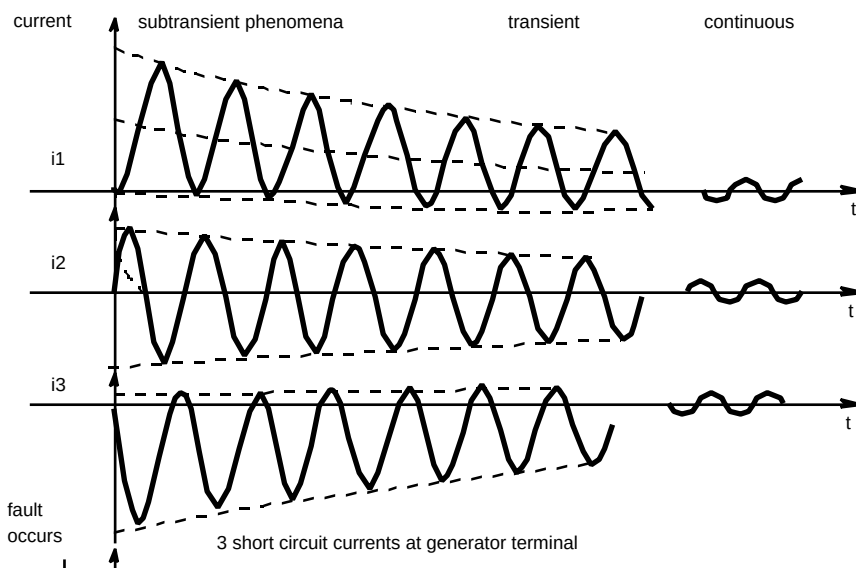
■ **subtransient:** (approx. 0.01 to 0.1 sec). Short-circuit current (rms value of the AC component) is high: 5 to 10 times permanent rated current.

■ **transient:** (between 0.1 and 1 sec). Short-circuit current drops to between 2 and 6 times rated current.

■ **continuous:** Short-circuit current drops to between 0.5 and 2 times rated current.

The given values depend on the power rating of the machine, its excitation mode and, for continuous current, on the value of the exciting current, therefore on the machine's load at the time of the fault. Also, the zero sequence impedance of the AC generators is generally 2 to 3 times lower than their positive sequence impedance. Phase-to-earth short circuit-current is therefore stronger than three-phase current. By way of comparison, the three-phase short-circuit current at a transformer's terminals ranges between 6 and 20 times rated current depending on the power rating.

It can be concluded that short-circuits at generator terminals are difficult to assess, and that their low, decreasing value makes protection setting difficult.



calculation of short-circuit currents

The rules for calculating short-circuit currents in industrial installations are presented in IEC standard 909 issued in 1988.

The calculation of short-circuit currents at various points in a system can quickly turn into an arduous task when the installation is a complicated one. The use of specialized software enables these calculations to be performed faster.

equipment behaviour during short-circuits

There are 2 types of system equipment, the type that intervenes and the type that does not intervene at the time of a fault.

Passive equipment

This category comprises all equipment which, due to its function, must have the capacity to transport both normal current and short-circuit current without damage.

This equipment includes cables, lines, busbars, disconnecting switches, switches, transformers, series reactances and capacitors, instrument transformers. For this equipment, the capacity to withstand a short-circuit without damage is defined in terms of:

- electrodynamic withstand (expressed in peak kA), characterizing mechanical resistance to electrodynamic stress.
- thermal withstand (expressed in rms kA for 1 to 5 seconds) characterizing maximum admitted overheating.

Active equipment

This category comprises the equipment designed to clear short circuit currents: circuit breakers and fuses.

This property is expressed by the **breaking capacity** and if required, by the **making capacity** upon occurrence of a fault.

■ breaking capacity

This basic characteristic of a switching device is the **maximum current** (in rms kA) **it is capable of breaking** in the specific conditions defined by the standards, it generally refers to the **rms value of the AC component** of the short circuit current; sometimes, for certain switchgear, the rms value of the sum of the 2 components is specified: AC and DC; it is then "unbalanced current".

The breaking capacity requires other data such as:

- voltage,
- R/X ratio of broken circuit,
- system natural frequency,
- number of breaks at maximum current, for example the cycle: B - M/B - M/B (B = breaking; M = making),
- status of the device after test.

The breaking capacity appears to be a fairly complicated characteristic to define: it therefore comes as no surprise that the same device can be assigned different breaking capacities depending on the standard by which it is defined.

■ making capacity upon occurrence of a short-circuit

In general, this characteristic is implicitly defined by the breaking capacity: a device should have the capacity to "make" upon the occurrence of a short-circuit that it has the capacity to break.

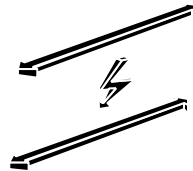
Sometimes making capacity needs to be higher, for example for AC generator circuit breakers.

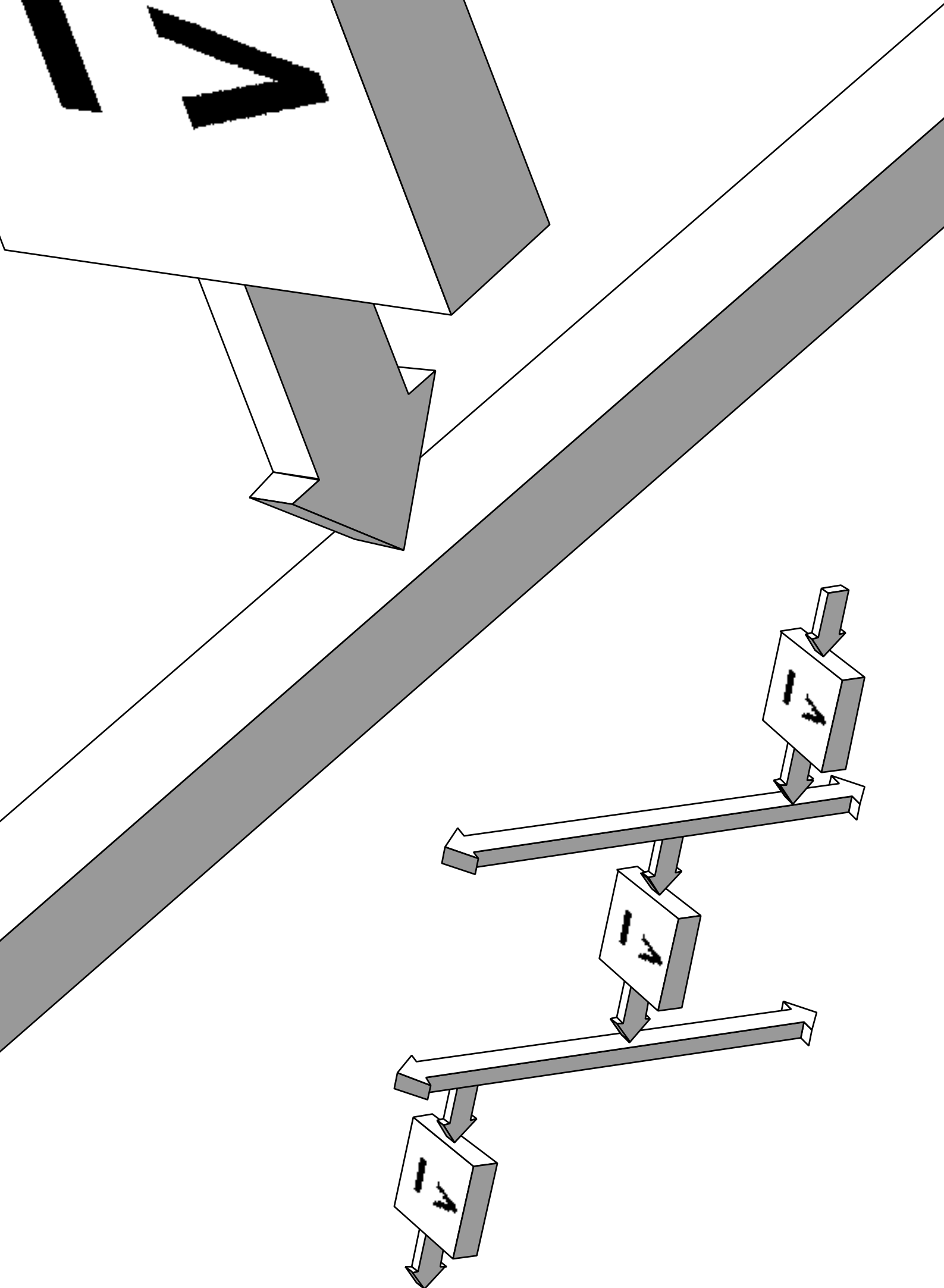
The making capacity is defined **at peak kA** since the 1st asymmetric peak is the most restrictive one from an electrodynamic point of view.

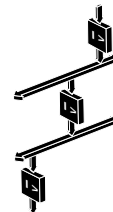
■ short-circuit current presumed to be "broken"

Some devices have the capacity to limit the current they are going to break.

Their breaking capacity is defined as the **maximum current presumed to be broken** that would develop in the case of a full short circuit at the upstream terminals of the device.







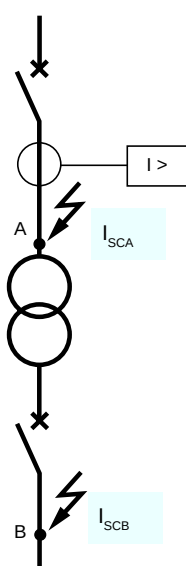
introduction

Protections comprise a coherent whole in relation to the structure of the system and its grounding. They should be looked upon as a system based on the principle of discrimination which consists of isolating as quickly as possible the part of the system affected by the fault and only that part, leaving all the fault-free parts of the system energized.

Various means can be implemented to ensure proper discrimination in electrical system protection:

- current discrimination,
- time discrimination,
- discrimination by data exchange, referred to as logic discrimination,
- discrimination by the use of directional protection devices,
- discrimination by the use of differential protection devices.

current discrimination



(fig.1)

example of current discrimination

Current discrimination is based on the fact that within a system, the further the fault is from the source, the weaker the fault current.

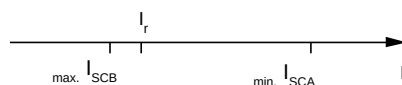
Current-based protection is installed at the starting point of each section: its setting is set at a value lower than the minimum value of short-circuit current caused by a fault in the monitored section, and higher than the maximum value of the current caused by a fault located downstream (beyond the monitored area). Set in this way, each protection device operates only for faults located immediately downstream from it, and is not sensitive to faults beyond.

In practice, it is difficult to define the settings for two cascading protection devices (and still ensure good discrimination) when there is no notable decrease in current between two adjacent areas (medium voltage system). However, for sections of lines separated by a transformer, this system can be used advantageously as it is simple, economical and quick (tripping with no delay).

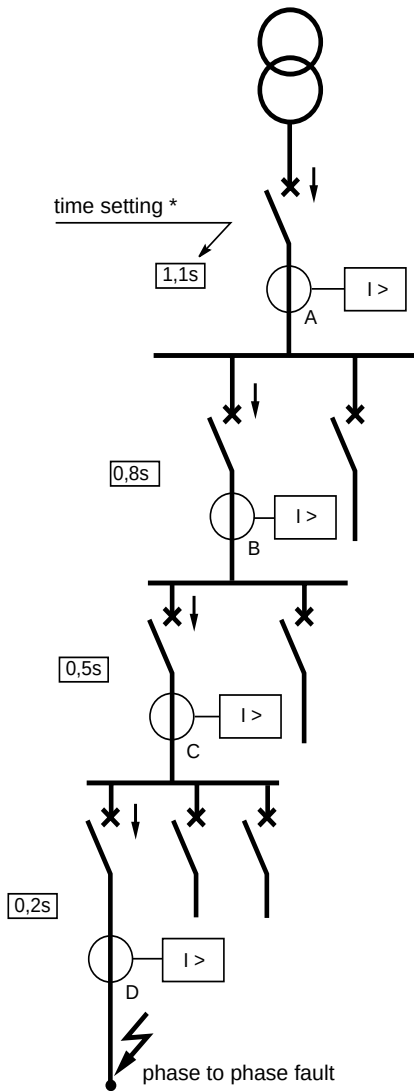
An example of the application is shown (fig.1).

$$I_{SCA} > I_r \geq I_{SCB}$$

I_{SCB} image at the transformer primary of the maximum short-circuit current on the secondary.



time discrimination



Time discrimination consists of setting different time delays for the current-based protection devices distributed throughout the system. **The closer the relay is to the source, the longer the time delay.**

The fault shown in the diagram opposite is detected by all the protections (at A, B, C, and D). The time-delayed protection at D closes its contacts more quickly than the one installed at C, which is in turn faster to react than the one at B, etc.

Once circuit breaker D has been tripped and the fault current has been cleared, protections A, B and C, which are no longer required, return to the stand-by position.

The difference in operation times Δt between two successive protections is the discrimination interval. It takes into account:

- circuit breaker breaking time T_c ,
- time delay tolerances dt ,
- time for the protection to return to stand-by: t_r

Δt should therefore correspond to the relation:

$$\Delta t \geq T_c + t_r + 2dt.$$

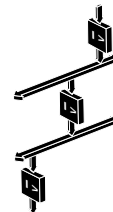
Considering present switchgear and relay performances, Δt is assigned a value of 0.3 sec.

This discrimination system has two advantages:

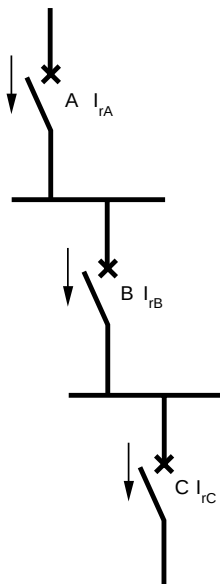
- it provides its own back-up (granted, by eliminating a fault-free part of the installation),
- it is simple.

However, when there are a large number of cascading relays, since the protection located the furthest upstream has the longest time delay, the fault clearing time is prohibitive and incompatible with equipment short-circuit current withstand and external operating necessities (connection of a distributor to electrical system, for example). This principle is used in radial networks.

(*)
 $I_{RA} \geq I_{RB} \geq I_{RC} \geq I_{RD}$
 I_R : setting of overcurrent protection



application of time discrimination

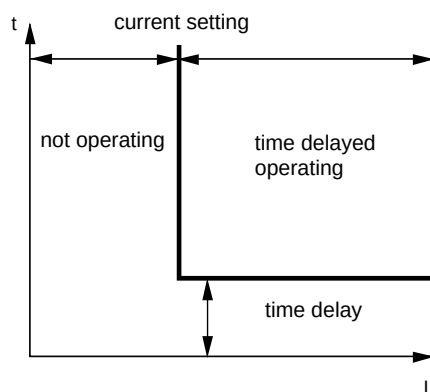


The time delays set for time discrimination are activated when the current exceeds the relay settings.

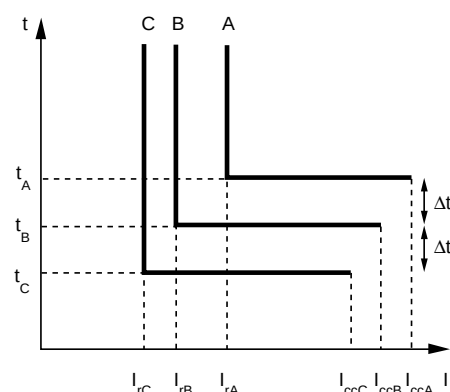
The settings must be coherent.

There are 2 types of time-delayed current-based relays:

■ definite time relays, the time delay is **constant** regardless of the current, provided it is higher than the setting.
 $I_{rA} > I_{rB} > I_{rC}$, $t_A > t_B > t_C$.



(fig.1)
definite time tripping curve

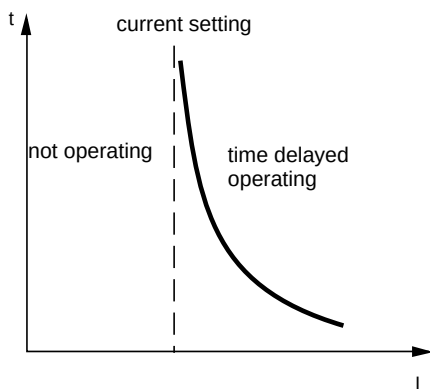


■ IDMT relays (fig. 2), the stronger the current, the shorter the time delay. If the settings are set to I_n , overload protection is ensured at the same time as short-circuit protection and setting coherency is guaranteed.

