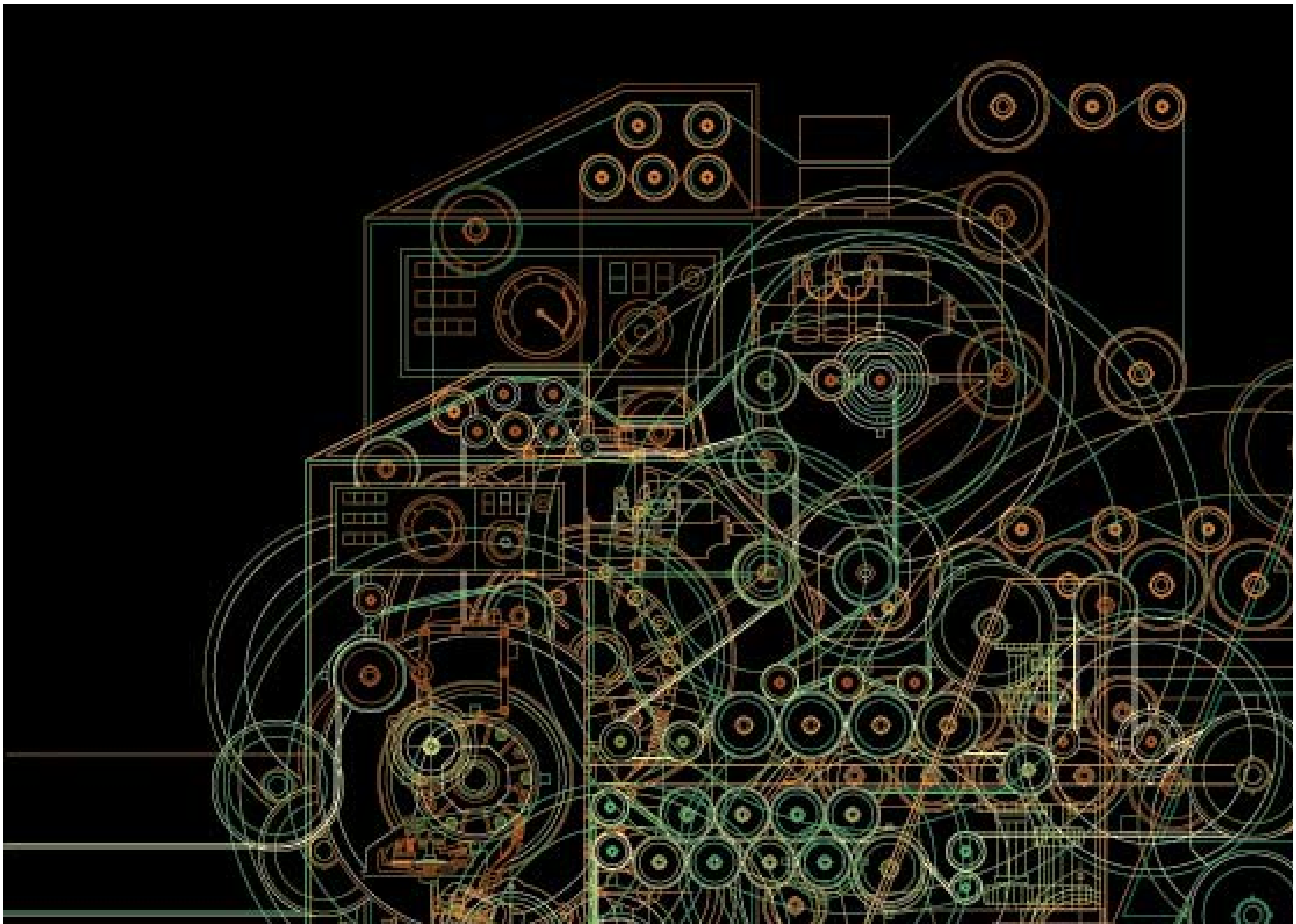

Medium voltage products

Technical Application Papers No.21
Protection criteria for medium voltage networks

Contents

1. Introduction

This booklet aims at illustrating the basic criteria needed for good protection of machines and plants in medium voltage networks.

Selection of the protection system and relays depends on and is correlated with the plant characteristics, type of industrial process and its service continuity requirements, with the status of the neutral, characteristics of the machines, levels and duration of the fault currents, etc.
An excessive number of protections may also be harmful, since, even if they operate correctly in the case of a fault, they can operate in an untimely way when there is no fault, causing more or less widespread disturbance and out-of-order conditions, sometimes more damaging than the faults themselves, as the cause cannot be found (even protections can go wrong).
It is important to underline at once that trip selectivity must always be looked for, but must only be looked for after having ensured protection of the network component.
The protection relays are normally provided for different objectives and aims. In some cases a protection relay is used with the aim of activating automatisms to manage the electric network. The latter is a special application although normal in plants, but in this case the relays cannot be considered as network and plant protections.

The main objectives of protection relays are:
- to provide the operator with an alarm indication under particular network or machine service conditions (for example protection against negative sequence for generators);
- to put the line or faulty machine out of commission within a short time, as defined in the selectivity study;
- to carry out automatisms under particular service conditions (for example, undervoltage protections which activate automatic changeover or automatic reclosing of the lines);
- control of the network parameters to prevent false operations (for example, synchronism check);
- to activate network parameter recording to memorise the network disturbances (for example, the starting contacts of the overcurrent relay);
- to carry out protection of the interface with the external network (with contractual not protection settings).

Identification of the abnormal conditions mentioned is made by the protection relays, which operate to separate the faulty part of the network from the rest of the plant. The protection relay setting must be calculated to give the plant the highest possible service continuity to avoid damage to network components. The setting values must be selected above the transient conditions which can occur in the network without requiring disconnection.


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2. Network schemes

To size an electric network correctly, it is necessary to do the following network calculations either entirely or partly:
- **sizing calculations (machines, transformers, etc.);**
- **calculation of the short-circuit currents;**
- **definition of the status of the neutral;**
- **calculation of the voltage profiles (load flow);**
- **starting transient of the motors;**
- **study of dynamic stability;**
- **calculation of the network harmonic content;**
- **study of protection coordination.**

Before all these activities, the single-line diagram of the electric network must be defined on the basis of:
- LOADS: it is considered fundamental to establish the true user and service requirements these are destined for, in terms of quality, availability and continuity of the power supply;
- POWER SUPPLIES: it must be considered whether these are suitable or have to be integrated by resorting to other external ones, from self-production, in reserve, for emergency or for safety;
- ELECTRIC NETWORK STRUCTURE: this includes selection of the diagram, machine, cable and apparatus selection and sizing of the protection and control system.

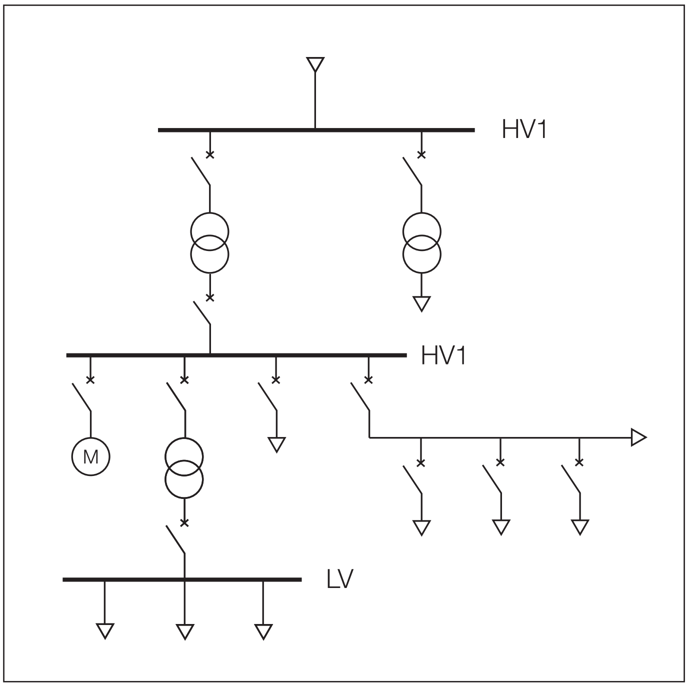
The protection system must adapt to the type of network making up the plant. In fact, depending on the types of machines and industrial process, the protection functions to be selected can be different and sometimes not homogeneous with each other.
Before defining the protection systems, the main network schemes are analysed, highlighting the advantages and disadvantages of the various solutions. Obviously these are qualitative considerations of a general kind and are not necessarily exhaustive. In any case, it must be pointed out that the role of the designer who has to succeed in building a network scheme which suits the industrial process requirements is always important.

2.1 Single radial network

This is the simplest, least costly network scheme and the one with least overall reliability. The single radial scheme for a network with several voltage levels has a tree structure, possibly with backbones which supply the loads distributed along the route.

The main advantages of this network configuration are:
- simplicity;
- economy.

Vice versa, the disadvantages are:
- maintenance (the network must be put out of service on the load side of the maintenance point);
- vulnerability (in the case of a fault, the whole network on the load goes out of service).