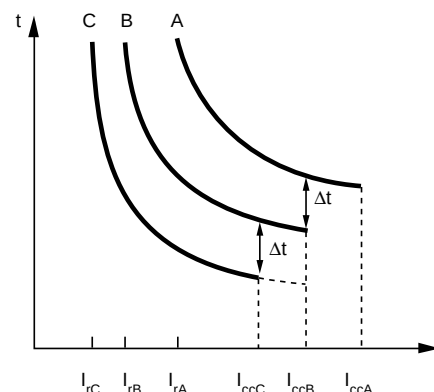
$$I_{nA} > I_{nB} > I_{nC}$$

$$I_{rA} = I_{nA} \quad I_{rB} = I_{nB} \quad I_{rC} = I_{nC}$$

The time delays are set for the discrimination interval Δt of the maximum current detected by the upstream protection relay.



(fig.2)
IDMT tripping curve



logic selectivity

This principle is used when **short fault clearing time is required**.

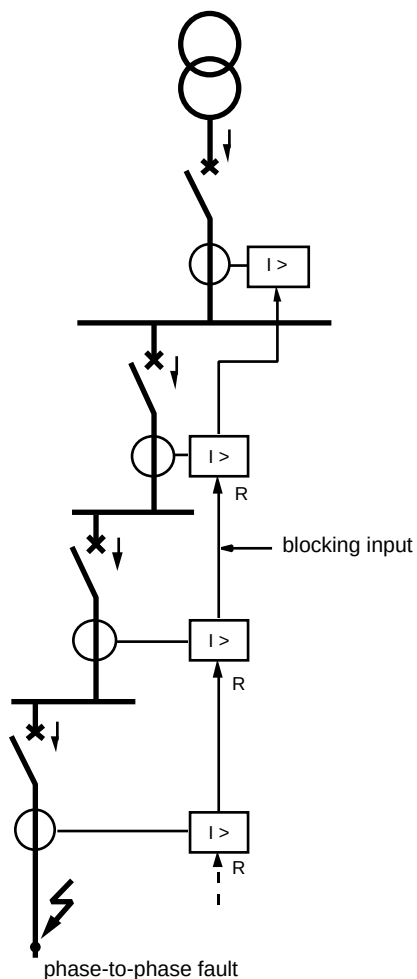
The exchange of logic data between successive protection devices **eliminates the need for discrimination intervals**.

In a radial system, the protections located upstream from the fault point are activated; those downstream are not. The fault point and the circuit breaker to be controlled can therefore be located without any ambiguity. Each protection activated by a fault sends:

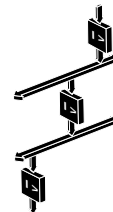
- a blocking input to the upstream stage (order to increase the upstream relay time delay),
- a tripping order to the related circuit breaker unless it has already received a blocking input from the downstream stage. Time-delayed tripping is provided for as back-up.

Advantage

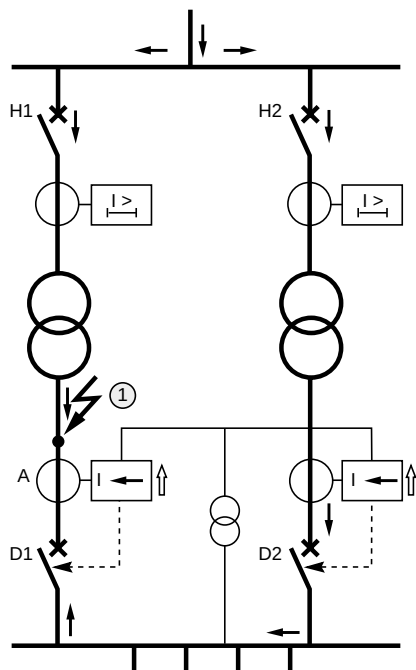
Tripping time is no longer related to the location of the fault within the discrimination chain.



logic selectivity system



directional discrimination



↑ way of detection
example of use of directional protections

In a looped system, in which faults are fed from both ends, it is necessary to use a protection system that is sensitive to the direction of the flow of fault current in order to locate and clear it.

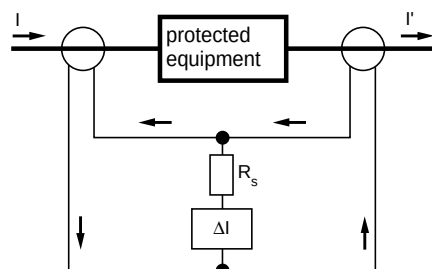
Example of the use of directional protections:

D1 and D2 are equipped with instantaneous directional protections; H1 and H2 are equipped with time-delayed overcurrent protections.

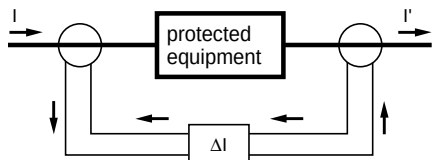
In the event of a fault at point ①, only the protections on D1 (directional), H1 and H2 detect the fault. The protection on D2 does not detect it (because of the direction of its detection system). D1 breaks. The H2 protection de-energizes and H1 breaks.

$$\begin{aligned} t_{H1} &= t_{H2} \\ t_{D1} &= t_{D2} \\ t_H &= t_D + \Delta t \end{aligned}$$

sélectivité par protection différentielle



high impedance differential protection diagram



percentage-based differential protection diagram

These protections compare the current at the ends of the monitored section of the system. Any difference in amplitude and phase between the currents indicates the presence of a fault. This is a self-discriminating protection system as it only reacts to faults within the area it covers and is insensitive to any faults outside this area.

The protected equipment can be: a motor, an AC generator, a transformer, or a connection (cable or line).

This protection is used to :

- detect fault currents lower than rated current
- trip instantaneously since discrimination is based on detection and not on time delays.

There are two main principles:

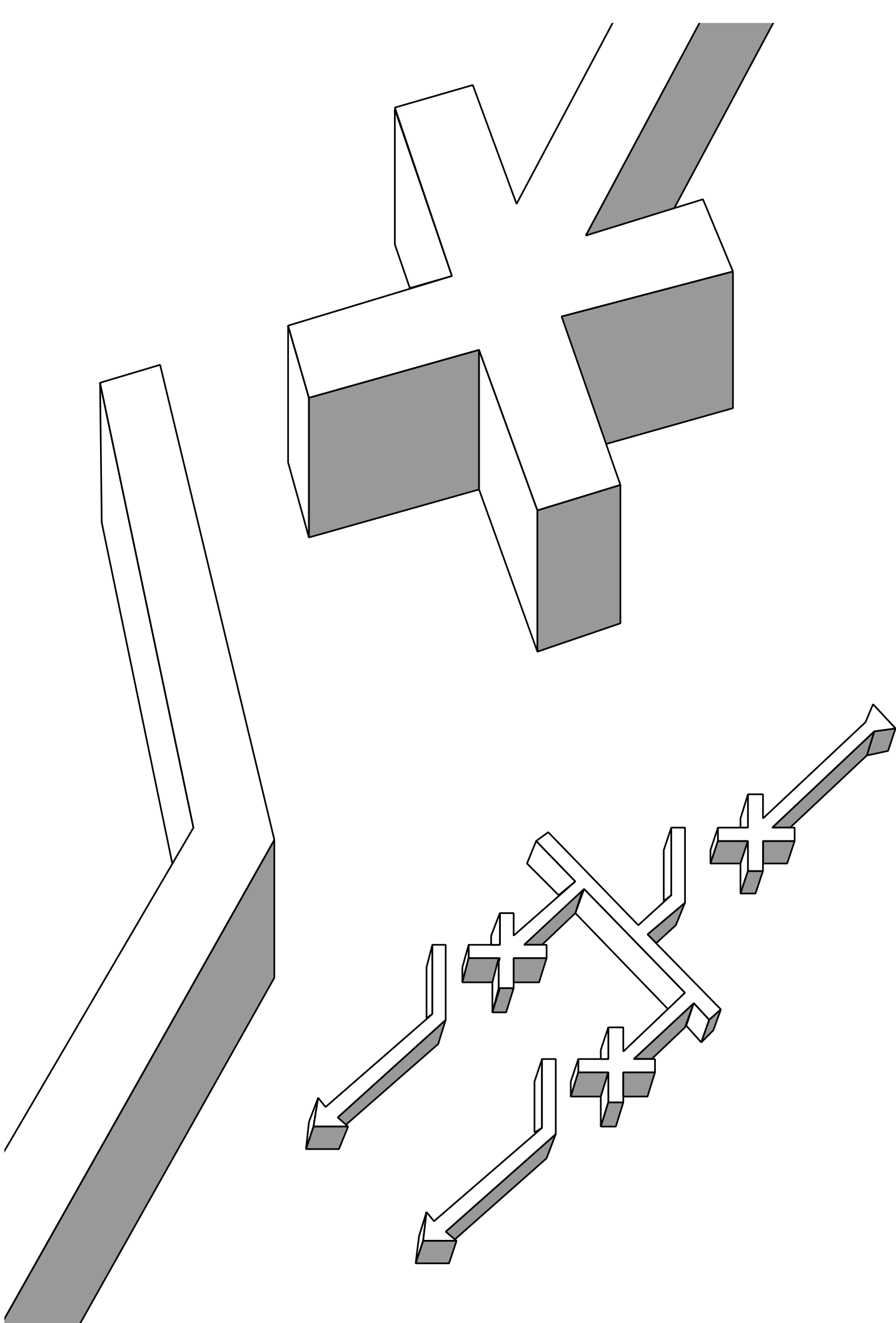
The high impedance protective device is series-connected with a stabilization resistor ⁽¹⁾ in the differential circuit.

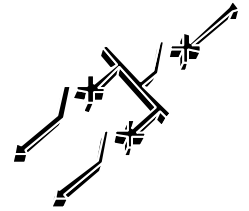
The percentage-based differential protective device is connected separately to the I and I' current circuits.

The difference between these currents I - I' is determined in the protective device and the protection stability ⁽¹⁾ is obtained by a restraint related to the measurement of let-through current $\frac{I + I'}{2}$.

⁽¹⁾ The stability of the differential protective device is its capacity to remain dropped out when there are no faults within the zone being protected, even if a differential current is detected:

- transformer magnetizing current,
- line capacitive current,
- error current due to saturation of the current sensors.





introduction

Electrical system protection should:

- detect faults,
- cut off of the faulty parts of the electrical system, keeping the fault-free parts in operation.

Protection systems are chosen according to the electrical system configuration (parallel operation of AC generators or transformers, loop or radial system, grounding system...).

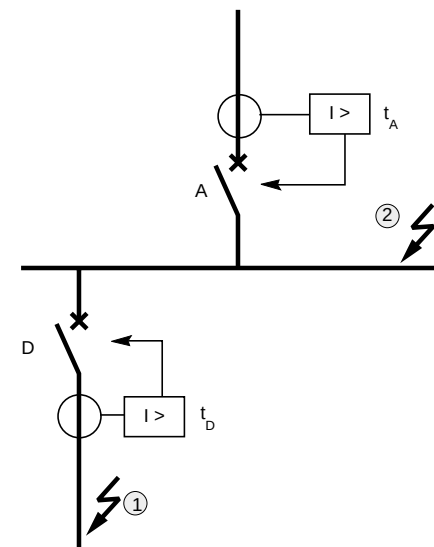
Protection against each of the following types of faults is to be considered:

- phase-to-phase faults,
- earth faults (protections related to electrical system grounding).

This will be done by successively examining the following cases:

- a single incoming line,
- two incoming lines,
- a busbar,
- a loop.

electrical system with a single incoming line

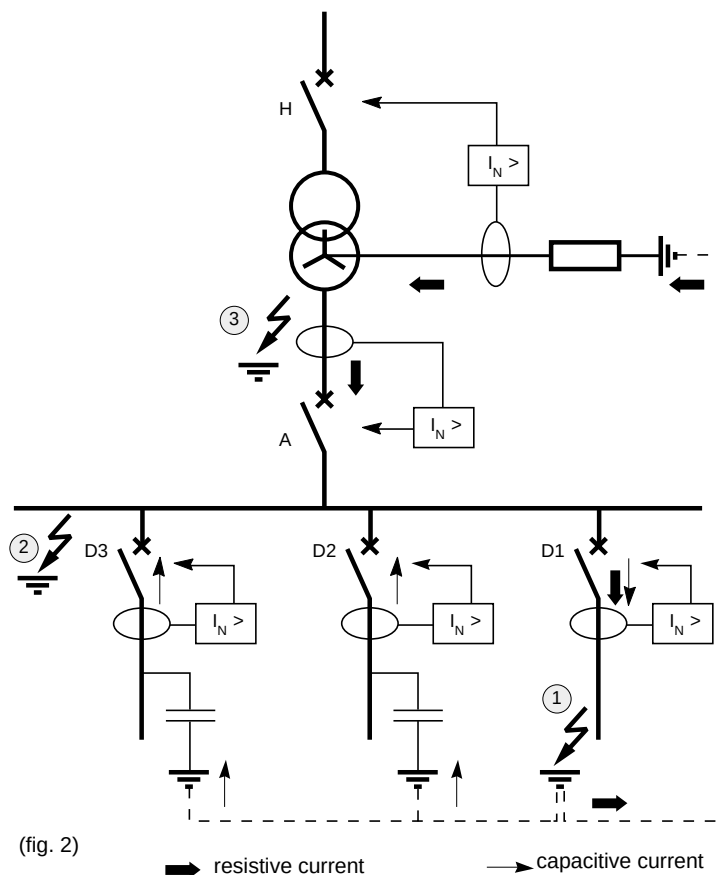


(fig. 1)

phase-to-phase faults (fig. 1)

The protection device at D detects faults ① on the outgoing lines and is tripped following a time delay t_D . The protection device at A detects the faults ② on the busbars and is tripped following a time delay t_A . It also acts as back-up in the event of a malfunction of protection D.

Choose : $I_{rA} \geq I_{rD}$ and $t_A \geq t_D + \Delta t$
 Δt : discriminator interval
 (generally 0,3 s).



(fig. 2)

➡ resistive current

→ capacitive current

phase-to-earth faults

Grounding by resistance on transformer (fig.2)

Outgoing lines, the incoming line and the grounding connection are equipped with earth fault protection devices.

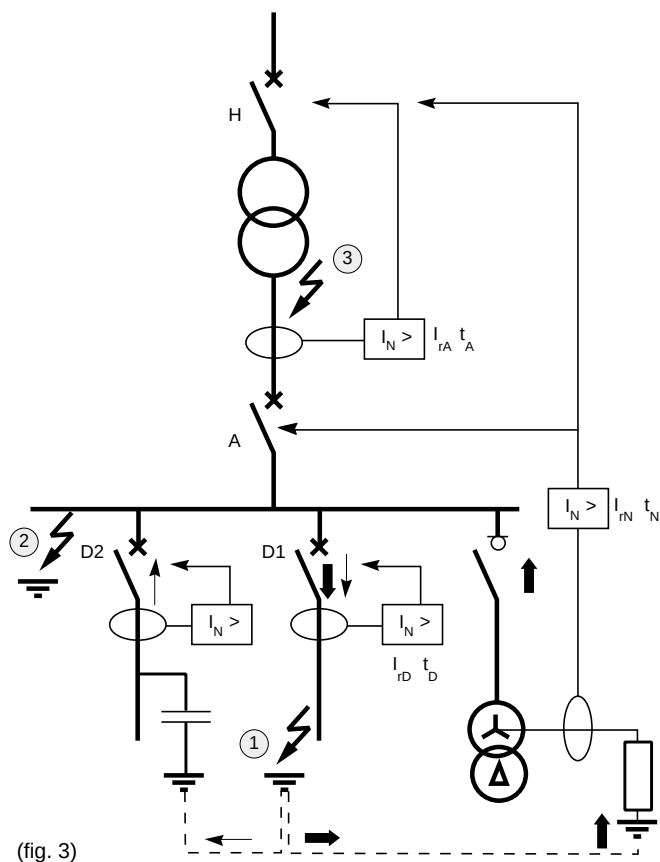
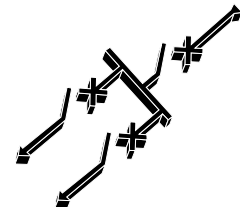
These devices are necessarily different from multiphase fault protections as the fault currents are in a different range.

Outgoing line protections are set selectively in relation to the incoming line protection, which is itself set selectively in relation to the protection equipping the grounding connection (respecting discrimination intervals).

The fault current is fed back by the capacitances of the fault-free outgoing lines and the grounding resistance. All the fault-free outgoing line sensors detect capacitive current.

So as to prevent inadvertent tripping, the protection device on each outgoing line is set at a setting higher than the outgoing line's own capacitive current.

- fault at ① : the D1 circuit breaker trips, actuated by the protection device linked to it,
- fault at ② : the A circuit breaker trips, actuated by the incoming line protection device,
- fault at ③ : the protection device located on the neutral grounding connection causes circuit breaker H to trip at the transformer primary.



Grounding by resistance on the busbar (fig.3)

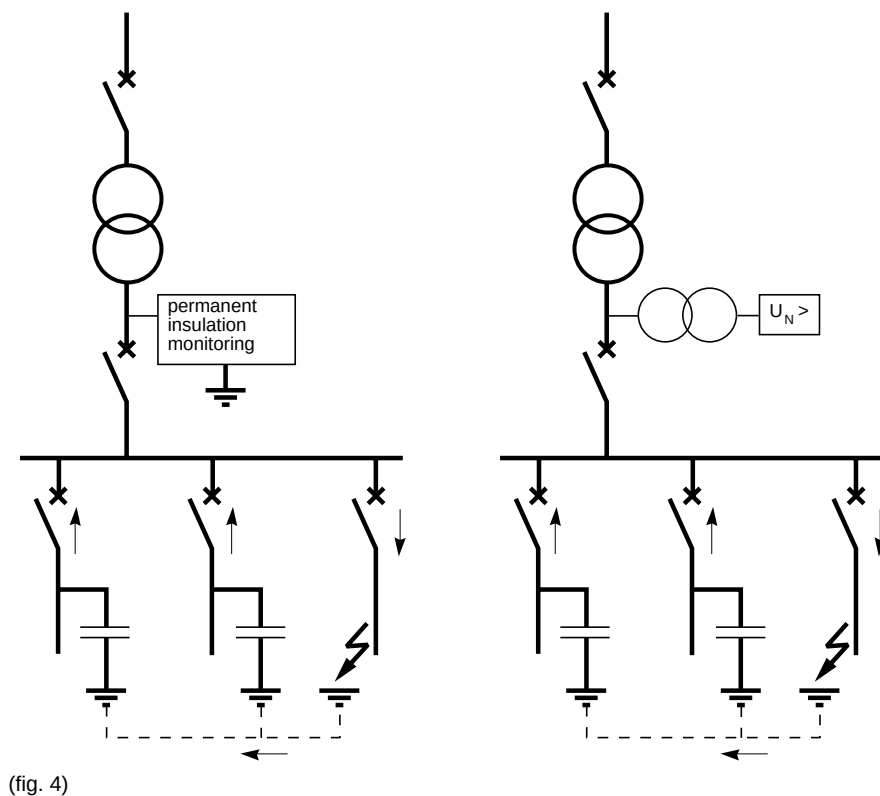
The outgoing and ingoing line protections are selectively set in relation to the protection equipping the grounding impedance. As in the previous case, the protection on each outgoing line is set at a setting higher than the outgoing line's own capacitive current.

In the event of a fault on outgoing line ① only the D1 outgoing line circuit breaker trips.

In the event of fault on the busbar ②, only the protection equipping the grounding connection detects the fault. It causes tripping by circuit breaker A.

In the event of fault on the transformer secondary ③, the incoming line protection detects the fault. It causes tripping by circuit breaker H.

Note: when circuit breaker A is open, the transformer secondary is ungrounded.



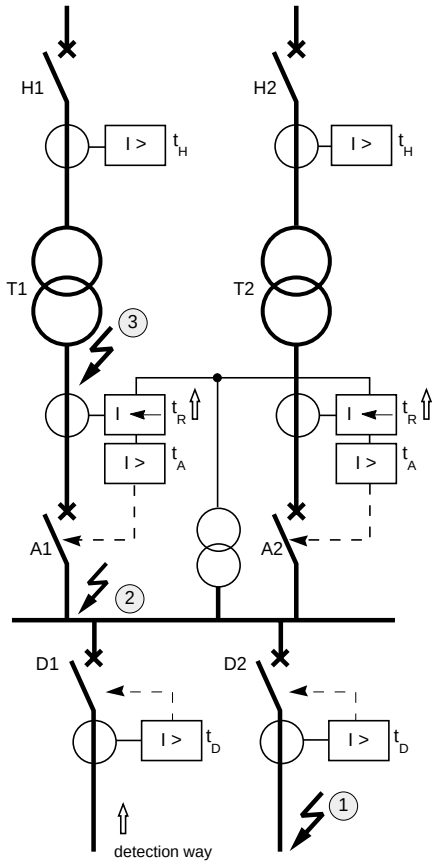
Ungrounded neutral (fig.4).

A fault, regardless of its location, produces current which is fed back by the capacitance of the fault-free outgoing lines.

In industrial system, this current is generally weak (a few amperes), allowing operations to carry on while the fault is being tracked. The fault is detected by a permanent insulation monitor (Vigilhom) or a neutral voltage displacement protection device. In the case of a system with high total capacitive current (tens of amperes), added measures are required to quickly clear the fault.

Directional earth protection can be used to selectively trip the faulty outgoing line.

system with two incoming lines



(fig. 1)

phase-to-phase faults (fig.1)

System with two transformer incomers or with two incoming lines

The outgoing lines are equipped with phase overcurrent protections with a time delay of t_D . The two incoming lines A1 and A2 are equipped with phase overcurrent protections selectively set with the outgoing lines, i.e. at a value of $t_A \geq t_D + \Delta t$.

They are also equipped with directional protection devices with time delays set at $t_R < t_A - \Delta t$.

Therefore, a fault at ① is cleared by the opening of D2 with a time delay of t_D .

A fault at ② is cleared by the opening of A1 and A2 with a time delay of t_A (the directional protections do not detect the fault).

A fault at ③ is detected by the A1 directional protection which opens at time t_R , allowing continued operation of the fault-free part of the system. The fault at ③ however is still fed by T1. At time $t_H \geq t_A + \Delta t$, H1 is actuated by the phase overcurrent protection with which it is equipped.

phase-to-earth faults (fig. 2)

System with two transformer incomers

Grounding by resistance on the transformers. The outgoing lines are equipped with earth fault protection devices set at a setting higher than the corresponding capacitive current with a time delay of t_D .

The incomers (A1 and A2) are equipped with directional protections with a time delay of t_R .

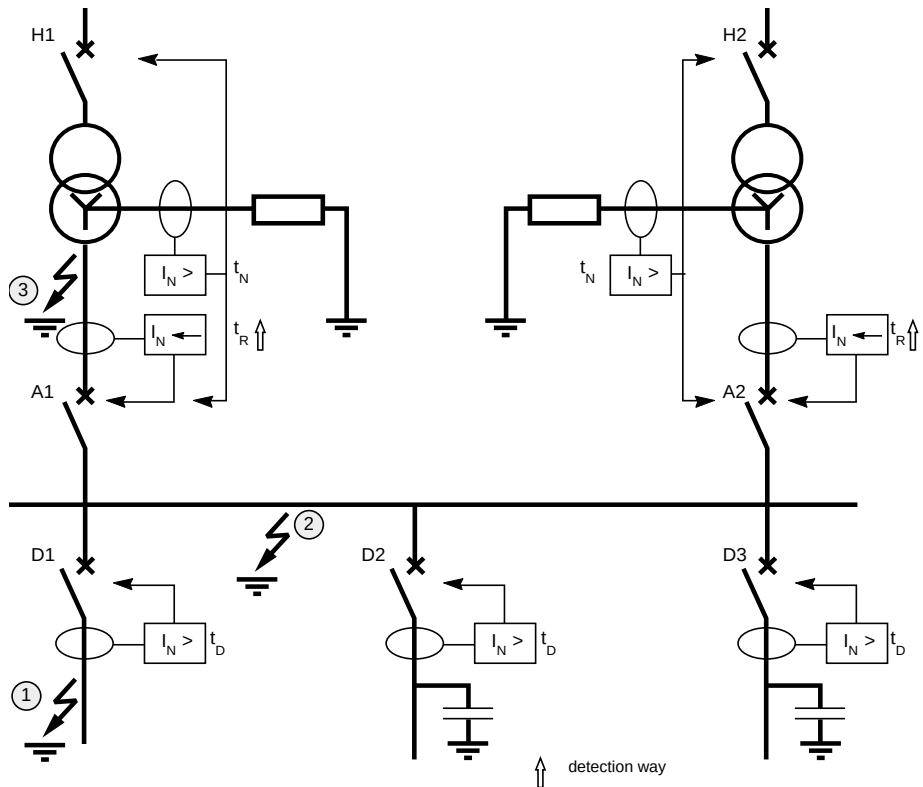
The grounding connections are equipped with earth fault protections, the setting of which is higher than the settings of the incomer and outgoing line protections with a time delay of $t_N \geq t_D + \Delta t$.

Therefore, a fault at ① is cleared by the opening of D1.

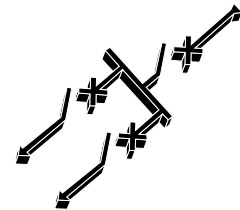
A fault at ② is cleared by the opening of A1, A2, H1 and H2, triggered by the protections located on the grounding connections of the 2 transformers.

A fault at ③ is detected by the A1 directional earth fault protection which opens at time t_R , allowing continued operation of the fault-free part of the system.

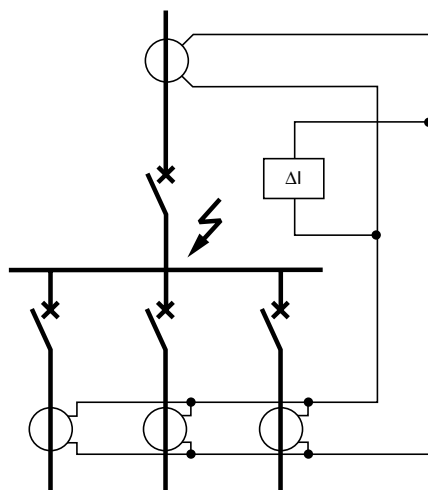
However, fault ③ is still fed up to time t_N , the moment at which the protection located on the corresponding transformer's grounding connection triggers the opening of the H1 circuit breaker.



(fig. 2)



busbars



(fig. 3)

In addition to the protections described earlier, a busbar can be equipped with a specific protection device, referred to as high impedance differential protection, the aim of which is to be sensitive, quick and selective.

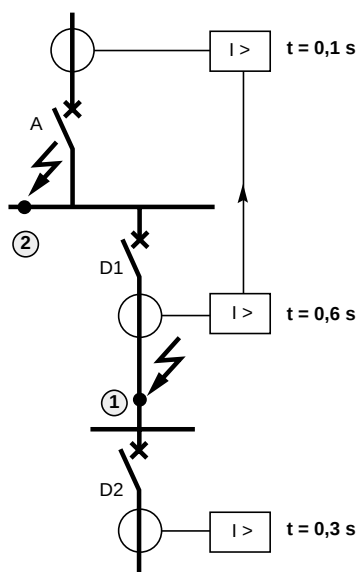
The differential protection (fig.1) takes the vectorial sum per phase of currents entering and leaving the busbar; whenever this sum is not equal to zero, it trips the busbar power supply circuit breakers.

Logic discrimination (fig.2) applied to overcurrent protections provides a simple, simple solution for busbar protection .

A fault at ① is detected by the D1 protection which transmits a blocking input to the A protection.

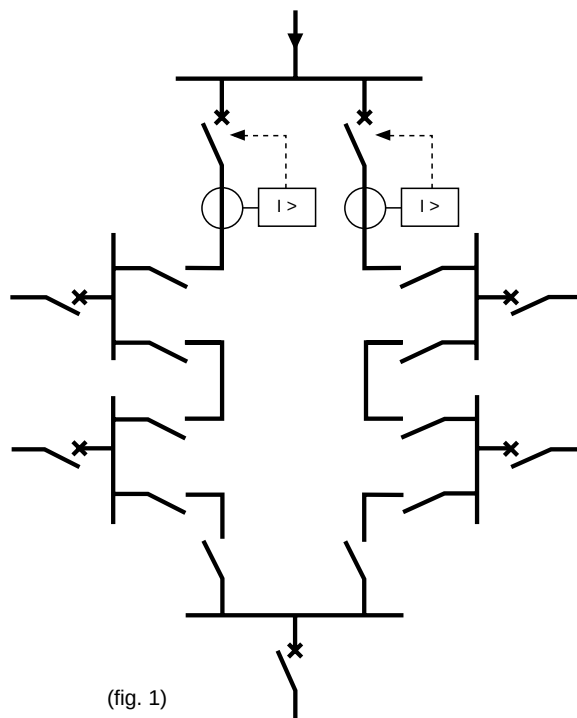
The D1 protection is tripped 0.6 sec. later

A fault at ② is detected only by the A protection which is tripped 0.1 sec. later.



(fig. 4)

open loop closed loop



In a distribution system comprising substations fed in a loop, protection can be at the head of the loop or by sections:

Protection at the head of the loop (fig. 1)

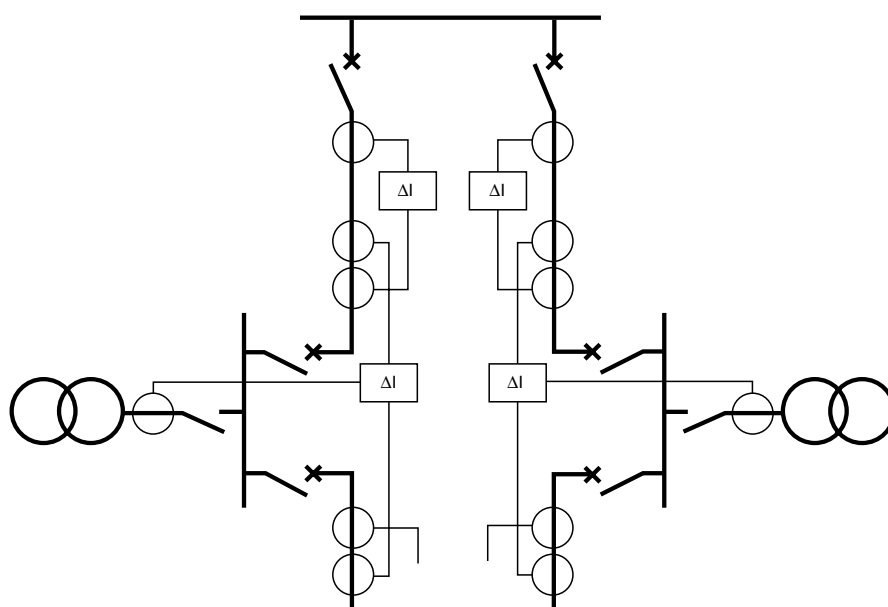
The loop is always open.

The circuit breaker at the head of each loop is equipped with an overcurrent protection device.

A fault in a cable joining up 2 substations causes the opening of one of the two circuit breakers at the head, depending on the position of the loop opening.

Protection is often completed by an automation system which:

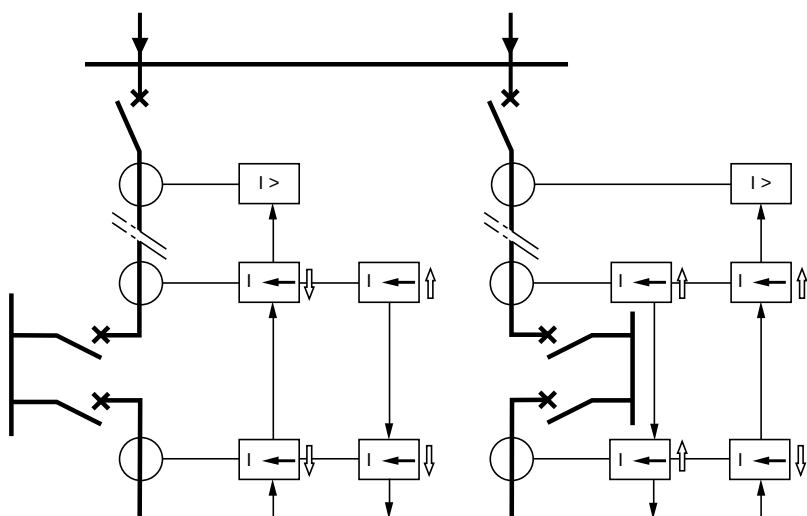
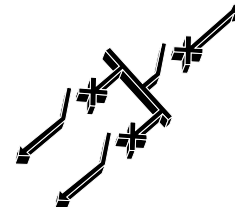
- clears the fault with the power off by opening the devices located at the ends of the cable involved, after localisation of the faulty cable (by cable fault detector),
- close the incomer circuit breaker that tripped,
- closes the device which ensured the normal opening of the loop.