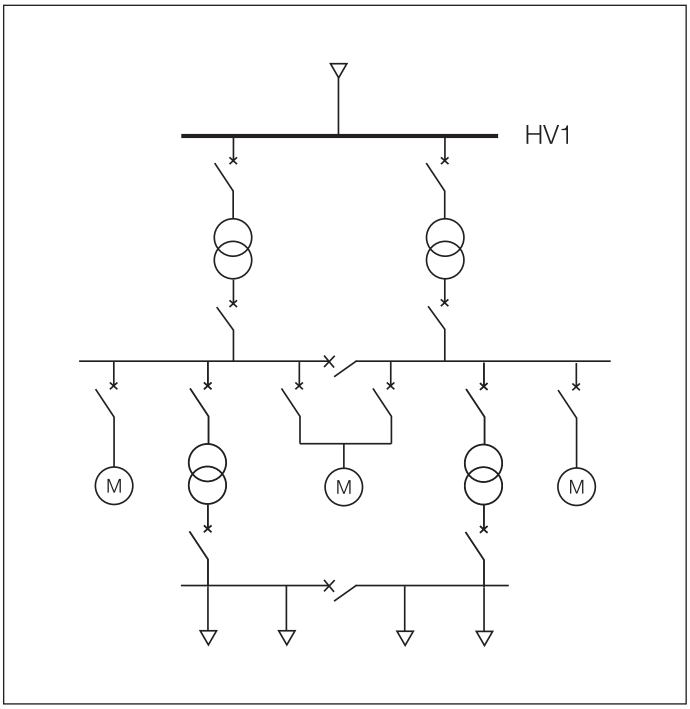
2. Network schemes

2.2 Double radial network

The particularity of this scheme consists of having two equal alternative paths, made up by doubling a basic radial type network. Duplication of the scheme can be extended as far as the individual user, or more frequently, as far as one or more distribution nodes (busbars).
Their major use is in networks of industrial plants with process plants where a high level of service continuity is required.

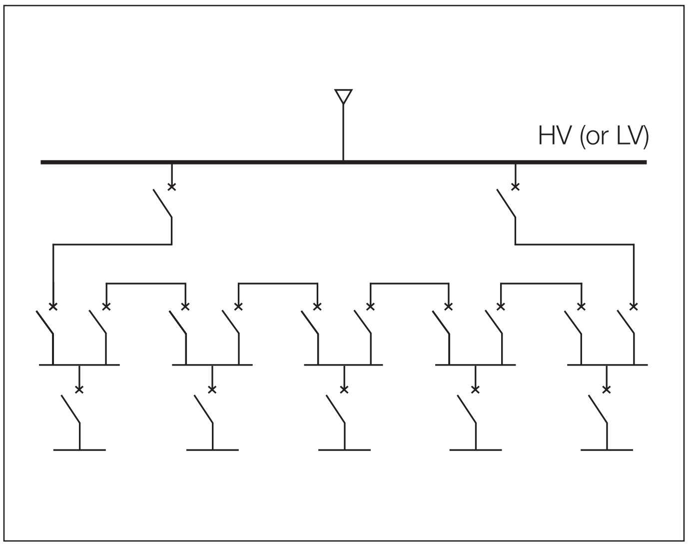
The main advantages of this network configuration are:
- the limited duration of out of service in the case of a fault;
- possibility of carrying out maintenance on parts of the plant without causing out of services or plant stoppages.

On the other hand, the disadvantage is the high costs for its realization.



2.3 Ring network

Ring networks make it possible to always have two power supplies for each plant substation. In practice, the ring scheme is characterised by the presence of at least one side more (n+1) compared with the minimum needed to connect the loads to the power supply node. Their main use is in networks where there are considerable distances between the users, characterised by small absorbed powers. In the presence of large plant loads, building a ring network can be more onerous than other types of network.
On the in-out of each substation, the ring networks can be equipped with protection devices (and operating parts) or just with switch-disconnectors (not able to open the circuit in the case of a fault). Obviously in the first case a protection system which only eliminates the faulty trunk from service can be studied, whereas in the second case the only device which can detect a fault in the network and command circuit opening will be positioned at the departure of the ring.
Running ring networks equipped with devices able to identify and interrupt the fault in the ring substations is, in any case, very different according to whether the ring is run open or closed.
The main advantages of ring networks equipped with protections and circuit-breakers on the in-out of each substation are:



- service continuity, i.e. the possibility of only eliminating from service the part of the network where the fault is, keeping the remaining part of the ring in operation;
- the possibility of carrying out maintenance on parts of the plant without causing out of services or plant stoppages.

On the other hand, the disadvantages are:
- realisation costs linked to the extension of the network;
- complexity of the protection system.

2.3.1 Network run with open ring

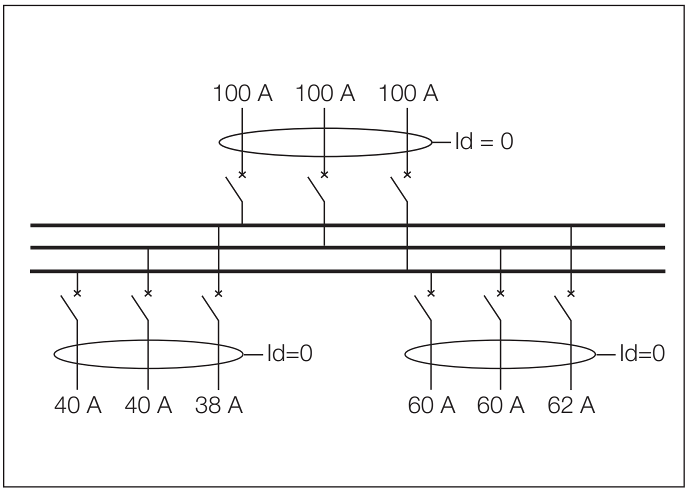
If the ring is run open, the network configuration is practically the radial type, therefore in the case of a fault the whole part of the network on the load side of the fault point will be put out of service. The disadvantages are those already been listed for single radial networks. The advantage is being able to restore service within relatively short times, counter-supplying the substations from the sound side of the network and being able to carry out checks and repairs without the worry of production stoppage.

2.3.2 Network run with closed ring

Running with a closed ring makes it possible to always have two sources in parallel in every substation inside the ring and therefore, theoretically, not to have any out of services in the plant due to faults in the ring.
To identify faults in ring networks two different techniques can be used, for instance:

- differential protections against phase faults and directional type ground protection with changeover of consent on tripping for internal faults;
- directional overcurrent protections both against phase faults and against ground faults wired with logical selectivity.

It is necessary for there to be the pilot wires between the relays at the two ends of the line to make both the protection systems described.
With the new protection technologies, only the second solution is in any case now widespread (phase and directional ground protections).
The logics with which the locking signals between the protections can provided are very varied (for example, channels, either independent or not, against phase and ground faults)



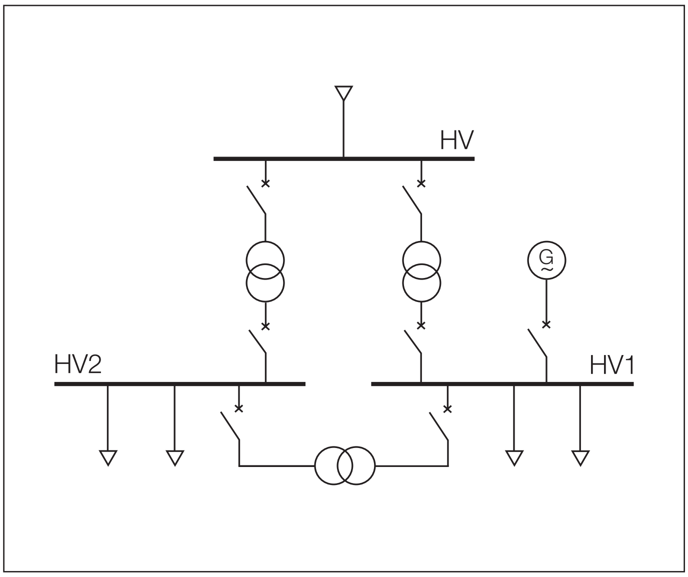
and additional protections can also be provided exploiting the potential logics and protection functions available in digital relays.
The “from the theoretical point of view” statement, is to underline that, from the theoretical point of view, it is possible to identify and therefore eliminate just the trunk fault from service. From the practical point of view, in many plants this is not possible since the times needed to eliminate the fault on the delivery point do not allow it.
To run ring networks, the difficulties in correctly identifying the ground faults according to the status of the network neutral and the settings of the protections defined on the supply side must be considered, particularly in the case of a ring distribution with grounded network with low fault currents. In fact, where the setting threshold of the ground protections is a few Amperes, the risk is systematic false tripping of the protections due to problems linked with construction of the plant and which it is often not possible to eliminate.
Consider, for example, that the two outgoing feeders of the ring from the main substation are loaded with unequal currents on the three phases.
As can be seen, the total load of the ring is perfectly balanced (100 A), but the currents on the two outgoing feeders have an unbalance which can be due to various factors, such as different tightening of the cables, the non- homogeneity of the length of the single-phase cords (typical of short distances), the fact of having provided a longer cable than foreseen (then left abandoned in a substation, perhaps coiled up thereby creating a reactance), etc. In this situation, the ground relays which read the vectorial sum of the currents by means of ring CTs, measure a current on both the outgoing feeders exactly as if there was a fault present.
These two currents are in phase opposition with each other (180°).
Directional type ground relays are used on the ring feeders (even if they may not be strictly necessary on the outgoing feeders of the ring), and in the absence of homopolar voltage the relay does not operate, even when the ground current threshold is exceeded. When a ground fault occurs in a metallically connected network (perhaps in the network of another user connected to the same distributor line) there will be a homopolar voltage in the network and consequently the ground relays which were previously locked, are put under trip conditions when the angle returns to the foreseen sector.
In this condition, unwanted trips can occur which are not homogeneous with each other since, according to the load and position along the ring, there may or may not be unbalances with angles which are in any case variable and therefore there can be variability in tripping of the protections. In the past, this phenomenon was not noted since, there not being ring CTs, the ground fault remained in alarm (isolated neutral), or protection tripping was certain since there were high ground

2. Network schemes

fault currents very far from the possible unbalances due to the plant characteristics.
In the past, this phenomenon was not noted since, there not being toroidal CTs, the earth fault remained in alarm (isolated neutral), or protection tripping was certain since there were high earth fault currents very far from the possible unbalances due to the plant characteristics.