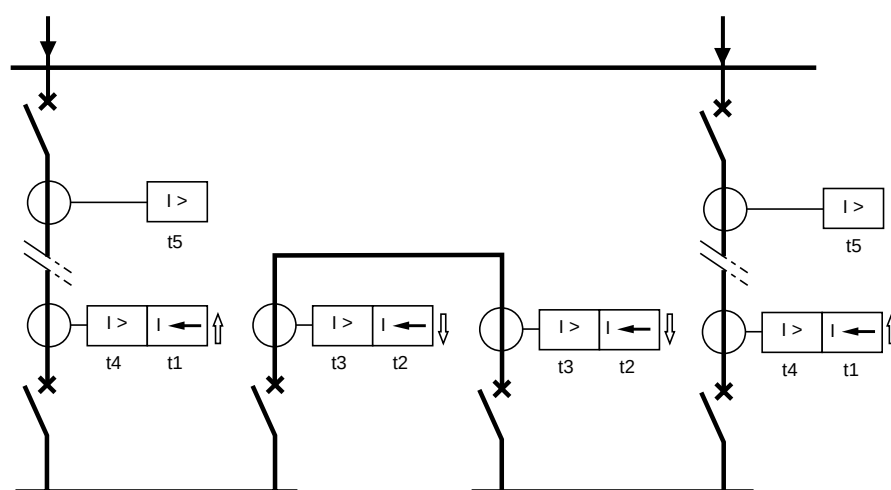
Loop section protection

Each end of the cable is equipped with a circuit breaker, with several protection solutions.

- **differential protection solution (fig. 2):** each cable is equipped with a differential line protection device and each substation is equipped with a busbar differential protection device. This type of protection is very quick but expensive. Also, if the neutral is resistance grounded, the sensitivity of the differential protections must cover phase-to-earth faults. This solution may be used in both open and closed loops.



(fig. 3)



time gap between $t_1, t_2, \dots, t_3$ is Δt discrimination interval

↑ detection way

(fig. 4)

Loop section protection (cont.)

Overcurrent protection and directional logic discrimination (fig. 3)

The circuit breakers in the loop are fitted with overcurrent protection and directional protection devices. The principle of logic discrimination is also used to clear faults as quickly as possible.

A fault in the loop activates:

- all the protection devices when the loop is closed,
- all the protection devices upstream from the fault when the loop is open. Each protection device sends a blocking input to one of the devices adjacent to it within the loop, according to the data transmitted by the directional protection device. Protection devices that do not receive a blocking input trip within a minimum amount of time regardless of the fault's position in the loop:

- the fault is cleared by two circuit breakers, one on either side of the fault if the loop is closed, and all the switchboards remain energized,
- the fault is cleared by the upstream circuit breaker if the loop is open. This solution is a full one since it protects the cables and switchboards. It is quick, discriminating and includes back-up protection.

Overcurrent and directional overcurrent protection (fig. 4)

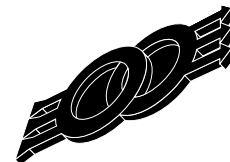
In the case of a loop limited to two substations, time discrimination can be used with overcurrent and directional overcurrent protection devices as shown in the diagram. A higher number of substations results in prohibitive time delays.

The time gap between delays $t_1, t_2, \dots, t_5$ is the discrimination interval Δt .

Long distance protection

This solution is only useful for very long connections (several kilometers long). It is costly and very seldom used, in medium voltage.





introduction

The transformer is a particularly important system component. It requires effective protection against all faults liable to damage it, whether of internal or external origin. The choice of a protection system is often based on technical and cost considerations related to the power rating.

types of faults

The main faults affecting transformers are:

- overloads,
- short-circuits,
- frame faults

An **overload** can result from an increase in the number of loads being fed simultaneously or from an increase in the power absorbed by one or more loads. It results in an overcurrent of long duration causing a rise in temperature that is detrimental to the preservation of insulation and to the service life of the transformer.

Short circuits can be inside or outside the transformer:

- **internal:** faults occurring between winding conductors with different phases or faults in the same winding. The fault arc damages the transformer winding and can cause fire. In oil transformers, the arc causes the emission of decomposition gas. If the fault is a weak one, there is a slight gas emission and the accumulation of gas can become dangerous. A violent short circuit can cause major damage that can destroy the winding and also the tank frame by the spread of burning oil.

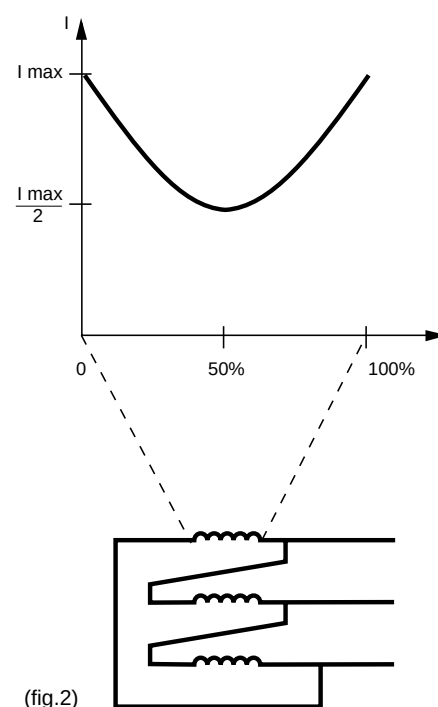
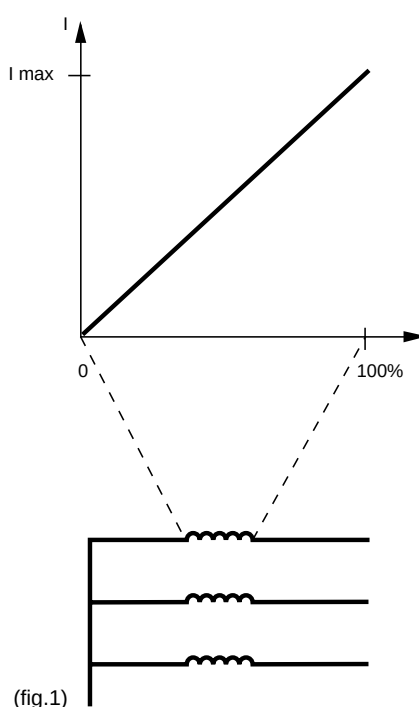
- **external:** phase-to-phase faults in the downstream connections. The downstream short circuit current produces electrodynamic forces in the transformer that are liable to affect the windings mechanically and then develop in the form of internal faults.

A **frame fault** is an internal fault. It can occur between the winding and the tank frame or between the winding and the magnetic core. It causes gas emission in oil transformers. Like internal short circuits, it can cause transformer damage and fire.

The amplitude of the fault current depends on the upstream and downstream grounding systems, and also on the position of the fault within the winding.

- in star connections (fig.1), the frame current varies between 0 and the maximum value depending on whether the fault is at the neutral or phase end of the winding.

- in delta connections (fig.2), the frame current varies between 50 and 100% of the maximum value depending on whether the fault is in the middle or at the end of the winding.



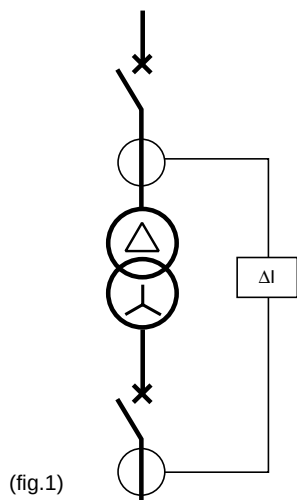
fault current according to the winding fault position

protection devices

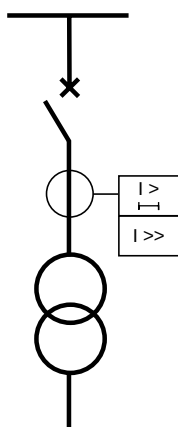
Overloads

Overcurrent of long duration is generally detected by a direct time or IDMT delayed overcurrent protection which is discriminating with respect to secondary protection.

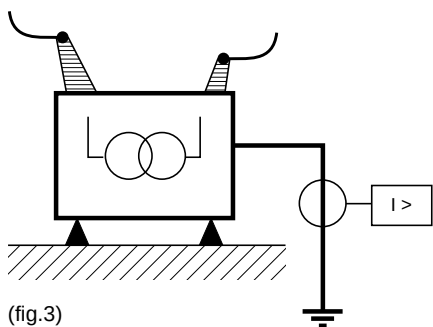
Thermal overload protection is used to monitor the temperature rise: overheating is determined by simulation of heat release as a function of the current and temperature lag of the transformer.



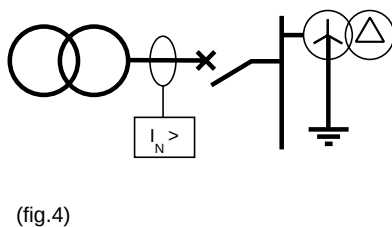
(fig.1)



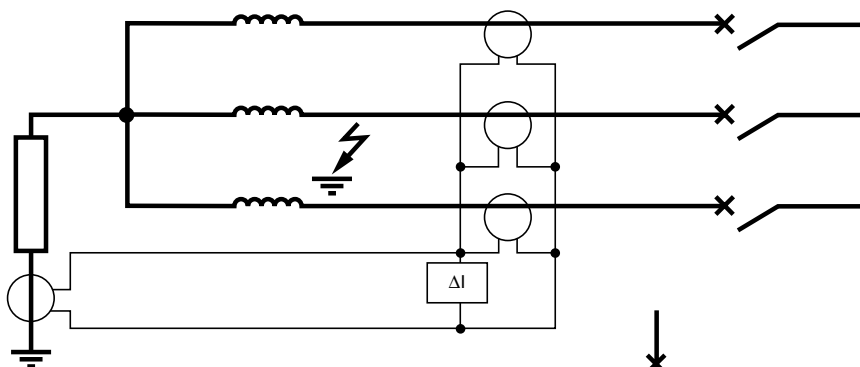
(fig.2)



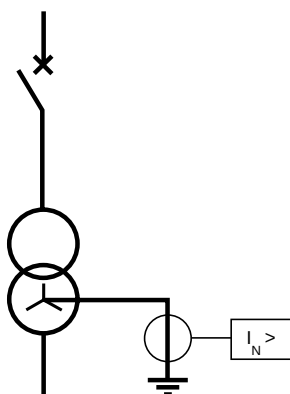
(fig.3)



(fig.4)



(fig.5)



(fig.6)

Short-circuits

For oil transformers:

- a Buchholz relay or DGPT gas pressure temperature detector that is sensitive to gas release or oil movement is used, causing respectively a short-circuit between turns of the same phase and a violent phase-to-phase short-circuit.

- differential transformer protection (fig.1) ensures rapid protection against phase-to-phase faults. It is sensitive to fault currents in the range of 0.5 I_n and is used for important transformers.

- an instantaneous overcurrent protection (fig.2) device linked to the circuit breaker located at the transformer primary ensures protection against violent short circuits. The current setting is set at a value higher than the current due to a short circuit on the secondary, thus ensuring current discrimination.

- for low power transformers, a fuse is used for overcurrent protection.

Tank frame faults

- tank frame protection (fig.3):

This instantaneous overcurrent protection device installed on the transformer frame earthing connection constitutes a simple, efficient solution for internal winding-to-frame faults (provided its setting is suitable with grounding system used) the transformer tank has to be insulated from the ground.

This form of protection is discriminating, being sensitive only to transformer frame faults.

Another solution consists of using earth fault protection:

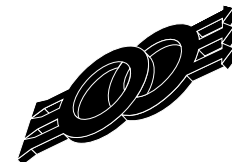
- earth protection located on the upstream system for frame faults affecting the transformer primary.

- earth fault protection located on the incoming line of the board being fed, if the neutral of the downstream system is earthed on the busbars (fig.4).

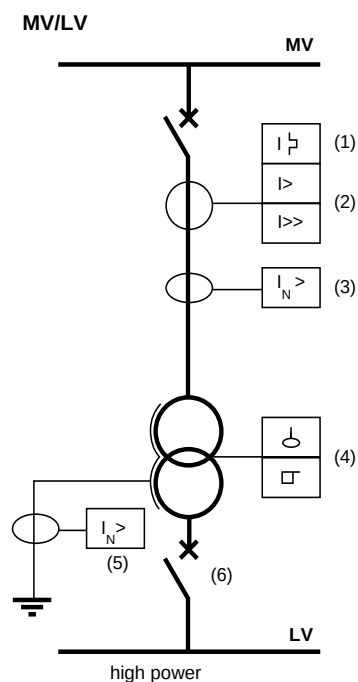
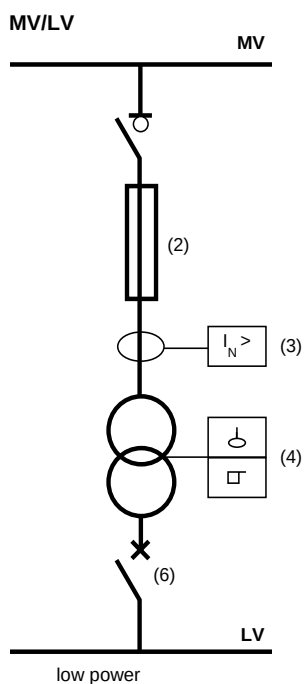
These protections are discriminating: they are only sensitive to phase-to-earth faults located in the transformer or on the upstream and downstream connections.

- restricted earth protection if the neutral of the downstream system is earthed at the transformer (fig.5). This is a high impedance differential protection system which detects the difference in residual currents measured at the grounding point and at the three-phase transformer outlet.