2.4 Meshed network

This is the typical scheme of transmission networks and does not have any particular applications in industrial plants.
This scheme is characterised by many connections among the network nodes, to an extent to allow, for some of these, alternative power supply routes, aimed not only at establishing a reserve connection, but also to improve the load division in the various branches and among different power supply sources.



3. Selection of switching devices

There are three main types of electric circuit opening and closing devices which are used in medium voltage networks.

Circuit-breakers

Apparatus able to close and interrupt the short-circuit current.

Contactors

Apparatus able to carry out a high number of operations and interrupt limited short-circuit currents.

Switch-disconnectors

Switch-disconnectors or isolators able either to open the rated current or not (obviously with a high power factor).
Together with the devices mentioned previously, the fuses which are associated both with the contactors and often also with the switch-disconnectors, must also be considered.
There are other devices for particular applications (such as short-circuit limiting devices) which are for particular applications.
The various types of circuit are analysed below regarding the advantages and disadvantages of selecting the switching device with the only criterion of the protection system. Other considerations regarding types of plant, maintenance, etc. are excluded from this analysis, but which the designer must keep well in mind when selecting the switching device.

Generators

The importance and cost of the machine, the low number of operations required, and the need to delay opening in the case of a fault to guarantee selective trip of the protections, recommend use of a circuit-breaker.
Attention must in any case be paid to the value of asymmetry which the circuit-breaker is able to interrupt since in networks near generators the unidirectional component of the fault current is high.

Transformers

Selection of the switching device is influenced by how many and which possible faults in the machine are to be recognised and eliminated. To make correct selection, it must be known which switching device and any relative protections are used on the secondary.
Whereas measurement on the primary side for overloads and two- and three-phase short-circuit provides precise indications regarding the type and position of the fault, in the case of a ground fault (if the transformer connection unit is star delta as it normally is for distribution transformers), there are two independent circuits which have to be monitored.
Using switch-disconnectors with fuses,

3. Selection of switching devices

only protection against short-circuit (and partially against large overloads by means of fuses) can be guaranteed for the machine, but safe and rapid protection cannot be given against ground faults in the secondary, with the risk of possibly seriously damaging the machine without any device eliminating the fault within the times normally guaranteed for transformers (2 seconds) withstand.
If it is chosen to use contactors with fuses, it must be checked that the fuse has a sufficiently high rated current to prevent false trips on magnetisation of the transformer, whereas protection relays which control contactor opening for overloads and ground faults can be provided.
Attention must in every case be paid to the fact that the fuses only exist with fairly limited rated currents (a few hundred Amperes) and they could therefore be an important limitation to selection of this type of switching device.
Use of circuit-breakers is always compulsory when differential protections which have instantaneous trip (not compatible with outgoing feeders equipped with contactors plus fuses) are to be used for rapid elimination of the fault.

Motors

The choice is normally between contactors plus fuses and circuit-breakers.
From the point of view of protection, the two systems are comparable, with an advantage for the solution with contactors and fuses since for serious faults, the fault elimination time of the fuses (a few milliseconds) is decidedly lower than the time required for outgoing feeders with a circuit-breaker (about 80 ms for the relay plus about 50 ms for the circuit-breaker arc interruption time - about 130 ms in all).
As for the transformer outgoing feeders, the use of a circuit-breaker is also compulsory for outgoing motor feeders, or in the case where differential protection is to be activated.
The rated current of the fuse is a function of the rated current of the motor (generally at least 1.35 times the rated current of the motor) and of the starting characteristics (current, time and number of hourly starts).
The maximum size (rated current) of the fuses is often a limitation to the possibility of using contactors instead of circuit-breakers.

Capacitors

Having to switch capacitive type currents excludes the use of switch-disconnectors. Otherwise, the considerations made regarding transformers are valid for selecting either a contactor with fuse or a circuit-breaker, with the usual caution taken in checking that the fuse does not trip on connection of the capacitor bank.

Feeders

The requirement of making trip selectivity for polyphase short-circuit faults can be decisive in selection of the switching device. The use of fuses does not allow delaying the trip time and so eliminates the possibility of obtaining time selectivity which can only be obtained if a circuit-breaker is used.

4. Current and voltage transformers

The CTs (current transformers) and VTs (voltage transformers) are provided in the plants to:
- **reduce the voltage and current values of the plant to values such as to be able to be detected by measurement and protection apparatus;**
- **make the secondary measurement and protection circuits galvanically independent in relation to the primary power circuit, at the same time guaranteeing greater safety for operators (a point of the secondary winding of the instrument transformer must always be connected to ground).**

For correct identification and removal of the fault it is necessary for all the components to operate correctly. In particular, all the apparatus which contributes to carrying out the measurement (CTs, VTs and relays) must provide an indication coherent with the primary network parameters, and the actuators (operating parts) must operate correctly to interrupt the circuit and eliminate the fault.
The transducers, CTs and VTs, represent an extremely important element in the protection chain and inadequate selection of their respective characteristics can lead to inadequate protection of the network and machines or to unwanted trips (which in many cases are even more damaging).
The instrumentation which is installed in the plants is generally of electronic or digital type which has reduced consumption on the secondary of the measurement transducers, CTs and VTs (in general less than or equal to 0.5 VA, unlike the old electromechanical apparatus which had consumptions of several VA (e.g. 5-10 VA per phase).
The presence of digital instruments has also had a significant impact on the current and voltage transformers, leading to CTs and VTs being constructed with different technologies. In practice, since only one signal is required at the CT and VT secondary and no longer a significant power (the power needed to make the protection relay operate is taken from the auxiliary power supply), the use of air transformers (CTs) and voltage dividers (VTs) is becoming increasingly widespread.

4.1 Inductive transformers

The main Standard references for the inductive type of CTs and VTs (with iron laminates) in medium voltage networks are:
- IEC 61869-1: Instrument transformers - General requirements
- IEC 61869-2: Additional requirements for current transformers
- IEC 61869-3: Additional requirements for inductive voltage transformers.

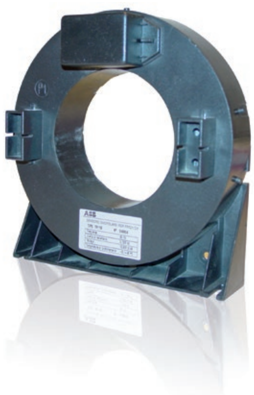
The construction characteristics and definition of the precision classes are given in these Standards.
It must be considered that the precision class for instrument CTs and VTs and protection VT, is a function of the load connected to the secondary: precision is only guaranteed when the secondary load is higher than 25% of the rated performance of the transformer.
Considering the present low consumptions of the apparatus connected to the secondary, it is therefore essential for the performance of the VTs (both of measurement and of protection) as well as of the instrument CTs to be limited to guarantee that the transducer operates in the precision class for which it has been provided.

4.2 Inductive current transformers (CTs)

An important clarification must be made regarding the CTs relative to their construction shape and to the method of measurement. This refers particularly to ring CTs which are CTs to all effects and must be classified as such.

The CT can be of:
- wound type (as CTs inside medium voltage switchgear normally are), with the two terminal clamps of the primary circuit and the two terminal clamps of the secondary circuit taken outside.
  The primary circuit can, in this case, also have a number of turns different from 1;
- busbar bushing type where there is a piece of busbar (normally made of copper) already embedded in resin. In this

case, the terminals of the primary winding are the ends of the busbar, whereas the ends of the secondary winding are taken to external terminals. In any case, the number of primary turns in this case is always 1;
- ring type where the primary is not provided and it will be made up of the conductor which passes through the central hole of the CT. The ends of the secondary winding are taken to two external terminals. In this case the number of primary turns is in any case normally 1 unless the conductor is made to pass several times in the CT. These CTs can also be constructed as the openable type for easier installation in existing plants.



The precision classes are the same for all the types of CTs, and are defined in accordance with the Standard. According to how the CT is inserted in the network, it can carry out very different measurements. In particular:
- the CT which is inserted on just one phase (for example, a ring CT which embraces just one phase) measures line currents (of phase);
- the CT which is inserted on three phases (for example, a ring CT which encloses the conductors of the three phases inside it) measures the vectorial sum of the currents (in reality the sum of the flux) and therefore the homopolar current.

What has previously been underlined is to indicate that regardless of the construction shape, the measurement which is obtained at the secondary of the CT is a function of the way in which it is inserted in the network.
The CTs serve to translate currents from the power circuit to the measurement circuit. They are classified into two types by the Standard:
- Instrument CTs measuring instruments, such as ammeters, watt meters, converters, etc. are connected to;
- Protection CTs to whose secondary the protection relays are connected.