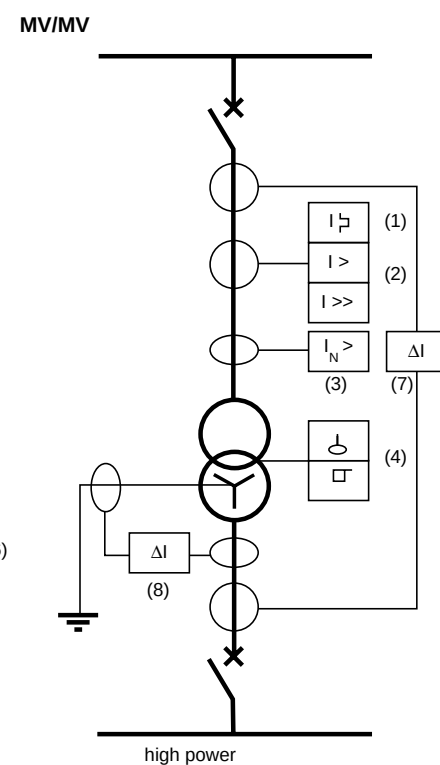
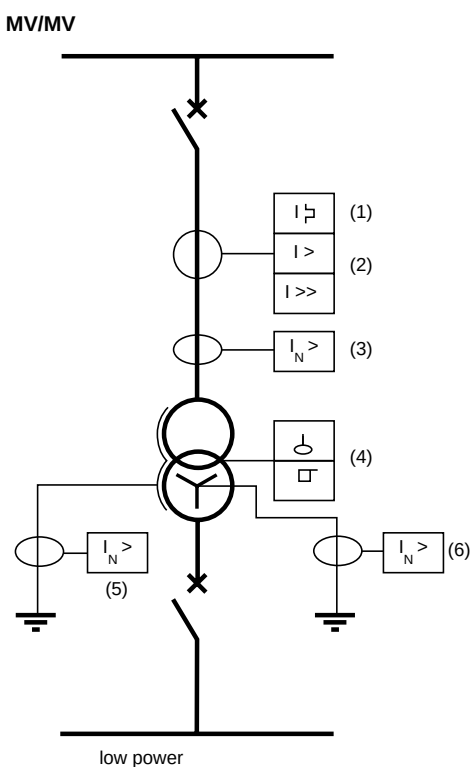
- neutral earth protection if the downstream system is earthed at the transformer (fig.6).



examples of transformer protection



- (1) Thermal overload
- (2) Fuse or 2-setting overcurrent
- (3) Earth fault
- (4) Buchholz or DGPT
- (5) Tank earth leakage
- (6) LV circuit breaker

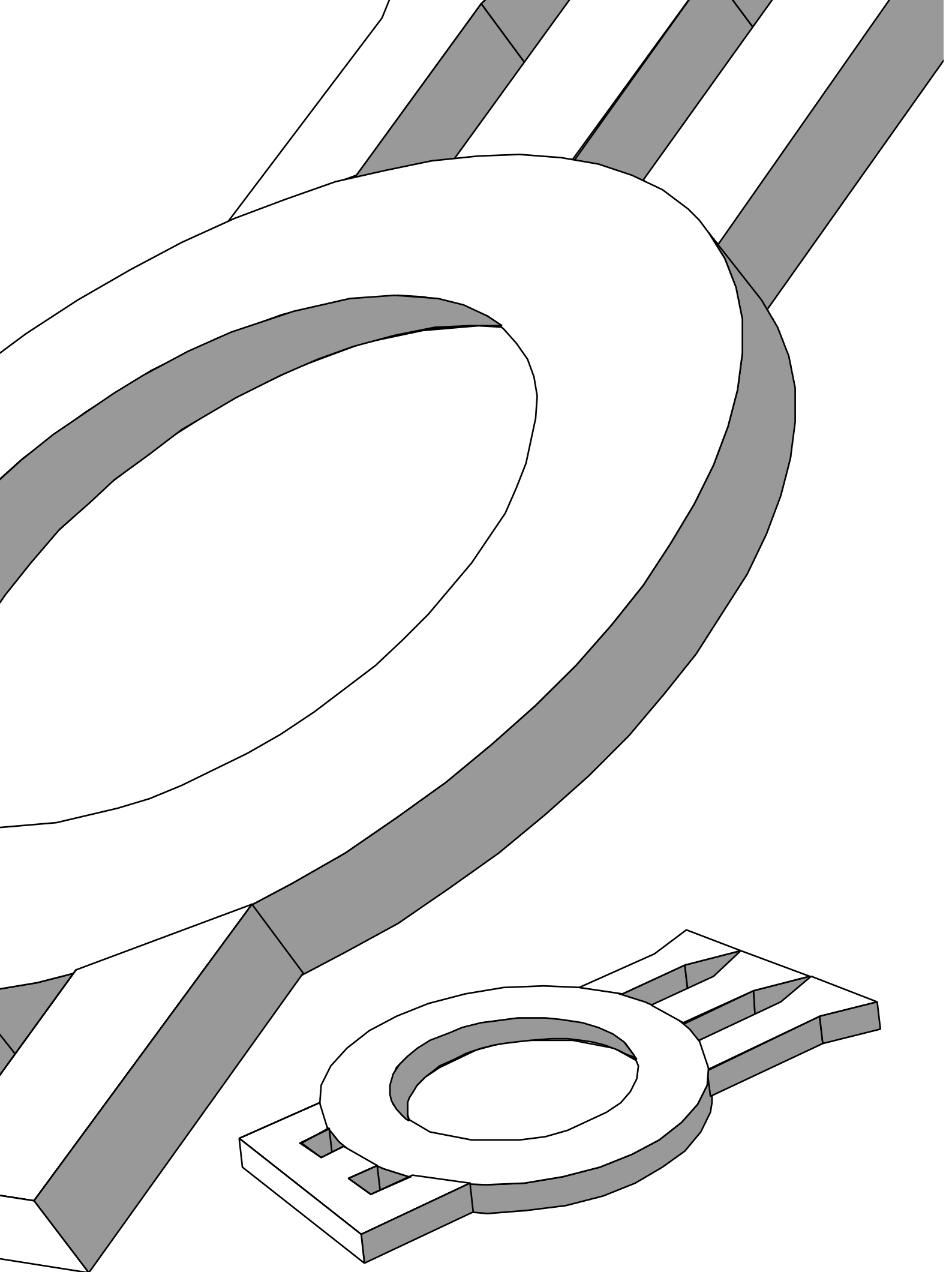


- (1) Thermal overload
- (2) Fuse or 2-setting overcurrent
- (3) Earth fault
- (4) Buchholz or DGPT
- (5) Tank earth leakage
- (6) Neutral earth protection
- (7) Transformer differential
- (8) Restricted earth fault protection

setting information

type of fault	settings
overload	■ LV circuit breaker: I_n (for MV/LV transformer) ■ thermal overload: time constant in the 10' range
short circuit	■ fuse: rating $> 1.3 I_n$, ■ direct time overcurrent lower setting $< 6 I_n$; time delay ≥ 0.3 s (selective with downstream), upper setting $>$ downstream I_{sc} instantaneous, ■ IDMT overcurrent IDMT lower setting (selective with downstream), high setting $>$ downstream I_{sc}, instantaneous, ■ differential transformer, 25% to 50% of I_n.
earth fault	■ tank earth leakage setting > 20 A 100 ms time delay, ■ earth fault current setting ≤ 20 % of maximum earth fault and $\geq 10\%$ of CT rating if fed by 3 CTs, time delay 0.1 s if grounded within the system, time delay according to discrimination if grounded in the transformer, ■ restricted earth fault protection setting approximately 10% of I_n when the 3 CT integrator assembly is used, ■ neutral earth protection setting approximately 10% of maximum earth fault current.







introduction

The motor constitutes an interface between the electrical and mechanical fields. It is found in an environment linked to the driven load, from which it is inseparable.

Furthermore, the motor can be subjected to inner mechanical stress due to its moving parts.

A single faulty motor may cause disturbance in a complete production process.

Modern motors have optimized characteristics which make them inappropriate for operation other than according to their rated characteristics.

The motor is therefore a relatively fragile electrical load that needs to be carefully protected.

types of faults

Motors are affected by:

- faults related to the driven load
- power supply faults
- internal motor faults

Faults related to the driven load

■ **overloads.** Since the power called upon is greater than rated power, there is overcurrent in the motor and an increase in losses, causing a rise in temperature.

■ **too long, too frequent start-ups.** Motor start-up creates substantial overcurrents which are only admissible since they are of short duration. If start-ups are too frequent or too long due to an insufficient gap between motor torque and load torque, the overheating that is inevitably produced becomes prohibitive.

■ **jamming.** This refers to a sudden stop in rotation for any reason related to the driven mechanism. The motor absorbs the start-up current and stays jammed at zero speed. There is no more ventilation and overheating very quickly occurs.

■ **pump de-energizing.** This causes motor idling which has no direct harmful effect. However, the pump itself quickly becomes damaged.

■ **reverse power.** This type of fault occurs due to a voltage drop when a synchronous motor driven by the inertia of the load sends power back into the network. In particular, should the normal network power supply be released, the synchronous motor can maintain the voltage in an undesirable fashion and feed the other loads which are connected in parallel.

Power supply faults

■ **drop in voltage.** This reduces motor torque and speed: the slow-down causes increased current and losses. Abnormal overheating therefore occurs.

■ **unbalance.** 3-phase power supply can be unbalanced because:

- the power source (transformer or AC generator) does not provide symmetrical 3-phase voltage,
- all the other consumers together do not constitute a symmetrical load, unbalancing the power supply network,
- the motor is fed on two phases due to fuse melting.

Power supply unbalance produces reverse current causing very high losses and therefore quick rotor overheating.

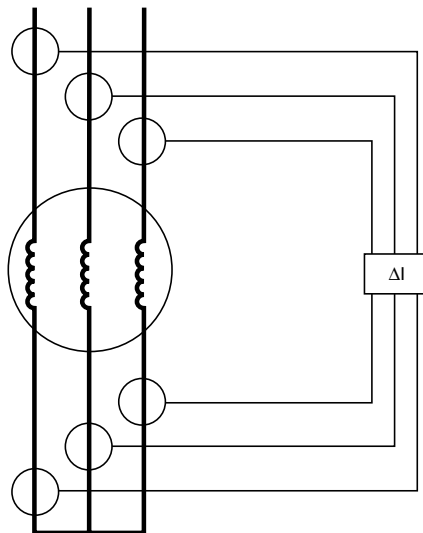
Internal motor faults

■ **phase-to-phase short-circuits:** these can vary in strength depending on the position of the fault within the coil; they cause serious damage.

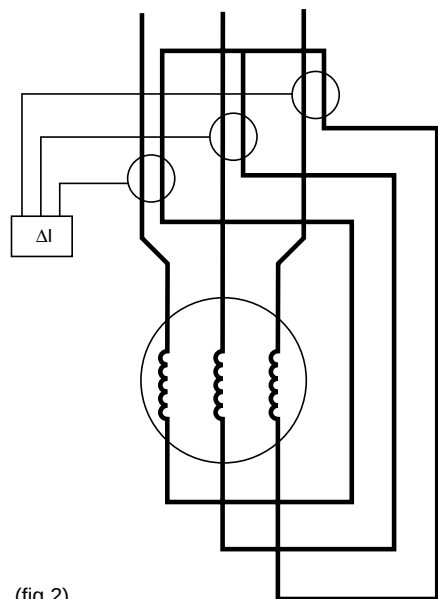
■ **frame faults:** fault current amplitude depends on the power supply network grounding system and on the fault's position within the coil. Phase-to-phase short-circuits and frame faults require motor rewinding, and frame faults can produce irreparable damage to the magnetic circuit.

■ **loss of synchronism.** This fault involves synchronous motors losing their synchronism due to field loss: motor operation is asynchronous but the rotor undergoes considerable overheating since it is not designed for this.

motor protection devices



(fig.1)



(fig.2)

Overloads

Overloads are monitored:

- either by IDMT overcurrent protection,
 - or by thermal overload protection.
- Thermal overload involves overheating due to current.
- or by a temperature probe.

Excessive starting time and locked rotor

The same function ensures both protections. This involves an instantaneous current relay set at a value lower than the start-up current, which is validated after a time delay beginning when the motor is turned on; this time delay is set at a value greater than or equal to the normal duration of start-up.

Starts per hour

The corresponding protection is sensitive to the number of starts taking place within a given interval of time or to the time between starts.

Pump de-energizing

Is detected by a direct time undercurrent protection device which is reset when the current is nil (when the motor stops).

Reverse power

Is detected by a directional real power protection device.

Drops in voltage

Are monitored by a time-delayed undervoltage protection device. The voltage setting and time delay are set for discrimination with the system's short-circuit protection devices and to tolerate normal voltage drops, for example during motor starts. This type of protection is often shared by several motors in the same switchboard.

Unbalance

Protection is ensured by IDMT or direct time negative sequence unbalance detection.

Phase-to-phase short circuits

Are detected by a time-delayed overcurrent protection device. The current setting is set higher than or equal to the start-up current and the time delay is very short; its purpose is to make the protection insensitive to the first peaks of making current.

When the corresponding breaking device is a contactor, it is associated with fuses which ensure short-circuit protection.

For large motors, a high impedance or percentage-based differential protection system is used (fig. 1).

Through appropriate adaptation of the connections on the neutral side and by the use of summing current transformers, a simple overcurrent protection device ensures sensitive, stable detection of internal faults (fig.2).

Frame faults

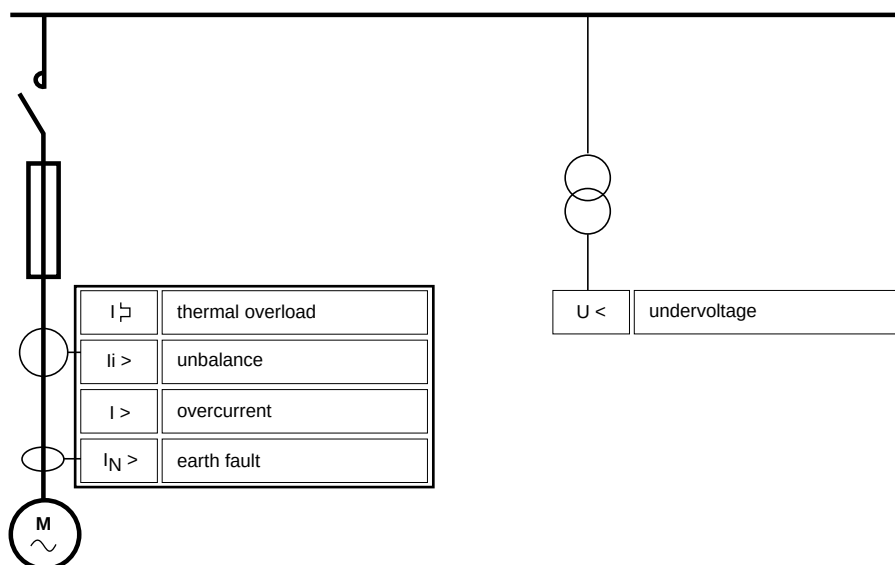
This type of protection depends on the grounding system. Higher sensitivity is sought so as to limit damage to the magnetic circuit.

Field loss

(for synchronous motors). It is detected by a time-delayed max. reactive power protection device.



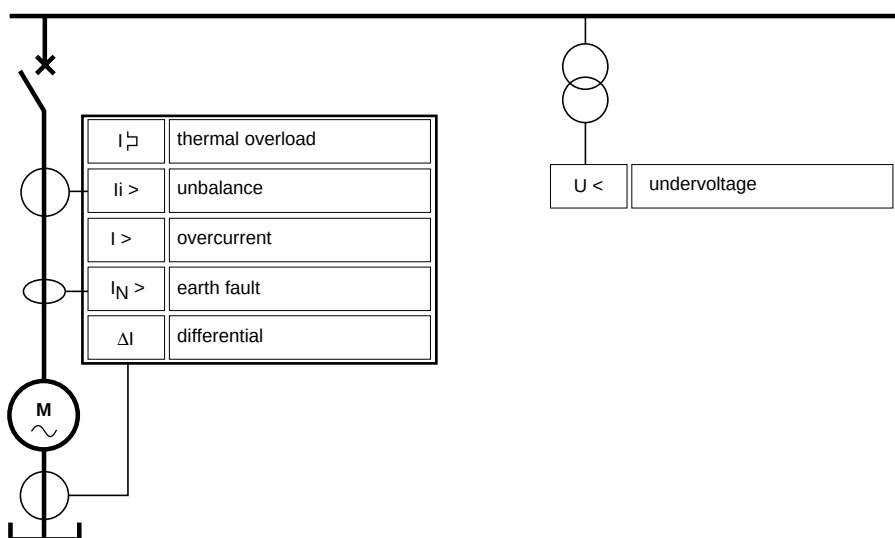
examples of protection



Contactor-controlled or circuit breaker-controlled asynchronous motor

Additional protection according to the type of load:

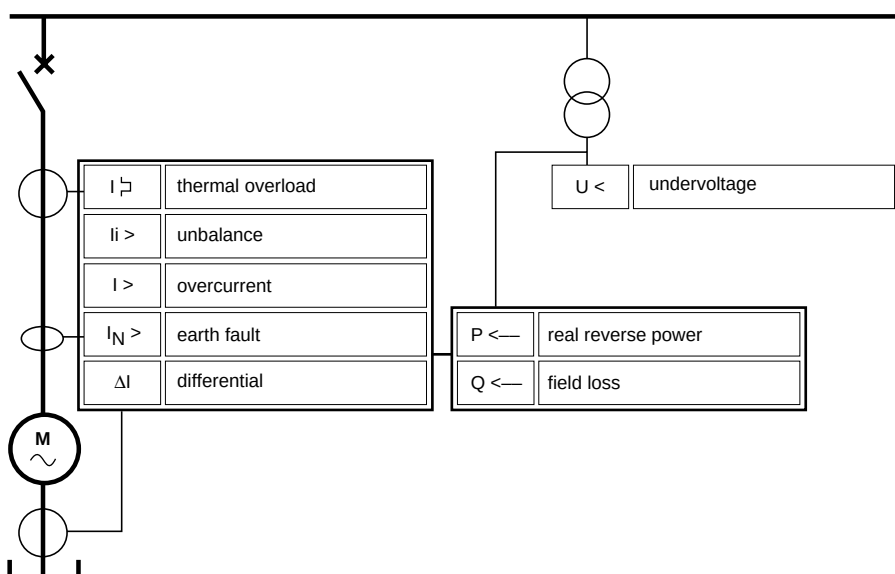
- excessive starting time + locked rotor
- starts per hour
- undercurrent