This classification refers to independent measurement and protection systems. Nowadays with digital apparatus (REF 54x Unit), protection and measurement are carried out by the same piece of apparatus and separate inputs (measurement and protection) from CTs with different characteristics are not provided. Consequently, to obtain correct use of the digital relays, the CTs must be chosen with double precision class, for example:

100/1 A - 4 VA - Cl. 0.5 + 5P10

The two precision classes are defined for different ranges of CT operation and can therefore coexist.
In the same way as described for the CTs, the same reasoning can be made for the VTs. Therefore when digital REF 54x type relays are used, foresight lies in selecting VTs with double precision class, for example:

6000:√3 / 100:√3 V - 10 VA - Cl. 0.5 + 3P

4.2.1 Instrument CTs

An essential factor in selecting the instrument CT characteristics is the precision class to be guaranteed for secondary loads 25% higher than the rated performance. When instrumentation was electromechanical, it was therefore logical to purchase CTs with high performances, but nowadays with digital instrumentation it becomes compulsory to purchase CTs with truly limited performances (typically 5 or maximum 10 VA).
The instrument CTs have as their prerogative the characteristic of saturating for currents just a little above the rated primary current to guarantee protection of the instruments (typically able to support a maximum of 20 In for 0.5 seconds) in the case of a short-circuit.
For instrument CTs, in accordance with the Standard, a safety factor (Fs) must therefore be defined so that, for currents higher than Fs x In, the CT is definitely saturated (therefore protecting the secondary circuit).
In actual fact, the CT is not loaded at the secondary with its rated performance but at a lower load. The real safety factor (F’s) is therefore higher than the rated one and a check is essential to guarantee that the instruments connected to the secondary circuit are suitably protected.
The ultimate true safety factor can be calculated using the following relation:

$$F'_S = F_S \cdot \frac{S_{TA} + S_N}{S_{TA} + S_{VERO}}$$

With
F'_S = true safety factor at the actual secondary load;
F_S = CT rated safety factor;
S_N = CT rated load;
S_{CT} = CT self-consumption = $R_{CT} \times I_{2N}^2$;
I_{2N} = CT rated secondary current;
R_{CT} = CT secondary resistance at 75 °C;
S_{TRUE} = true load at CT secondary = $I_{2N}^2 \times (R_{INSTRUMENTS} + R_C)$;
R_C = rexistence of the wiring circuit;
$R_{INSTRUMENTS}$ = load (self-consumption) of the instruments connected to the CT secondary

Two examples can be of help regarding selection of the characteristics of the instrument CT and the errors which are made in the case of oversizing.

Consider a CT with a 100/1 ratio with secondary load made up of an ammeter (0.5 VA self-consumption) and a multi-function converter (0.5 VA self-consumption). 0.1 ohm resistance in the secondary circuit between the CT terminals and the instruments.

Example 1

CT 100/1 A - Cl. 0.5 - 4 VA - F_S = 5 - R_{CT} = 0.8 ohm

The real secondary load is 1.1 VA, i.e. 27.5% of the rated performance, therefore the precision class is guaranteed.

The real safety factor is:

$$F'_S = F_S \cdot \frac{S_{TA} + S_N}{S_{TA} + S_{VERO}} = 5 \cdot \frac{0.8 + 4}{0.8 + 1.1} = 12.6$$

The CT saturates for currents lower than the withstand one of the instruments connected to the secondary and is therefore suitably dimensioned.

Example 2

CT 100/1 A - Cl. 0.5 - 10 VA - F_S = 10 - R_{CT} = 0.8 ohm

The real secondary load is 1.1 VA, i.e. 11.5 % of the rated performance, therefore the precision class is not guaranteed. The real safety factor is:

$$F'_S = F_S \cdot \frac{S_{TA} + S_N}{S_{TA} + S_{VERO}} = 10 \cdot \frac{0.8 + 10}{0.8 + 1.1} = 57$$

The CT saturates for currents higher than the withstand one of the instruments connected to the secondary and therefore in the case of a short-circuit in the network there can be destruction of the instruments and consequent opening of the secondary circuit, with a serious safety hazard for personnel (overvoltages).

It is therefore obvious how every secondary of the instrument CT must be precisely dimensioned so as to avoid serious damage to the plant in the case of a fault and to be able to obtain measurements in the required precision class.

4.2.2 Protection CTs

The CTs which are associated with the protections have the peculiarity of not saturating until protection tripping is guaranteed for the overcurrent short-circuit.
The parameter which defines the value within which the response is linear in protection CTs is the ultimate precision factor (FL), normally equal to 10-15-20 or even higher.

In selection of the protection CT characteristics (performance and ultimate precision factor) the following conditions must be respected:

- the performance of the CT must be higher than the secondary load (relays and cabling);
- the CTs to be associated with the overcurrent protections must not saturate until safe operation is guaranteed. Generally for the ABB relays it can be considered that saturation must take place at least at double the setting value with a minimum of 20 In, but precise values can be found in the catalogues of the various types of relays;
- the CTs to be associated with particular protections, such as differential, distance relays, etc. must have safety factors defined case by case and indicated in the relay catalogues of the relays;
- the CTs must saturate for very high currents to preserve the relay and the secondary circuits in the case of a short-circuit. Typically overcurrent relays have a tolerability of 100 In for 1 second and 250 In peak, but more precise values can be found in the catalogues of the various relays.

The latter condition is generally not highly considered and can be the cause of serious damage to the components if it is not verified.
As for the ultimate safety factor for the instrument CT, the true ultimate precision factor for the protection CT must also be calculated according to the load actually connected to the secondary, and can be calculated using the following relation:

$$F'_L = F_L \cdot \frac{S_{TA} + S_N}{S_{TA} + S_{VERO}}$$

With
- F'_L = true accuracy limit factor at the real secondary load;
- F_L = rated accuracy limit factor of the CT;
- S_N = rated load of the CT;
- S_{CT} = CT self-consumption = $R_{CT} \times I_{2N}^2$;
- I_{2N} = rated current of the CT secondary;
- R_{TA} = resistance of the CT secondary at 75 °C;
- S_{REAL} = true load at the CT secondary = $I_{2N}^2 \times (R_{RELAY'} + R_C)$;
- R_C = resistance of the wiring circuit;
- $R_{RELAY'}$ = load (self-consumption) of the relays connected to the CT.

As for the instrument CT, two examples can be significant for verifying the characteristics of protection CTs.
Consider a CT with a 100/1 ratio with secondary load made up of an overcurrent relay (self-consumption 0.05 VA). Resistance of the secondary circuit between the CT terminals and 0.1 ohm relay, therefore the real secondary load is equal to 0.15 VA.

Example 1

CT 100/1 A – 4 VA – 5P10 - R_{CT}= 0.8 ohm

4. Current and voltage transformers

The ultimate real precision factor is:

$$F'_L = F_L \cdot \frac{S_{TA} + S_N}{S_{TA} + S_{VERO}} = 10 \cdot \frac{0.8 + 4}{0.8 + 0.15} = 50.5$$

The CT saturates for sufficiently high current for an overcurrent protection (maximum relay setting, in general not higher than 20 In). The relay and the whole secondary circuit (terminals and wiring) are adequately protected against very high short-circuit.

Example 2

CT 100/1 A – 10 VA – 5P20 - R_{CT} = 0.8 ohm

The ultimate real precision factor is:

$$F'_L = F_L \cdot \frac{S_{TA} + S_N}{S_{TA} + S_{VERO}} = 20 \cdot \frac{0.8 + 10}{0.8 + 0.15} = 227$$

If the CT is inserted in a circuit in which the short-circuit current is high (for example a 31.5 kA switchgear), in the case of a short-circuit instead of tripping of the protection due to the opening command of the circuit-breaker, there is probably destruction of the relay with the consequences which can be imagined.
It is therefore obvious how every secondary must be precisely calculated for the protection CTs as well, so as to avoid serious damage to the plant in the case of a fault and to be able to guarantee the safe protection of the subtended part of the network.

4.3 Inductive voltage transformers (VT)

For voltage transformers, both for measurement instruments and for protection relays, the same rule as the one for the instrument CT is valid regarding the range within which the precision class is guaranteed: the precision class is only guaranteed if the secondary load is 25%higher than the rated performance.
It is not easy to manage to ensure that a VT operates in the precision class when an instrument is connected to the secondary (relay or measurement instrument) which has a self-consumption of fractions of VA.
The use of ballast loads (resistances) to be inserted on the secondary of the VT when these have been chosen with performances which are too high to be able to guarantee the precision class, presents two problems:
– an element is added to the circuit (which can also be for protection) which can break down and therefore reduce the overall reliability of the system;
– a heating element is introduced in the instrument compartments of the switchgear with obvious problems for extracting the heat.

When selecting the VT, any ferroresonance must be taken into account. The ferroresonance phenomenon is a typical aspect of VTs inserted in cable networks with isolated neutral or not

efficiently grounded. The cable capacity, together with the VT inductance, makes up an oscillating circuit (R L C). The conditions for which the circuit itself goes into resonance can therefore occur on the circuit (capacitive reactance = inductive reactance saturates the VT) and, although the cause of the saturation ceases (for example, an ground fault), a transient oscillation remains (i.e. a multiple frequency of that of the network) of reactive energy put into play by the components of the oscillating circuit. Owing to the frequency of this oscillation, a permanent and high circulation of current is produced just in the primary winding. Since this current is only magnetising, the secondary winding is little involved, so there is a lot of heating at the primary and negligible heating on the secondary. Abnormal heating of the windings always produces a strong internal pressure, consequently breaking the external housing.
The measures taken to prevent ferroresonance phenomena are mainly to:
– increase the magnetisation impedance of the VT;
– use VTs which work with lower induction than the predicted one;
– use VTs with high permeability iron;
– insert damping resistances (or, in any case, devices with non-linear resistance) in series with the secondary windings connected with open delta (the voltage relay must be connected in parallel with the anti-ferroresonance resistance).

In the past, a secondary set of three VTs connected with open delta was used to measure the homopolar voltages (needed to identify the ground faults). In modern digital apparatus (REF 54. type relay), it is no longer necessary to provide this secondary of the VTs since the homopolar voltage (vectorial sum of the three phase voltages) is calculated inside the relay itself (the signal which comes from the secondary with open delta is often less precise).

Combined current – voltage sensors

4.4 Non-inductive current and voltage sensors

Since the power aborbed by the devices connected to the secondary circuit is extremely limited, it is no longer necessary to have magnetic circuits for the coupling between the primary and secondary circuit. Current sensors or air CTs (Rogowsky coils) and voltage sensors (voltage dividers) have therefore been developed, which eliminate the negative aspects of the inductive type of transformers (hysteresis cycle). Particular reference is made to:
– saturation: the saturation phenomenon does not exist with current sensors (there is no iron) and therefore definition of the ultimate precision factor is no longer a problem;
– performance: the previous examples showed how difficult it is to reconcile the performance of the instrument transformers with the loads connected to the secondary. In fact, the need to have at least 25% of load to guarantee precision is no longer a problem;
– rated primary currents and voltages: the linearity of response allows 95% of the applications to be covered with just two or three types of transducers, with considerable advantages for standardisation of the switchgear compartments and the possibility of their rapid re-conversion;
– there is no longer the need to have instrument CTs or VTs and/or Protection CTs or VTs since precision is constant and there is no longer the problem of saturation.