High power asynchronous motor

Additional protections according to the type of load:

- excessive starting time + locked rotor
- starts per hour
- undercurrent



High power synchronous motor

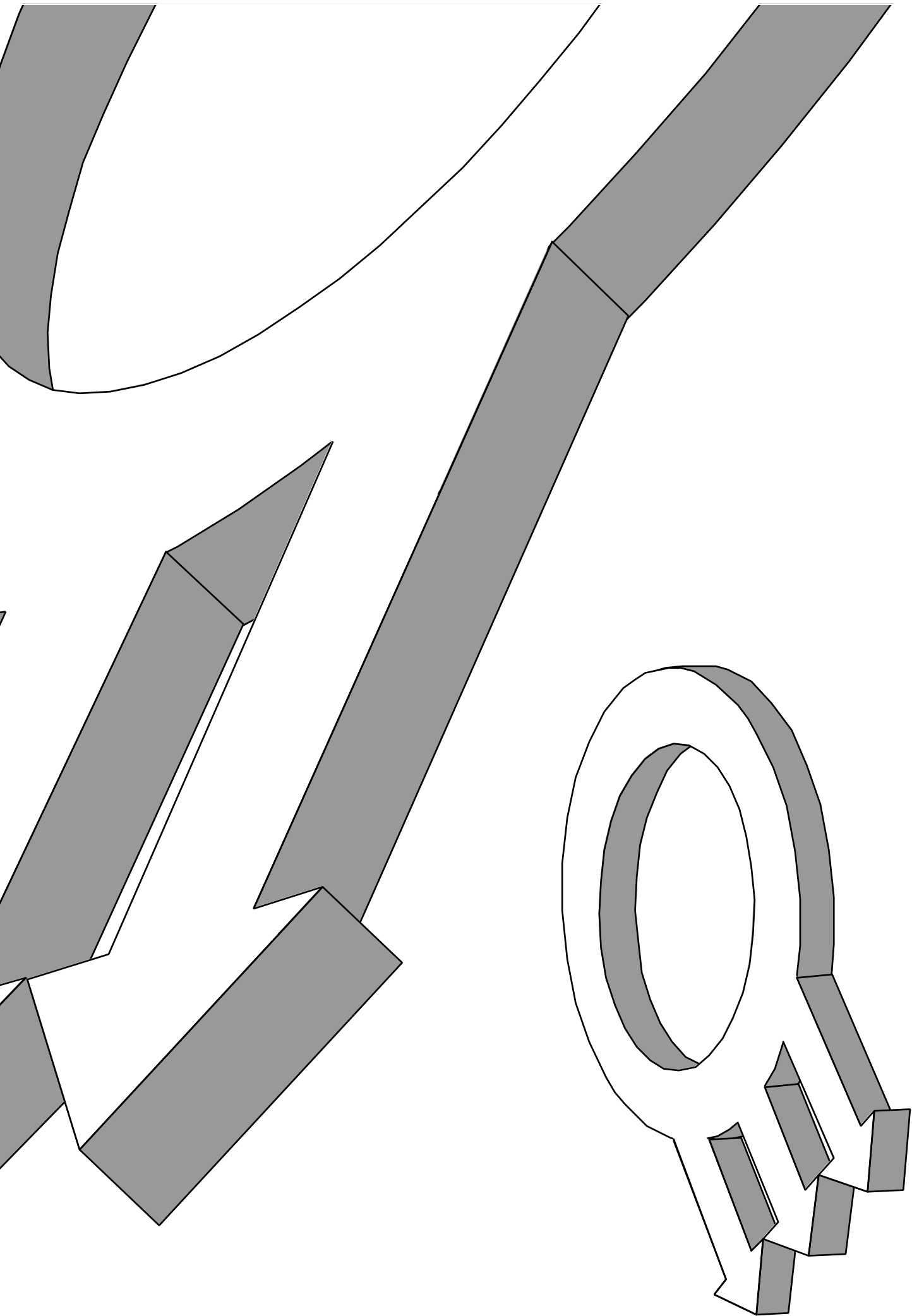
Additional protection according to the type of load:

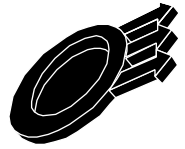
- excessive starting time + locked rotor
- starts per hour
- undercurrent

setting information

type of fault	settings
overloads	■ thermal overload parameters should be adapted to fit the characteristics of the motor (time constant in the 10' range), ■ IDMT overcurrent relay setting should allow starting.
breaking unbalance and phase reversal	■ negative sequence unbalance setting between 0.3 and 0.4 In, time delay: approximately 0.6 sec. If the system can function with almost continuous unbalance, an IDMT characteristic is used: setting allowing 0.3 In during starting without tripping
short circuits	■ fuse rating > 1.3 In, allowing starting, ■ direct time overcurrent setting ≥ 1.2 start-up current, time delay approximately 0.1 sec. differential: setting 10% to 20% of In
stator frame	■ resistance grounding The lowest setting compatible with the protected outgoing line's capacitive current is selected, setting between 10 and 20% of maximum earth fault current, time delay: 0.1 sec. approximately.
excessive starting time	■ setting approximately 2.5 In, time delay 1.1 x starting time.
locked rotor	
drop in voltage	■ setting between 0.75 and 0.8 Un, time delay: approximately 1 sec.
real reverse power	■ approximate settings setting 5% of Pn time delay 1 sec.
field loss	■ approximate settings setting 30% of Sn time delay 1 sec.







introduction

AC generator operation can be altered by both faults within the machine and by disturbances occurring in the electrical system to which it is connected. An AC generator protection system therefore has a dual objective: protecting the machine and protecting the system.

types of faults

Faults such as overloads, unbalance and internal phase-to-phase faults are the same type for AC generators as for motors.

However, there are other types of faults that are characteristic of AC generators.

When a **short circuit occurs** in an electrical system close to an AC generator, the fault current looks like that shown in figure 1.

The maximum short-circuit current value should be calculated taking into account the machine's subtransient impedance X''_d .

The value of the current detected by a protection device, which is very slightly time-delayed (by about 100 milliseconds), should be calculated taking into account the machine's transient impedance X'_d .

The value of steady state short-circuit current should be calculated taking into account the synchronous impedance X . This current is weak, generally less than the AC generator's rated current.

Internal phase-to-frame fault

This is the same type of fault as for motors and its effects depend on the grounding systems adopted. A particularity in relation to motors, however, lies in the fact that AC generators can operate decoupled from the electrical system during the start-up and shutdown periods, and also when operating for testing or on stand-by. The grounding system may differ depending on whether the AC generator is coupled or decoupled and the protection devices should be suitable for both cases.

Field loss

When an AC generator previously coupled with a system loses its field, it becomes desynchronized from the system. It then operates asynchronously, overspeeding slightly, and it absorbs reactive power.

Motor-like operation

When an AC generator is driven like a motor by the electrical power system to which it is connected and it applies mechanical energy to the shaft, this can cause wear and damage to the driving machine.

Voltage and frequency variations

Voltage and frequency variations during steady state operating are due to the malfunction of the related regulators. These variations create the following problems:

- too high a frequency causes abnormal motor overheating,
- too low a frequency causes motor power loss,
- variations in frequency cause variations in motor speed which can bring about mechanical damage,
- too high a voltage puts stress on all parts of the network,
- too low a voltage causes torque loss and an increase in current and motor overheating.

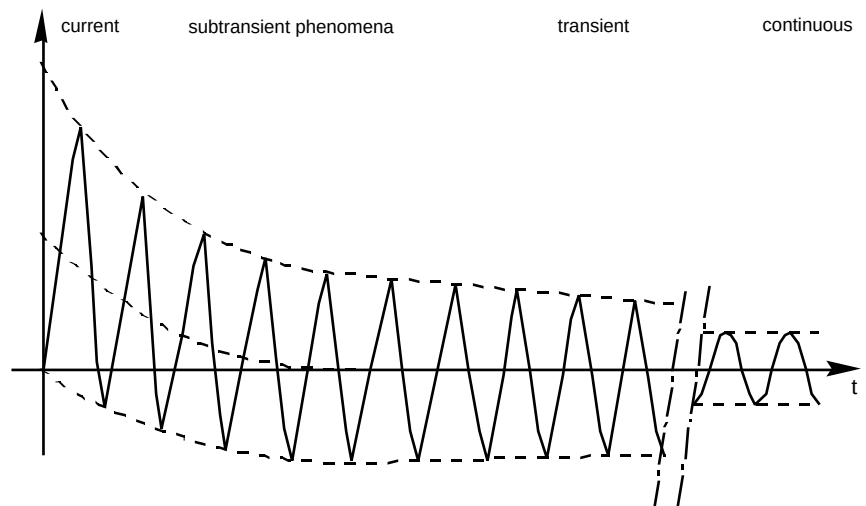
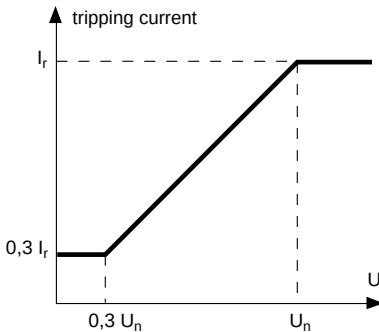


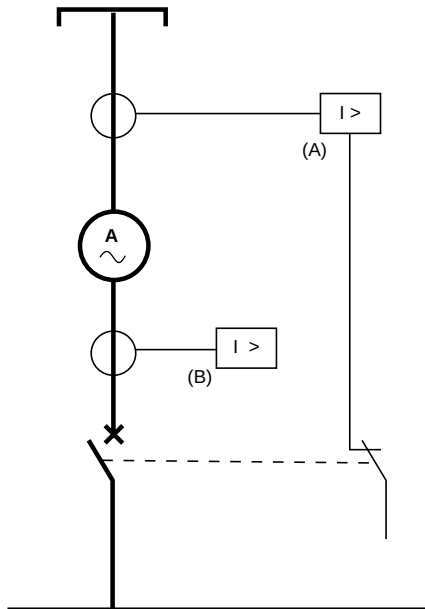
fig.1

protection devices



(fig.2)

I_r : setting current



(fig.3)

AC generator connected to other power sources

Overloads

The overload protection devices for AC generators are the same as for motors:

- IDMT overcurrent,
- thermal overload,
- temperature probe.

Unbalance

Protection, like for motors, is ensured by IDMT or direct time negative sequence detection.

External phase-to-phase short-circuits

As the value of short-circuit current decreases over time to within the range of rated current, if not weaker, in steady state operation, a simple current detection device can be insufficient.

This type of fault is effectively detected by a voltage restrained overcurrent detection device, the setting of which increases with the voltage (fig.2). Operation is delayed.

Internal phase-to-phase short circuits

- high impedance or percentage-based differential protection provides a sensitive, quick solution.

■ In certain cases, especially for an AC generator with a low power rating compared to the system to which it is connected, the following combination can be used for internal phase-to-phase short-circuit protection (fig.3):

- instantaneous overcurrent protection (A), validated when the AC generator circuit breaker is opened, with current sensors located on the neutral side, with a setting lower than rated current,
- instantaneous overcurrent protection (B), with current sensors located on the circuit breaker side, with a setting higher than AC

generator short-circuit current.

Stator frame fault

- if the neutral is grounded at the AC generator neutral point, earth fault or restricted earth fault protection is used.

■ if the neutral is grounded within the system rather than at the AC generator neutral point, stator frame faults are detected by:

- earth fault protection on the AC generator circuit breaker when the AC generator is coupled to the electrical system,
- by an insulation monitoring device for ungrounded systems when the AC generator is uncoupled from the system.

■ If the neutral is ungrounded, protection against frame faults is ensured by an insulation monitoring device. This device operates either by detecting residual voltage or by injecting DC current between the neutral and earth.

If this device exists in the system, it monitors the AC generator when it is coupled, but a special AC generator device, validated by the circuit breaker being in the open position, is needed to monitor insulation when the AC generator is uncoupled.

Rotor frame faults

When the exciting current circuit is accessible, frame faults are monitored by a permanent insulation monitor (Vigilohm).

Field loss

This type of fault is detected either by measuring the reactive power absorbed or by monitoring the excitation circuit if accessible, or else by measuring the impedance at the AC generator terminals.

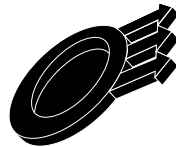
Motor-like operation

This is detected by a relay that senses the real power absorbed by the AC generator.

Voltage and frequency variations

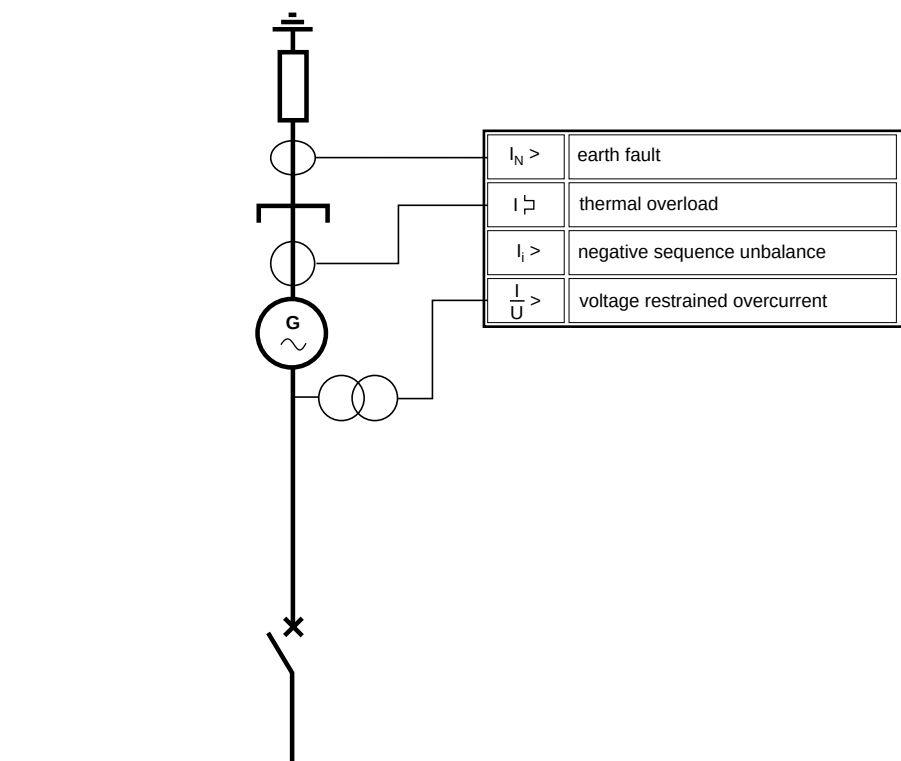
These are monitored respectively by an overvoltage-undervoltage protection device and an underfrequency device.

These protection devices are time-delayed since the phenomena do not require instantaneous action and because the electrical system protections and voltage and speed controller must be allowed time to react.