The reference Standards for the current and voltage sensors are:
– IEC 61869-6: Additional general requirement for low-power instrument transformers;
– IEC 60044-8: Electronic current transformers;
– IEC 60044-7: Electronic voltage transformers.

For current sensors or air CTs, the main characteristic is that these are transformers whose magnetic circuit is replaced by air. A peculiar fact about these types of CTs is that the secondary signal is not proportional to the primary size, but to its derivative (which, when suitably integrated in the devices connected to the secondary, allows current measurement to be obtained). As already pointed out, there are no saturation phenomena, but as a negative aspect there generally the precision class, which in present-day design does not reach the characteristics which can be had for the inductive type of instrument CTs.
The main characteristic for the voltage sensors is the lack of ferroresonance phenomenon (obviously because there is no longer any iron).
This is not a negligible advantage where there is still the use of networks run with isolated neutral. As for air CTs, in the current state of technology, the precision class of voltage dividers (VTs) does not yet reach that of the inductive type of VTs either.

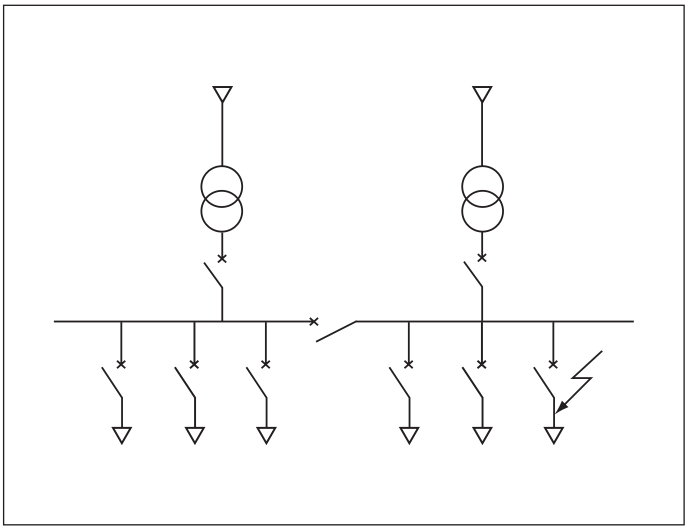
5. Short-circuit

Short-circuit

Accidental or intentional contact, with relatively low resistance or impedance, between two or more points at different voltages in a circuit.

Short-circuit current

Overcurrent resulting from a short-circuit due to a fault or to incorrect connection of an electric circuit.



From the theoretical point of view, calculation of the short-circuit currents should be processed using the data obtained from studying the voltage profiles. In reality, the Standards envisage that the calculation be made at the rated plant values and appropriate correction coefficients are introduced for compensation (voltage factor ‘c’).
It is necessary to calculate the short-circuit currents to:

- establish adequate sizing of the operating and interruption parts;
- define the thermal and mechanical stresses of the plant elements;
- calculate and select the protection system settings;
- carry out suitable protection for people and the plants.

When studying electric networks it is important to define the short-circuit currents under the various different operating conditions. In particular the maximum short-circuit currents are important for sizing the apparatus, the minimum short-circuit currents allow protection coordination to be checked: the protection trip current must always be lower than the minimum short-circuit current at the point of connection.
It must be remembered that a short-circuit causes passage of currents through the accidental or intentional connection making up the short-circuit itself and through the various components as far as the source, and is therefore a potential cause of damage and fires.

The reference Standards for calculation of the short-circuit currents are:

- IEC 60909-0 2016: Short-circuit currents in three-phase a.c. systems - Part 0: Calculation of currents
- IEC 61363-1 1998: Electrical installations of ships and mobile and fixed off shore units – Part 1: procedure for calculating short-circuit currents in the three-phase a.c.

The IEC 61363-1 Standard is for naval plants, but provides a calculation method which is well suited to small networks supplied by generators since it provides calculation of the short-circuit currents over time, taking into account the time constants of the rotating machines (motors and generators).

The IEC 60909 Standard provides some basic hypotheses on development of the calculation:

1) for the duration of the short circuit there is no change in the type of short circuit involved, that is, a three-phase short-circuits remain three-phase and a line-to-earth short circuit remains line-to-earth during the time of short circuit;
2) for the duration of the short circuit, there is no change in the network involved;
3) the impedance of the transformers is referred to the tap-changer in main position. This is admissible, because the impedance correction factor KT for network transformer is introduced;
4) the arc resistance is not taken into account;
5) all line capacitances and shunt admittances and non-rotating loads, except those of the zero-sequence systems, are neglected.

The relation the IEC 60909 Standard calculates the short-circuit current with is:

$$I = \frac{c \cdot Un}{\sqrt{3} \cdot Z}$$

The ‘c’ parameter, called voltage factor, takes on different values (in the range 0.95-1.1) according to the voltage value of the fault point and to the type of calculation (maximum short-circuit or minimum short-circuit).

5. Short-circuit

The Standard justifies introduction of the voltage factor for:

1) the variations in voltage in space and in time;
2) the variations in the sockets of the transformers;
3) not taking into account the loads and capacity in the calculations;
4) taking into account the subtransient behaviour of the alternators and motors.

The c x Un result must not in any case exceed the maximum voltage of the network apparatus.
There are different types of fault which occur in a three-phase system:

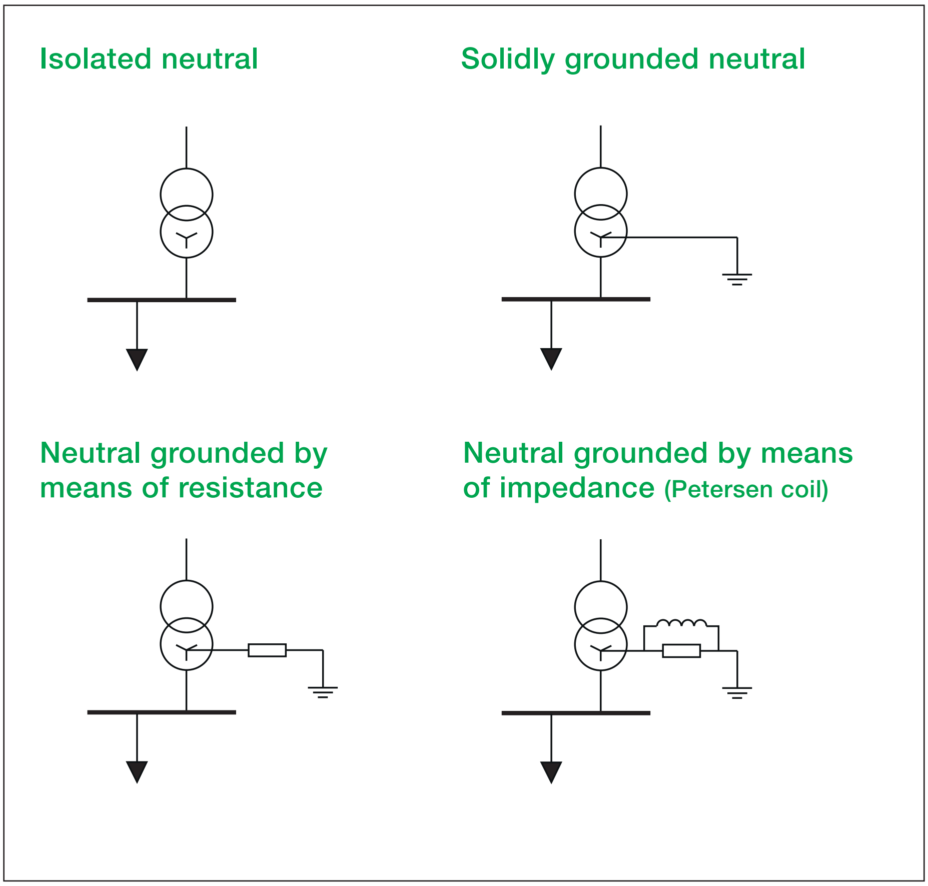
– Three-phase short-circuit (only the phases are short-circuited with each other);
– Two-phase short-circuit (only two phases are short-circuited with each other);
– Two-phase short -circuit to ground (two phases and ground are short-circuited with each other);
– Single-phase short-circuit to ground (short-circuited between one phase and ground).

There are different statistics regarding the percentage of the various types of fault which show how in general more than 80% start as a single-phase fault to ground. This situation must be kept in evidence when the protection system of a plant is studied and designed: managing to identify (and possibly eliminate) a ground fault rapidly and selectively allows it to be prevented from evolving into two-three-phase faults with much greater damage and loss of service.
When the calculation of the short-circuit currents is developed, one tends to examine the case where there are the maximum fault currents (and this check is in actual fact very important for sizing the plant components). On the other hand, when one analyses the protection system, it is important to know the minimum short-circuit currents and in even more detail the currents in the various branches and not on the switchgear busbars. In fact, the overcurrent protections are connected to the lines and therefore it is precisely the minimum short-circuit current of each branch which must be used as the reference to define the protection system setting.
It must be remembered that the protection system is truly such when a protection has been installed and is correctly set. An overcurrent protection set to 10 kA when there is a short-circuit current of 8 kA in the branch it is connected to, is a relay but it is not the protection of the plant.
A further aspect to consider when calculating short-circuit currents is the contribution of motors. This datum is essential for sizing the apparatus, but it must be taken into account that for three-phase faults the contribution dies out after a few cycles, whereas for two-phase type faults the motors continue to sustain the fault (even with lower currents than those contributed for three-phase faults).

6. Status of the neutral

To identify ground faults in a network and therefore carry out effective protection, it is necessary to know in detail how the neutral is run. Identification of ground faults is made by means of voltage and/or homopolar current measurements and therefore knowing the existence and order of these parameters is fundamental in being able to select and set the protection system.

Unlike the protections against overload or polyphase short-circuit, no signal (voltage or current) normally comes to the protections which have to identify ground faults, but, on the other hand, only comes when there is a ground fault in the network. This condition makes the protection system to be provided very simple, generally only requiring one threshold (voltage and/or current) with relatively short trip times.
By analysing the various types of status of the neutral, the types of protections which can be associated can be defined.



6.1 Isolated neutral

In networks with isolated neutral, no circulation of homopolar current is generated deliberately (by means of grounding systems) in the case of a fault between a phase and ground. However, there is a circulation of homopolar current in the plant linked to the phase ground capacities of the machines and cables (for what regards the transformers, the phase to ground capacities are very small and they can be overlooked). The difficulty (in any set-up the network may be found to run in) of being able to identify ground faults using selective protections which measure the fault current can be deduced from this. The only way to be able to ensure identification of the fault is measurement of the homopolar voltage (voltage normally equal to zero in the absence of a fault and different from zero only in the presence of a phase to ground fault). Unfortunately the voltage homopolar protection (like all voltage protections for that matter) is not of the selective type, i.e. it is not able to identify the position of the fault, but is only able to indicate that there is a fault in the network without specifying its position.

Homopolar current, homopolar voltage and angle between voltage and homopolar current in a network are:

- homopolar current only from capacitive contribution (operation of the metallically interconnected network) of variable value in any case and, in general, not guaranteed for all the conditions the network can be run in. Identification of the faults is not always certain by means of homopolar current measurements;
- homopolar voltage always present in the case of a ground fault. It is therefore definite identification but with uncertainty linked to the position of the fault since the voltmetric signal is practically the same for the whole network and does not allow selective identification;
- angle between voltage and homopolar current: the current is in advance by 90° compared with the voltage (capacitive type of network).

6. Status of the neutral

6.2 Solidly grounded neutral

With solidly grounded neutral, the single-phase to ground fault current is in the same order of size as the short-circuit current for polyphase faults. Consequently simple and selective identification of the faults by means of protections which measure the homopolar current is possible (or the homopolar protection could even be omitted and only the phase protection used).
Homopolar current, homopolar voltage and angle between voltage and homopolar current in the network are:

- homopolar current of high value. Therefore identification of the faults by means of measuring the current is always certain and of selective type (the part of the network seat of the fault can be identified correctly);
- homopolar voltage: if this voltage is measured between star point and ground, the voltage is nil, whereas, if the vectorial sum of the three phase voltages is measured, this is different from zero and gives indication of a fault in the network (but not of selective type);
- angle between voltage and homopolar current: the current is late (typical values 75-85°) compared to the voltage (inductive type of network source).

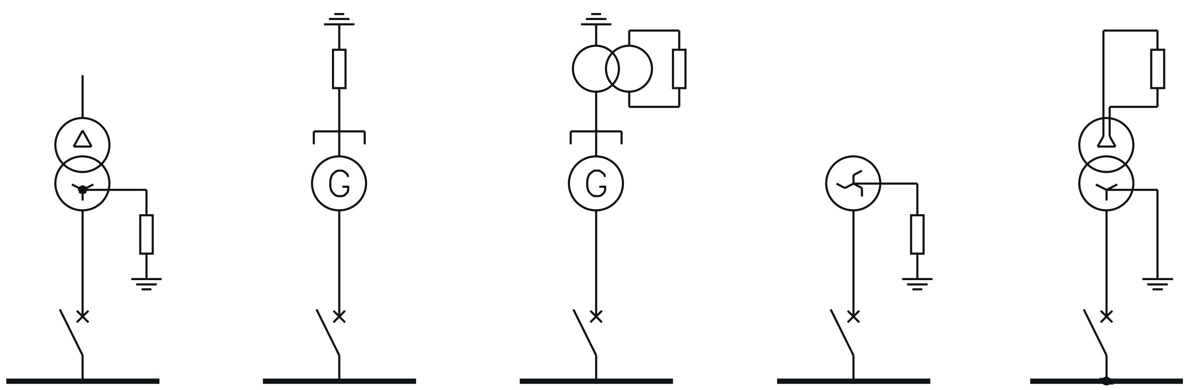
6.3 Neutral grounded by means of resistance

Grounding the neutral by means of resistance allows a definite current to be obtained in the case of a fault and consequently to be able to carry out selective protection of the network. Depending on the value of the resistance installed, fault current values which are higher or less high are obtained, but:

- the lower the fault current is, the small the damage to the machines is;
- the higher the fault current is, the more easily the fault is identified (and the protection with lower sensitivity is required).

Homopolar current, homopolar voltage and angle between voltage and homopolar current in the network are:

- homopolar current of known value. Identification of the faults is possible by measuring the homopolar current. The protection is therefore of the selective type;
- homopolar voltage: if this voltage is measured between the star point and ground, the voltage varies according to the value of the grounding resistance (for grounding resistances of high value one falls back into the situation of isolated neutral, for grounding resistances of very small value, one falls back into the situation of solidly grounded neutral). If the vectorial sum of the three phase voltages is measured, it is different from zero and gives indication of a fault in the network (but not of the selective type);
- angle between voltage and homopolar current: theoretically equal to zero (in phase). In reality, the angle is in



Direct connection to the real star point.

Direct connection to the real star point.

Connection to the real star point by means of a single-phase power transformer.

Direct connection to the artificial star point, in the case of non-accessible neutral, of a zig-zag reactance.

Indirect connection with a three-phase transformer star primary connected to ground and open delta secondary loaded with a resistance.

any case capacitive for the contribution of the to ground capacity of the network.

There are various methods to create network grounding according to the availability or lack thereof of the star point as shown in the figure.

6.4 Neutral grounded by means of impedance (Petersen coil)

Grounding the neutral by means of impedance allows the network capacitive currents to be compensated and therefore to reduce the current to relatively small values in the case of a fault (in Italy, utilities limit the fault current to 40-50 A) and with a fault angle about equal to zero (compensated network).
Homopolar current, homopolar voltage and angle between voltage and homopolar current in network are:

- homopolar current of known value. Identification of the faults by means of homopolar current measurement is possible. The protection is therefore of the selective type;
- homopolar voltage: the measurement of the vectorial sum of the three phase voltages is different from zero and gives indication of a fault in the network (but not of the selective type).
- angle between homopolar voltage and current: theoretically equal to zero (network tuned). In actual fact, the angle can in any case diverge slightly both in advance and delayed according to the setting of the compensation reactance and to changes in the network set-up.

6.5 Measurement of the ground fault current and identification of the faulted phase

Since the advent, first of electronic and then of digital protections which have low absorption on the current circuit, the use of ring type CTs has been possible (able to generally give very small performances), which allows the vectorial sum of flux to be measured instead of the vectorial sum of the three currents (residual connection).
When a homopolar overcurrent protection is connected to the residual connection of the phase CTs (Holmgreen connection) it performs a vectorial sum of the currents and the resultant is therefore affected by the aperiodic components linked to magnetisation of the transformers or to motor starting. In this case, very conservative settings of the protections are required and the stability of these is not normally guaranteed (risk of unwanted trips).
It is therefore suggested to systematically use (obviously where possible) CTs of ring type associated with the homopolar overcurrent protection.
In the case where it is necessary to identify which of the phases is the seat of the ground fault, identification is possible using undervoltage protections with measurement for each independent phase connected between the phase to ground (obviously to the VT secondary).

7. Protection relay codes

Numerical codes are sometimes used when defining the protection relay, whereas in other cases symbols are used. The numerical codes refer to the IEEE C37-2 Standard, whereas the symbols refer to the IEC Standards. In the definition of the symbols the IEC Standards have not detailed all the symbols to be used and so in practice one still uses the codes mentioned in IEEE C37-2.

An extract of the numerical codes is given below, as given in the IEEE Std C37.2-2008 Standard: IEEE Standard for Electrical Power System Device Function Numbers, Acronyms, and Contact Designation relative to protection systems. The description is a summary of what is given in the Standard:

- 2 starting timer;
- 21 distance relay (impedance);
- 24 overfluxing relay (volts per hertz);
- 25 synchronizer or synchronism verifier;
- 26 apparatus for temperature control;
- 27 undervoltage relay;
- 32 directional power relay;
- 37 undercurrent or under-power relay;
- 40 loss of field relay;
- 46 negative sequence relay or for current balance by means of current measurement;
- 47 cyclic sequence relay by means of voltage measurement;
- 48 incomplete sequence relay;
- 49 thermal relay for transformers or machines;
- 50 instantaneous overcurrent relay;
- 51 overcurrent relay with inverse time;
- 55 power factor control relay;
- 59 overvoltage relay;
- 60 voltage balance relay;
- 62 stop timer;
- 63 pressure sensor;
- 64 relay to identify ground faults (not used for networks with grounded neutral);
- 66 apparatus which detects a certain number of operations;
- 67 directional overcurrent relay for alternating current;
- 68 locking relay (for example to prevent reclosing after loss of step);
- 74 alarm relay;
- 76 overcurrent relay for direct current;
- 78 loss of step relay or for measurement of phase angle;
- 79 reclosing relay for alternating current;
- 81 frequency relay;
- 82 reclosing relay for direct current;
- 83 automatic changeover relay of for selective control;
- 85 pilot wire relay;
- 86 look-out relay;
- 87 differential relay;
- 90 regulator device;
- 91 directional voltage relay;
- 92 directional power voltage relay;
- 94 trip relay.