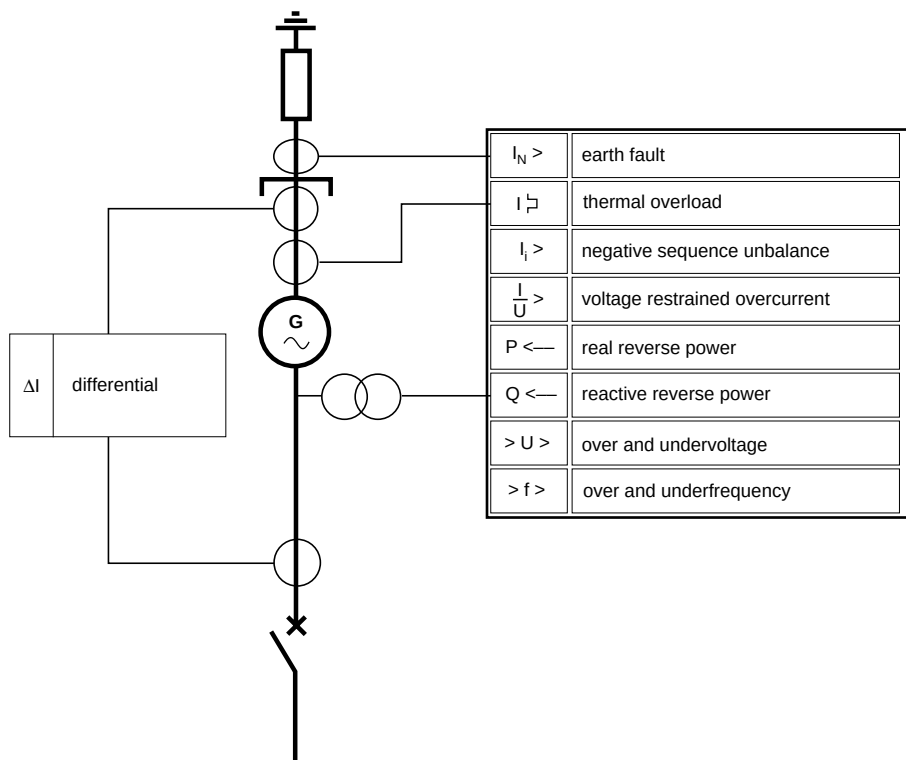


examples of applications

Low power AC generator, uncoupled

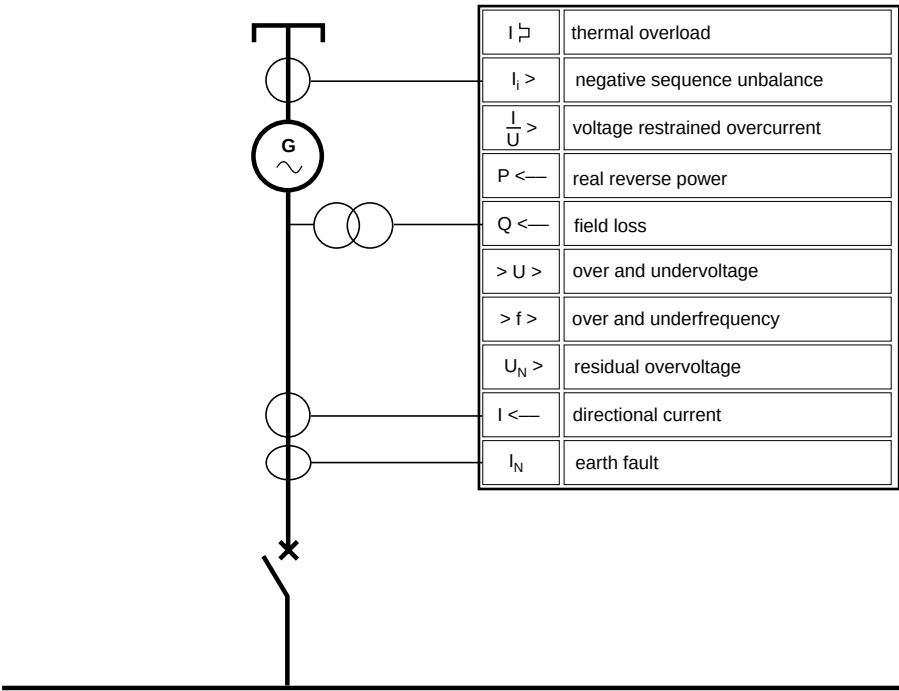


Medium power AC generators

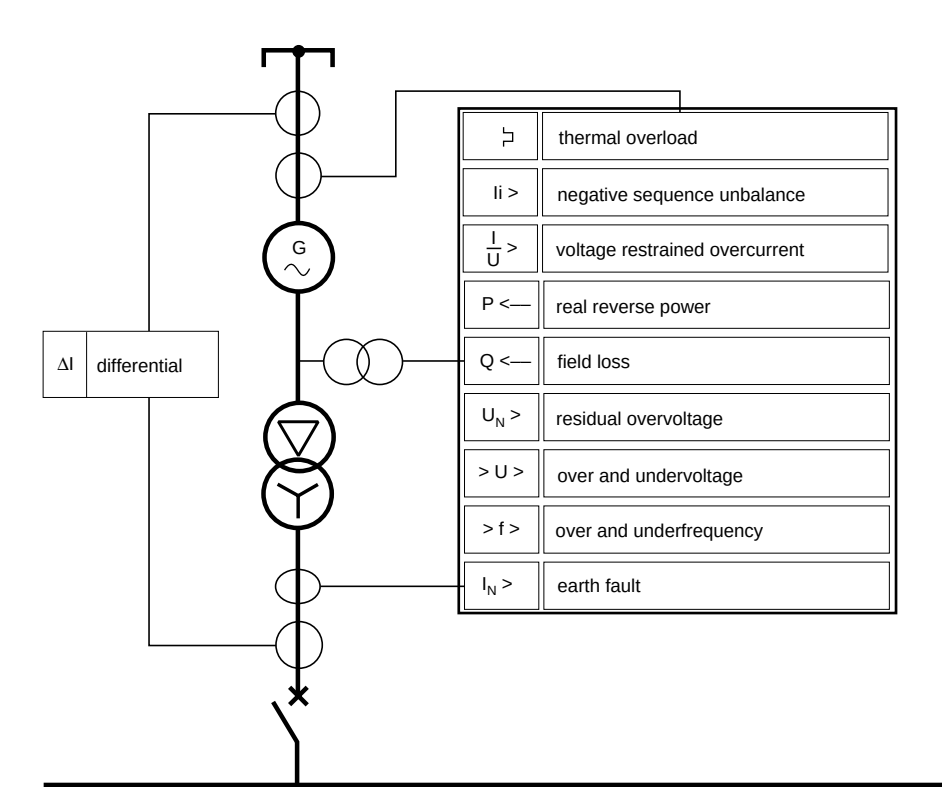


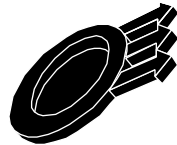
examples of applications

Medium power AC generator
(grounded in electrical system)



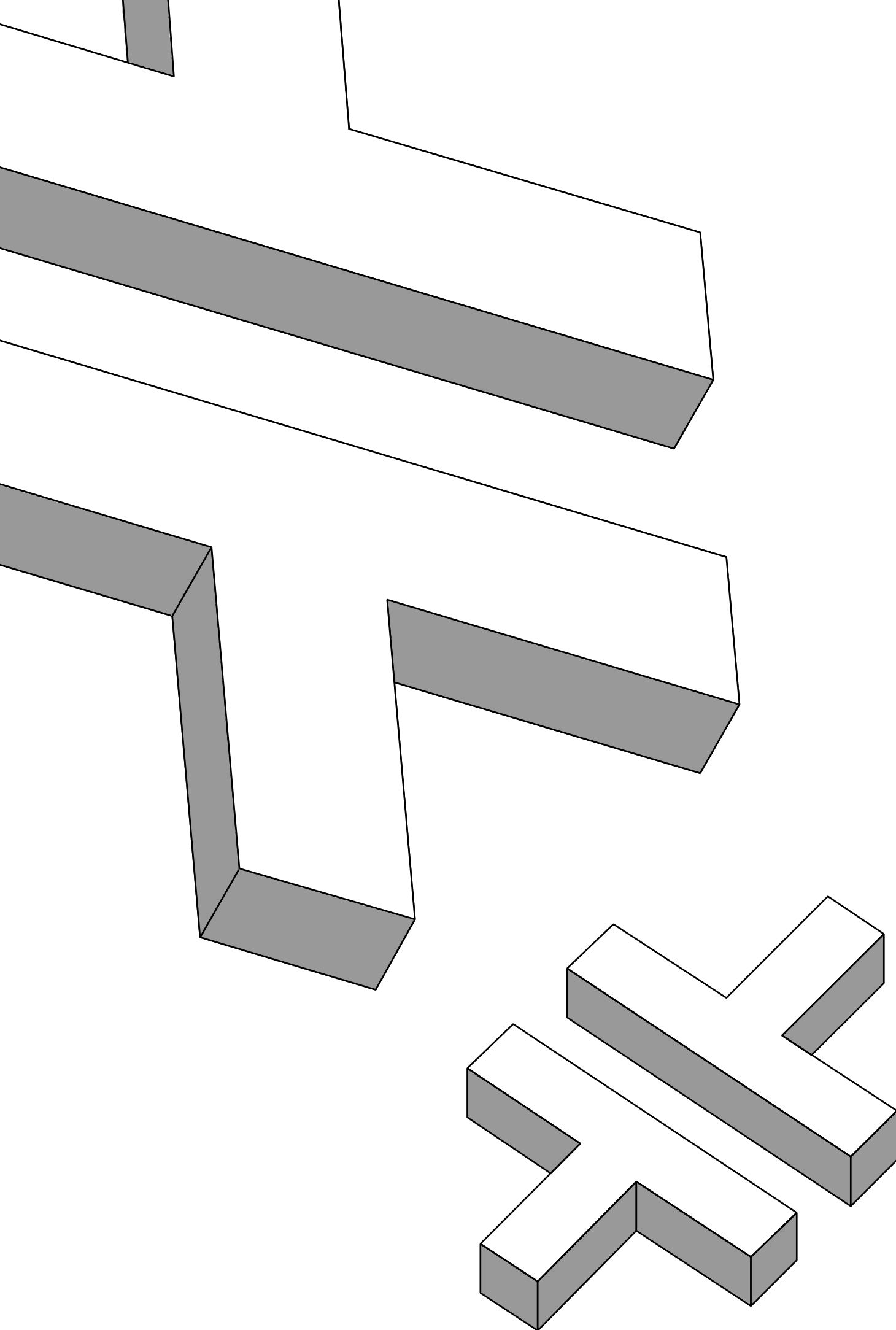
Medium power block generator





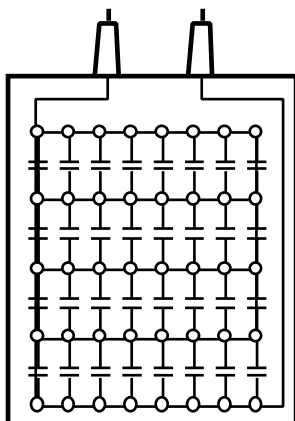
setting information

type of fault	settings
overloads	■ thermal overload to be adapted to rated characteristics (time constants in the 10' range)).
unbalance	■ max. neg. phase sequence component to be adapted to characteristics (if lack of data, setting 15% of I_n , IDMT).
external short-circuit	■ voltage restrained overcurrent setting 1.2 to 2 times I_n , time delay according to discrimination.
internal short-circuit	■ high impedance differential threshold approximately 10% of I_n .
frame faults	■ neutral grounded in electrical system earth fault, setting 10% to 20% of maximum earth fault current, time delay: instantaneous or 0.1 sec. ■ neutral grounded at AC generator neutral point earth fault setting approximately 10% I_n time delay according to discrimination ■ ungrounded residual overvoltage setting approximately 30% of V_n
field loss	■ reactive reverse power setting 30% of S_n , time delay of a few seconds.
motor operation	■ directional real power setting 1 to 20% of P_n , time delay ≥ 1 sec.
voltage variation	■ over and undervoltage $0.8 U_n < U < 1.1 U_n$, time delay: approximately a second.
speed variation	■ over and underfrequency $0.95 f_n < f < 1.05 f_n$, time delay: a few seconds.





introduction



Capacitor banks are used to compensate for reactive energy absorbed by electrical system loads, and sometimes to make up filters to reduce harmonic voltage. Their role is to improve the quality of the electrical system.

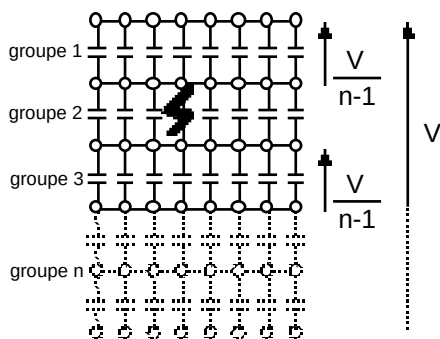
They may be connected in star, delta and double star arrangements, depending on the level of voltage and the system load.

A capacitor comes in the form of a case with insulating terminals on top. It comprises individual capacitances which have limited maximum permissible voltages (e.g. 2250 V) and are series-mounted in groups to obtain the required voltage withstand and parallel-mounted to obtained the desired power rating.

There are two types of capacitors:

- those with no internal protection,
- those with internal protection: a fuse is combined with each individual capacitance.

types of faults



(fig.1)

The main faults which are liable to affect capacitor banks are:

- overload,
- short-circuit,
- frame fault,
- capacitor component short-circuit.

An **overload** is due to temporary or continuous overcurrent:

- continuous overcurrent linked to:
 - raising of the power supply voltage,
 - the flow of harmonic current due to the presence of non-linear loads such as static converters (rectifiers, variable speed drives), arc furnaces, etc.,
 - temporary overcurrent linked to the energizing of a capacitor bank step.
- Overloads result in overheating which has an adverse effect on dielectric withstand and leads to premature capacitor aging.

A **short-circuit** is an internal or external fault between live conductors, phase-to-phase or phase-to-neutral depending on whether the capacitors are delta or star-connected. The appearance of gas in the gas-tight chamber of the capacitor creates overpressure which may lead to the opening of the case and leakage of the dielectric.

A **frame fault** is an internal fault between a live capacitor component and the frame created by the metal chamber.

Similar to internal short-circuits, the appearance of gas in the gas-tight chamber of the capacitor creates overpressure which may lead to the opening of the case and leakage of the dielectric.

A **capacitor component short-circuit** is due to the flashover of an individual capacitance.

- with no internal protection: the parallel-wired individual capacitances are shunted by the faulty unit:

- the capacitor impedance is modified
- the applied voltage is distributed to one less group in the series
- each group is submitted to greater stress, which may result in further, cascading flashovers, up to a full short-circuit.

- with internal protection: the melting of the related internal fuse eliminates the faulty individual capacitance:

- the capacitor remains fault-free,
- its impedance is modified accordingly.

protection devices

Capacitors should not be energized unless they have been discharged. Re-energizing must be time-delayed in order to avoid transient overvoltage. A 10-minute time delay allows sufficient natural discharging. Fast discharging reactors may be used to reduce discharging time.

Overloads

- Overcurrent of long duration due to the raising of the power supply voltage may be avoided by overvoltage protection that monitors the electrical system voltage. This type of protection may be assigned to the capacitor itself, but it is generally a type of overall electrical system protection. Given that the capacitor can generally accommodate a voltage of 110% of its rated voltage for 12 hours a day, this type of protection is not always necessary.

- Overcurrent of long duration due to the flow of harmonic current is detected by an overload protection of one the following types:

- ☐ thermal overload
- ☐ time-delayed overcurrent, provided it takes harmonic frequencies into account.

- The amplitude of overcurrent of short duration due to the energizing of capacitor bank steps is limited by series-mounting impulse reactors with each step.

Short circuits

Short-circuits are detected by a time-delayed overcurrent protection device. Current and time delay settings make it possible to operate with the maximum permissible load current and to close and switch steps.

Frame faults

Protection depends on the grounding system. If the neutral is grounded, a time-delayed earth fault protection device is used.

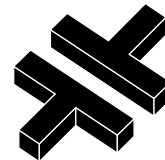
Capacitor component short-circuits

Detection is based on the change in impedance created

- by the short-circuiting of the component for capacitors with no internal protection

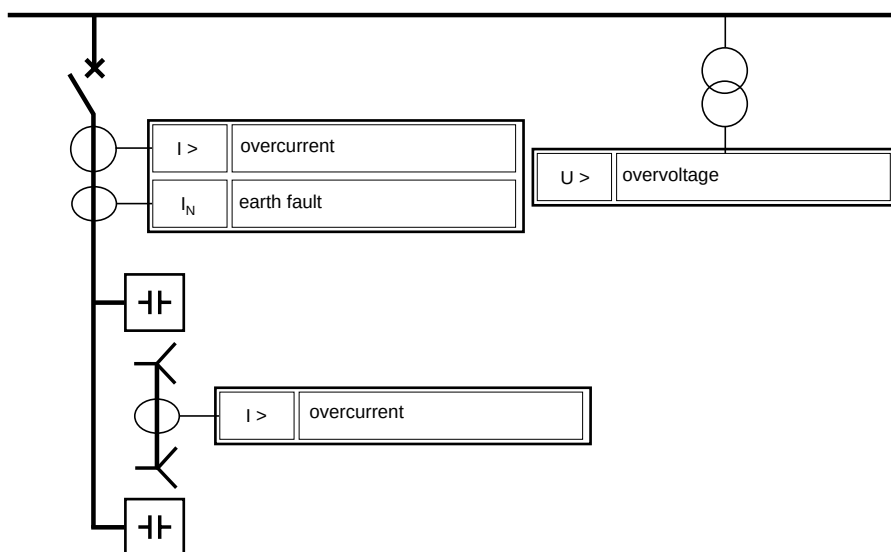
- by the elimination of the faulty individual capacitance for capacitors with internal fuses.