The meaning of the codes used most frequently is given in more detail since they are often the cause of misinterpretations and misunderstandings.

code 48: is a little known code which is, however, now commonly used to indicate the protection against prolonged motor starts. Sometimes it is confused with the protection called 51LR ('locked rotor' overcurrent). There are two codes to be used to indicate the protections which serve to control motor starting and locked rotor: 48 for the starting phase (prolonged starting) and 51LR for the locked rotor (when the motor is already running);

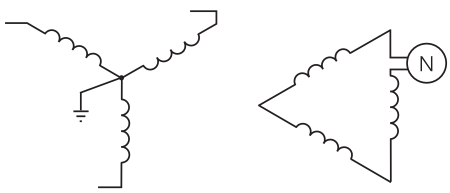
– code 50: for the Standard this is an overcurrent protection of instantaneous type. The definition of instantaneous relay was valid for the electromechanical, now the various thresholds of the overcurrent relays always have the possibility of introducing a delay. In common practice it is considered to be the overcurrent protection which identifies strong currents typical of short-circuit;

– code 51: for the Standard this is an overcurrent protection of the dependent (inverse) time type. The definition of a relay with inverse time is typical of American tradition. In common practice code 51 is used both for overcurrent relay with dependent (inverse) time characteristic and with independent (definite) time characteristic. In general it is considered the overcurrent protection which identifies weak currents typical of an overload or of short-circuits with high fault impedance.

Further clarifications are necessary in defining the numerical codes to be used for the protections against ground faults. The C37-2 Standard only specifies a code to be used for ground faults: 64, but specifies that this code cannot be used for the protections connected to the CT secondary in grounded networks where code 51 must by used with suffixes N or G.

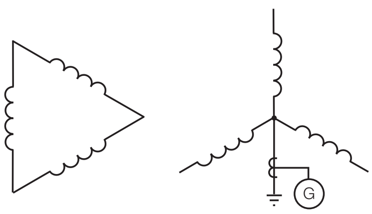
In defining the N and G suffixes, the C37-2 Standard is very clear and they are used as follows:

- N when the protection is connected by means of transducers which measure the phase parameters and the vectorial sum of the parameter to be measured (current or voltage) is sent to the relay. This connection is generally called residual connection (Holmgreen);

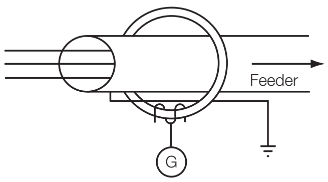


Open triangle in the VT secondary circuit

- G when the protection is connected directly to the secondary of a transducer (CT or VT) which measures the homopolar parameter directly (current or voltage);



Triangle-star transformer



Zero sequence current toroidal transformer, with connected three-phase cable screen

Therefore it is correct to use the following definitions for protection against ground fault:

- 51G for the overcurrent protection connected to the secondary of a ring CT which measures the ground current;
- 51G for the homopolar overcurrent protection connected to the secondary of a CT positioned on the grounding of the machine (star point generator or transformer);
- 51N for the homopolar overcurrent protection connected with residual connection to three phase CTs;
- 59N for the homopolar overvoltage protection connected on the vectorial sum of the three phase VTs (open delta - residual voltage);
- 59G homopolar overvoltage protection connected to the VT secondary positioned on the machine grounding (star point generator or transformer);
- 64 only applicable in networks with isolated neutral both for overcurrent and overvoltage protection.

Apart from the N and G suffixes, sometimes other suffixes are added to indicate the application of the protection in detail. For example:

- G generator (for example 87G differential protection for generator);
- T transformer (for example 87T differential protection for transformer);
- M motor (for example 87M differential protection for motor);
- P pilot (for example 87P differential protection with pilot wire);
- S stator (for example 51S overcurrent stator);
- LR motor protection against locked running rotor (51LR);
- BF failed opening circuit-breaker 50 BF (BF = breaker failure);
- R used for different applications:
  - reactance (for example 87R differential protection);
  - undervoltage to indicate residual voltage (27R);
  - rotor of a synchronous machine (64R ground rotor);
- V associated with the overcurrent protection (51) it indicates that there is voltage control or voltage restraint (51V);
- t indicates that the protection is timed (for example 50t protection against overcurrent short-circuit with delay added).

8. Philosophy of protection settings

The objectives of the protection system are to:

- **limit damage to people and to the plant;**
- **permit different service conditions;**
- **guarantee maximum service continuity for the plant not affected by faults;**
- **activate the automatisms provided.**

The peculiar characteristics of the protection system of an electric network are:

- dependence: it can be called on to work after either a short or long period after installation. In any case, it must work when it is called on to operate;
- safety: it must not operate when is not required (it must not operate during transients). It must allow the various service conditions and activate the automatisms provided;
- selectivity: it must operate only and when necessary, guaranteeing maximum service continuity with minimum disconnection of the network;
- speed: represented by the minimum fault time and by damage to the machinery;
- simplicity: measured by the number of pieces of equipment needed to protect the network;
- economy: assessed as the cost of the protection system in relation to the cost of malfunctioning.

The protection system is the ensemble of the instrument transformers and the relays with adequate settings. The relay is only one of the components making up the protection system.
Selection of the type of function and of the functions required to adequately protect a machine or a plant must be made on the basis of:

- Standards;
- interface with the external network;
- acceptable risk (consequences of the fault);
- short-circuit currents (maximum and minimum);
- status of the neutral;
- presence of self-production in plant;
- coordination with the existing system;
- configurations and network running criteria;
- practices.

The aim is to achieve the best technical-economic compromise which allows adequate protection against "faults" with "significant" probability and to verify that the investment is commensurate with the importance of the plant.
The electric protections are of different types and have different applications:

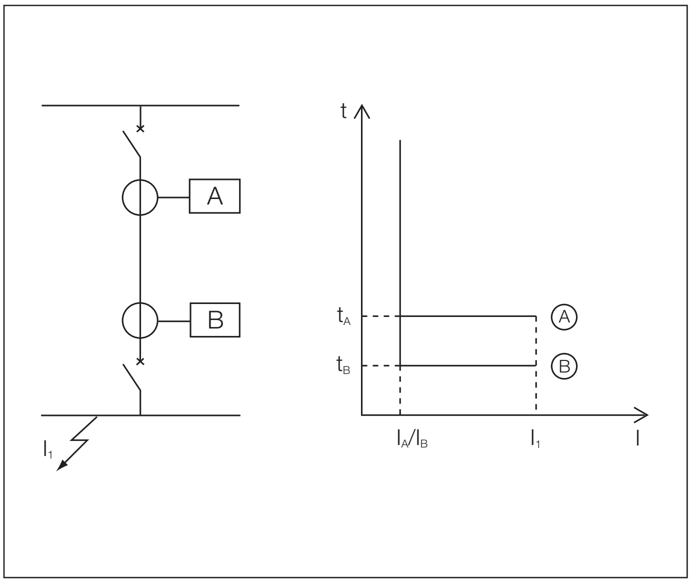
- zone protections (e.g. differential or with impedance);
- machine protections (e.g. reverse power);
- selective protections (e.g. overcurrent);
- non-selective protections (e.g. undervoltage, frequency);
- protections in support (e.g. fuses, overcurrent, undervoltage);
- interface protections (e.g. undervoltage protections; under/over and rate of change of frequency; overcurrent for disconnection between the plant network and the utility network);
- protections for making automatisms (e.g. synchronism check).

The criterion which is followed when the setting of a protection is calculated is to efficaciously protect the machine or plant and then look for trip selectivity. Trip selectivity means isolating the smallest area of plant in the case of a fault in the shortest time possible (selectivity) and then to ensure a reserve (back-up) in the case of failure of the primary protection.
There are various different selectivity criteria which can be used in plants.

8.1 Time selectivity

Time type of selectivity is obtained by graduating the trip times of the protections (time discrimination or time selectivity) so that the relay closest to the fault trips in a shorter time compared to the ones further away.
The protection settings are calculated assigning increasing times starting from the user as far as the energy sources.
With this criterion only the part of plant affected by the fault is eliminated. This criterion has the serious disadvantage that the times for eliminating the fault cannot in any case be too long because:

- the materials do not support faults for long times;
- in the presence of a short-circuit there is a voltage drop (with, for example, consequent possible stoppage of low voltage loads due to de-excitation of the contactors);
- the longer the short-circuit remains supplied, the greater the damage created at the point of the fault is (with serious consequences as well, such as fires, etc.).



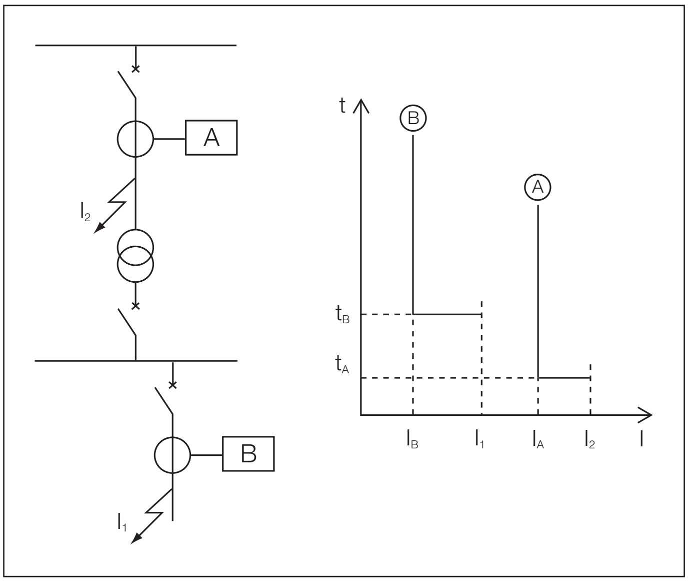
With regard to time graduation, this must take into account the characteristics of the apparatus present in the plant, and in the specific case of the medium voltage networks:

- opening time of the medium voltage circuit-breakers: ≈ 60 ms;
- inertia time of the protections: ≈ 20 ms;
- maximum timed trip error: ≈ 60 ms;
- safety margin: ≈ 50-100 ms;

from which a graduation of about 200-250 ms between two protections in series is necessary.