When the capacitor bank is double star-connected, the unbalance created by the change in impedance in one of the stars causes current to flow in the connection between the neutral points. This unbalance is detected by a sensitive overcurrent protection device.

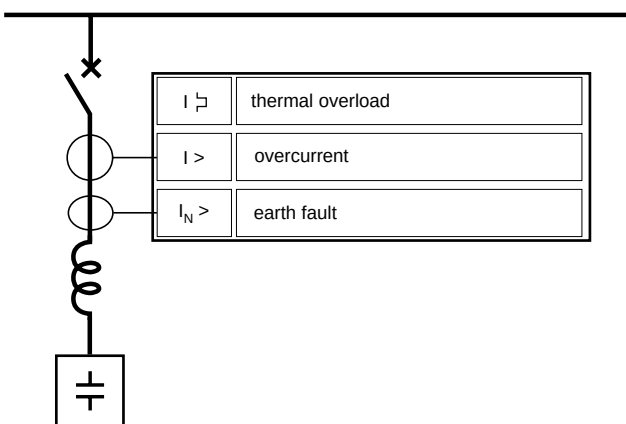


examples of capacitor bank protection

Double star connected capacitor bank for reactive power compensation



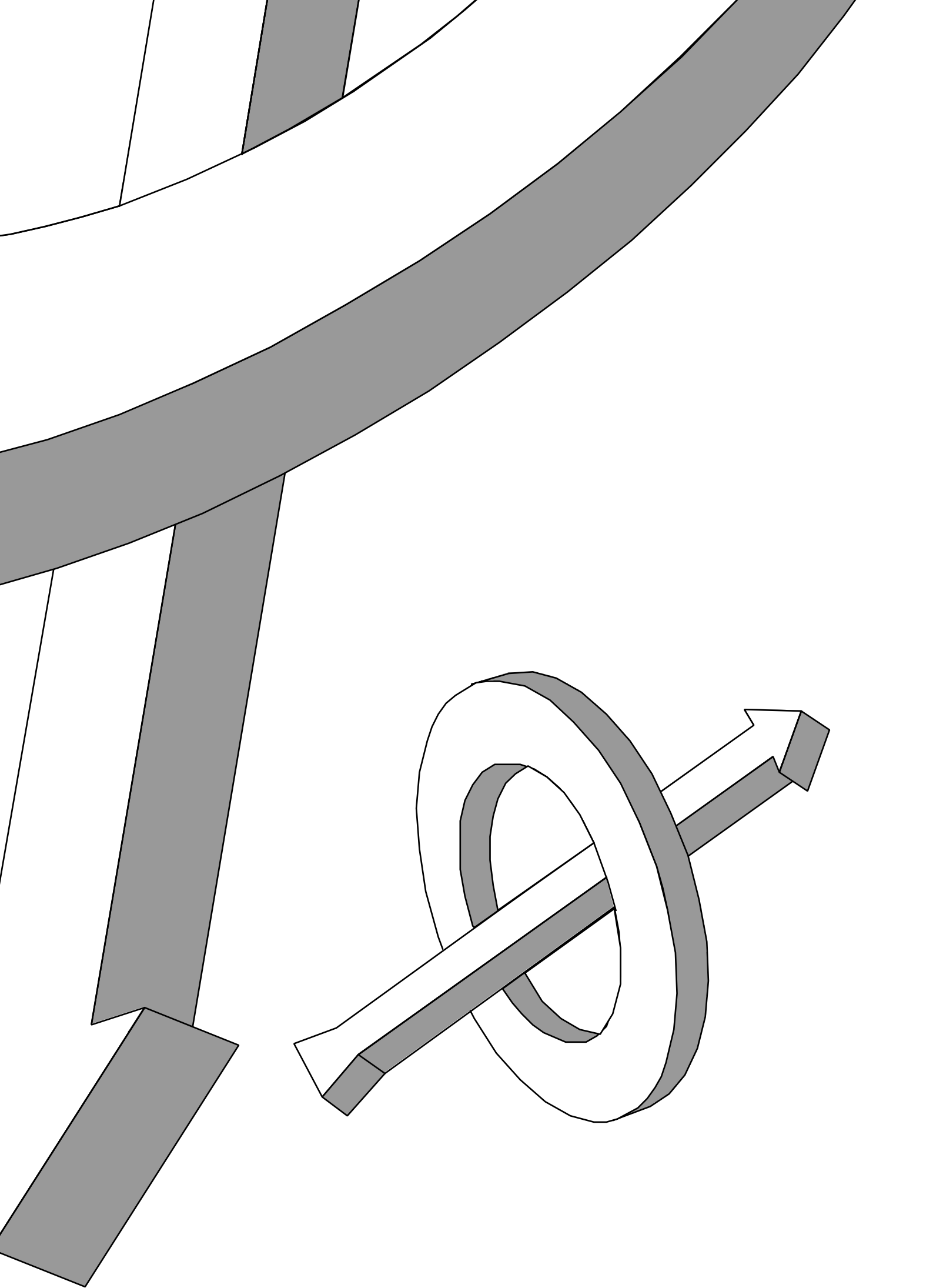
Filter



setting information

type of fault	setting
overload	■ overvoltage setting $\leq 110\%$ V_n ■ thermal overload setting $\leq 1.3 I_n$ or overcurrent setting $\leq 1.3 I_n$ direct time or IDMT time delay 10 sec
short-circuit	■ overcurrent direct time setting approximately 10 I_n time delay approximately 0.1 sec
frame fault	■ earth fault direct time setting $\leq 20\%$ maximum earth fault current and $\geq 10\%$ CT rating if supplied by 3 CTs time delay approximately 0.1 sec
capacitor component short circuit	■ overcurrent direct time setting < 1 ampere time delay approximately 1 sec







introduction

Protection or measuring devices require data on the electrical rating of the equipment to be protected.

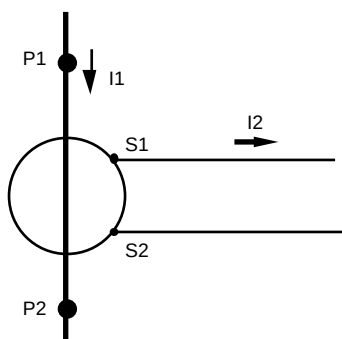
For technical, economic and safety reasons, this data cannot be obtained directly from the high voltage equipment power supply; the following intermediary devices are needed:

- voltage transformers (VT),
- current transformer (CT),
- core balance CTs to measure earth fault current.

These devices fulfill the following functions:

- reduction of the value to be measured (e.g. 1500/5 A),
- galvanic isolation,
- providing the power required for data processing and for protection operation itself.

current transformers (CTs)



The CTs are characterized by the following values (according to IEC 185 standards)*.

CT voltage

This is the operating voltage applied to the CT primary. Note that the primary is at the HV potential level and that one of the secondary terminals is generally earthed.

As for other equipment, the following is also defined :

- maximum 1 min. withstand voltage at standard frequency
- maximum impulse withstand voltage.

e.g. for 24 kV rated voltage, the CT must withstand 50 kV voltage for 1 min at 50 Hz and 125 kV impulse voltage .

Rated transformation ratio

It is usually given as the transformation ratio between primary and secondary current I_1/I_2 . Secondary current is generally 5 A or 1 A.

Accuracy level

It is defined by the composite error for the accuracy limit current.

e.g. 5P10 means 5% error for 10 I_n
10P15 means 10% error for 15 I_n

5P and 10P are the standard **accuracy classes**.

5 I_n , 10 I_n , 15 I_n , 20 I_n are the standard **accuracy limit currents**.

The accuracy limit factor is the ratio between the accuracy limit current and the rated current .

Class X is another way of specifying CT characteristics based on "knee-point voltage" (fig.1, CT response in saturated state).

Accuracy level power

Secondary power at rated current for which the accuracy level is guaranteed. Expressed in VA, it indicates the power that the secondary can deliver for its rated current, while respecting the rated accuracy class. It represents the total consumption of the secondary circuit, i.e. the power consumed by all the connected devices as well as the connecting wires.

If a CT is loaded at a power rating lower than its accuracy level power, its actual accuracy level is higher than the rated accuracy level. Likewise, a CT that is loaded too much loses accuracy.

Admissible short time current

Expressed in rms kA, the maximum current admissible for 1 second (I_{th}) (the secondary being short-circuited) represents CT thermal overcurrent withstand. The CT must have the capacity to withstand short-circuit current for the time required to clear it. If the clearing time t is other than 1 sec., the current the CT can withstand is $I_{th} / \sqrt{t}$.

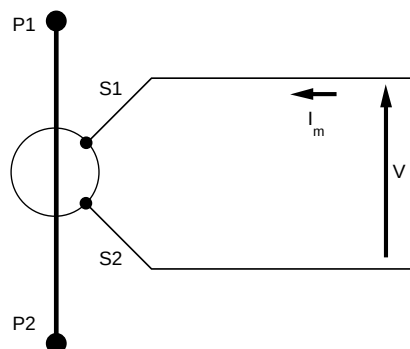
Electrodynamic withstand expressed in peak kA is at least equal to $2.5 \times I_{th}$

Normal values of rated currents:

- at the primary (in A)
- 10 - 12.5 - 15 - 20 - 25 - 30 - 40 -
- 50 - 60 - 75 and multiples or decimal submultiples.

* Also to be taken into account are elements related to the type of assembly, characteristics of the site (e.g. temperature), system frequency, etc...

CT response in saturated state

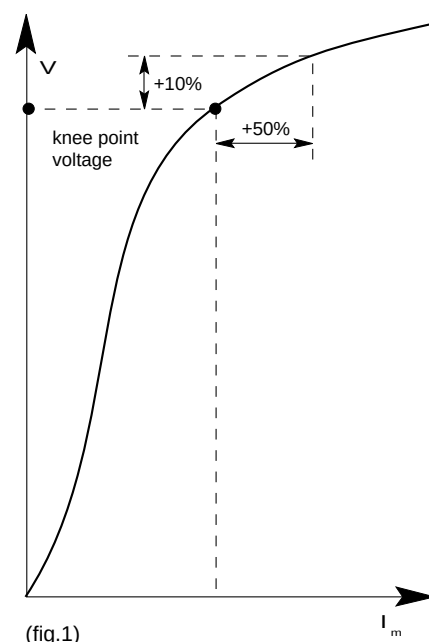


When subjected to very strong current, the CT becomes saturated, i.e. the secondary current is no longer proportional to the primary current.

The current error which corresponds to the magnetization current becomes very high.

Knee-point voltage (fig.1)

This is the point on the current transformer magnetization curve at which a 10% increase in voltage V requires a 50% increase in magnetization current I_m .



conclusion on CTs sending current into an overcurrent type protection device

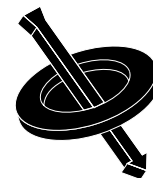
For direct time overcurrent protections, if twice the setting current does cause saturation, operation is ensured no matter how strong the fault.

For IDMT overcurrent protections, saturation must not be reached for current values in the working part of the operation curve (a maximum of 20 times the setting current).

specific "wide band" current sensors

These sensors, most often without magnetic circuits and therefore **not subject to saturation**. Linked to an electronic device, their **response is linear**.

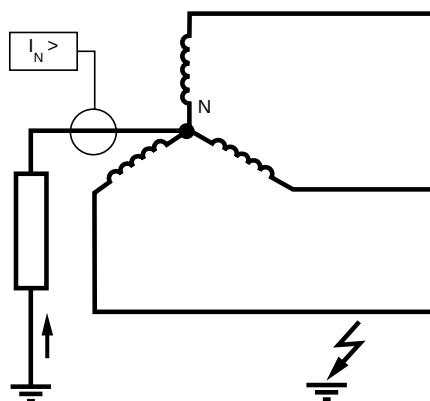
These CTs are used and supplied with the digital technology protection units. They only require knowledge of the primary rated current.



earth fault protection sensors

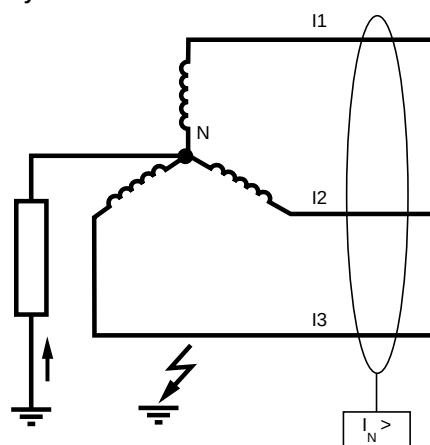
Earth fault current can be detected in several ways.

CT mounted on neutral point



(fig.1)

Differential measurement by core balance CT

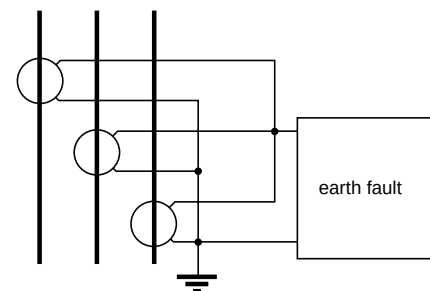


(fig.2)

3 CT summing integrator assembly (fig.3)

This assembly is only used if it is impossible to use core balance CTs.

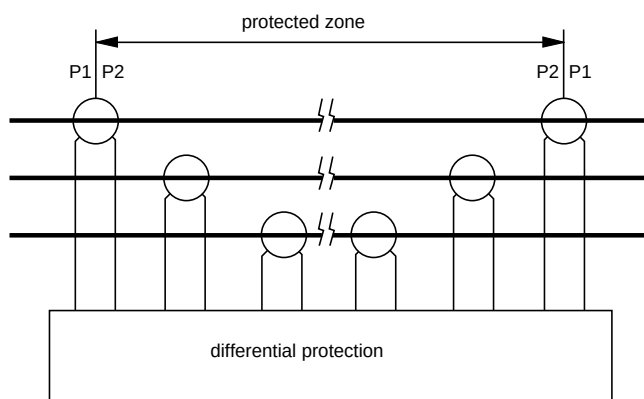
Because of the CT summing error, the minimum setting for residual current is approximately 10% of I_N .



(fig.3)

differential protection sensors

The CTs should be specified according to the operating principle of the protection system; refer to the instruction manual of the system being used.

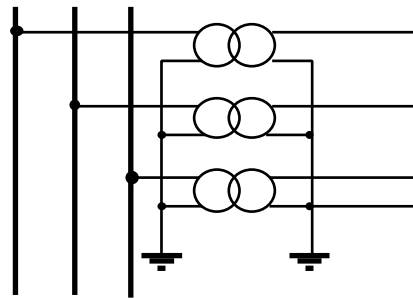


voltage transformers

Voltage transformers have the following characteristics (IEC186) ⁽¹⁾

- electrical system frequency generally 50 or 60Hz,
- system's highest primary voltage (secondary voltage is standardized 100, $100/\sqrt{3}$, 110, $110/\sqrt{3}$ Volts),
- rated voltage factor
- VA power rating and accuracy class

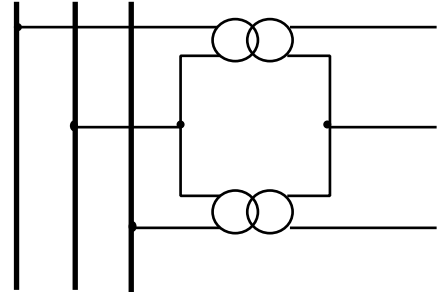
3-transformer assembly
(requires 1 insulated high voltage terminal per transformer)



voltage ratio:

$$\frac{U_n/\sqrt{3}}{100/\sqrt{3}}$$

2 transformer assembly ("V" assembly)
(requires 2 insulated high voltage terminals per transformer)

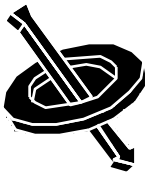


voltage ratio:

$$\frac{U_n}{100}$$

In ungrounded systems, all neutral phase VTs must be loaded enough to prevent the risk of ferromagnetic resonance.

⁽¹⁾ also to be taken into account are elements related to the type of assembly, characteristics of the site (e.g. temperature...) etc...



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