8.2 Current selectivity

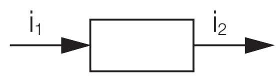
Current type of selectivity is obtained by graduating the trip threshold of the protections to current values higher than those which can involve the load side protections (current discrimination or current selectivity).
This can easily be made when an impedance of significant (typically a transformer or a reactance) is provided between two protections in series.
Current selectivity between the two protections is calculated by setting the supply side protection over the overcurrent which may involve the load side protection.
With this setting it is not necessary to introduce delay times between the two protections, and the supply side protection can be of instantaneous type since it only trips for faults in the part of plant included between the two protections.



8. Philosophy of protection settings

8.3 Differential protection and distance protection selectivity

This kind of selectivity exploits the first law of Kirchoff at the node, i.e. the sum of the currents in a node must be equal to zero, if the summation of the currents is different from zero it means there is a fault.
The most well-known application is with the differential relays (of transformer, generator, cable, motor, busbar, etc.).
With this criterion, the protection only identifies faults inside the component which is entrusted to it and consequently no selectivity control with other protections in the network is necessary and the trip can be of instantaneous type.
This selectivity criterion finds full application in high voltage as well, in setting the under-impedance (or distance) protections which only identify faults in the area of their competence.

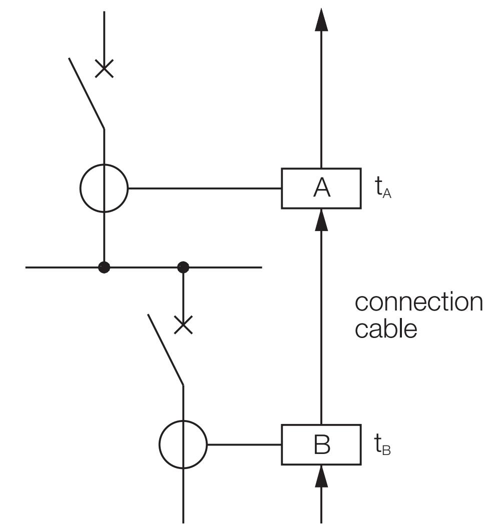


$\sum (i_1 - i_2) = 0$ the protection does not trip

$\sum (i_1 - i_2) \neq 0$ the protection trips

8.4 Logical selectivity

Logical selectivity, also known as zone selectivity, is a selectivity criterion which was only introduced recently with the advent of digital protections. This selectivity criterion can be applied both to the overcurrent protections which identify phase faults, and to the overcurrent protections which identify gound faults.
The trip logic of the protections foresees that each protection involved in the fault sends a locking signal to the protection/s placed immediately to the supply side, preventing tripping.
The protection closest to the fault is not locked by any load side protection and consequently on expiry of its own trip time it commands opening of the switching part, isolating the fault selectively.



Logical type selectivity allows trip times to be reduced and full selectivity to be obtained in any case. The protections must be interconnected to allow the changeover of locks and consents (by means of pilot conductors and not by means of supervision systems which have incompatible response times) to allow correct operation. If the protections were not interconnected, there would be rapid tripping of all the protections run through by the fault current.
To guarantee correct operation of logical selectivity between the protections, it is necessary to introduce a short time delay to allow the protections the correct changeover (sending and/or acquisition) of the locking signals.
In general, when logical selectivity is active, other overcurrent, phase and ground thresholds not subject to logical locks are also provided in back-up.

8.5 Study of protection coordination

Installing protections in a network and not setting them suitably is the same as not installing the protection system. The protection system is really only such if the protection functions necessary are provided and these are suitably set.
The protection coordination study or selectivity study has the following objective: to ensure that in the case of a fault or overload in a component the electric network, it is only and exclusively that component which is eliminated from service and not other machines or parts of the plant.
The protection coordination study basically consists of setting tables for the protections and selectivity diagrams (in bilogarithmic scale) where what the trip sequence of the network protections is highlighted for each current value which involves the circuit.
To work out a correct protection coordination study, some fundamental factors must be taken into account, such as:

- the study must be based on the short-circuit currents. It must be remembered that the protection is inserted in a circuit and therefore the current which it can measure is only the one which passes through that circuit (it can be also be much lower than the short-circuit overcurrent of the switchgear the circuit is connected to);
- for ground protections with isolated neutral or grounded by means of a limiting impedance, an independent selectivity diagram must be provided for phase or ground protections. Vice versa, in the case of solidly grounded neutral, since the ground fault current is of the same order size of the polyphase fault current, the selectivity curve of the phase and ground protections must be compared on the same sheet;
- the tolerability of the various components of the plant must be indicated in the selectivity diagrams to check that they are adequately protected. For example, the withstand of the transformers or of the cables;
- where particular service criteria of the plant require it, it is necessary for the trip curves of the voltage relay to be given as well in the selectivity diagrams to demonstrate trip selectivity between current and voltage protections;
- for the direct low voltage protections the trip curves corresponding to the operating times of the protection are given in the selectivity diagrams, which coincide with the circuit-breaker times. For medium or high voltage protections (therefore for indirect relays) the relay trip curves are generally given in the coordination diagrams to which the circuit-breaker operating time is obviously added in order to obtain the total time for eliminating the fault, so the two families of curves are not homogeneous.

Particular attention must paid in the protection coordination study to verifying that the protections do not cause unwanted trips. The latter are, in fact, often more devastating than a normal trip of the protections since, not finding faults in the network the operator does not know how and within what time to resume service.

9. Selection of the protection system for machines and plants

The protection system for a line or a machine must be selected and studied for the application it is destined for and it is not normally possible to define a single solution.

When selecting the protection system several variants come into play, among which:

- type and power of the machine to be protected;
- polyphase short-circuit voltage and current level: in particular, safe protection of the machine must in any case be ensured even with minimum fault currents;
- status of the neutral: as already illustrated, the presence or not of current in the case of a fault and its possible magnitude oblige selection of protection systems completely different from each other;
- service which the machine or industrial process is slave to: for example, the protection applied to two motors with the same power, dedicated to centrifugal pumps, is very different from the case where one machine is dedicated to the fire-fighting system and the other to the normal industrial process;
- function of the protection system: alarm or trip.

The numerical codes of the C37-2 Standard will be used below to indicate the protection functions and consequently make their univocal comprehension simpler.

9.1 Protections for synchronous machines (generators)

Only medium voltage generators are analysed and large machines (above 100 MVA), where selection of the protection system is necessarily made also according to the interface towards the transmission system, are excluded from this description.

The philosophy of protection relays is developed on the basis of knowledge that faults in generators can be divided into two main categories:

a) Abnormal operations and working conditions, such as:
   - overload;
   - over speed or under speed;
   - overvoltage and undervoltage;
   - unbalanced loads;
   - excitation faults (field circuit or voltage regulator);
   - prime motor faults (or of the speed regulator).

b) Insulation faults, such as:
   - ground faults (including rotor faults);
   - phase-phase and three-phase faults;
   - faults between the turns of the same phase.

Identification of the abnormal operating condition is made by protection relays whose setting must keep the machine in service for as long as possible without the risk of damage. The setting value of the protection must be calculated above the transient current, voltage and frequency values and the trip time must be such as to allow re-establishment of the electrical parameters to within the range of normal operating values.

The protections of a synchronous machine can then be divided into the following main sub-groups:

1. main protections or zone protections: these are the protection functions which must operate instantaneously for faults which occur inside the relative zone and must remain stable for external faults (through faults);
2. back-up protections: these are the protection functions which must operate for faults which occur on the load side of their connection point.
   These protection functions must have an intentional delay to allow a selective trip so as to only operate in the faulty zone;
3. protections for abnormal operating and service conditions: these are the protection functions which must operate or prepare an alarm for any abnormal condition which may occur during running. The anomalies are detected by measuring appropriate electric parameters.

The position of the CTs which supply the various protection functions of a generator is not fortuitous: the CTs which supply the various protection functions must be provided on the star point side and not on the line side.

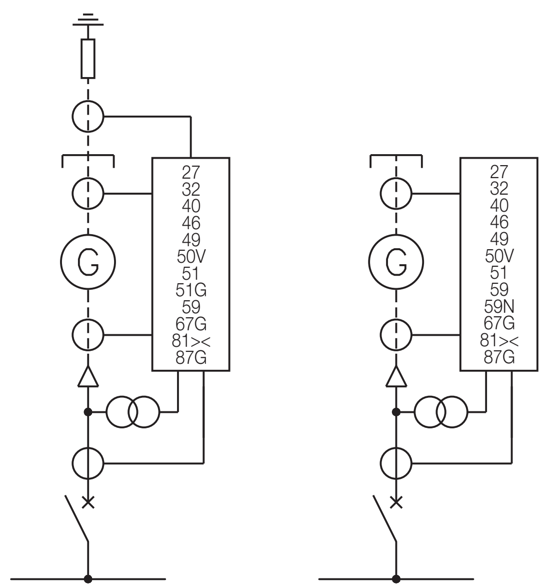
Depending on the rated power of the machine and on the type of application, all or some of the following protection functions can be used to protect the generator:

a	relay 87	differential protection generator (sometimes also called 87G);
b	relay 49	stator overload thermal protection;
c	relay 51	overcurrent protection;
d	relay 40	excitation fault protection (loss of field);
e	relay 32	reverse power protection (return energy);

f relay 46 negative sequence overcurrent protection;
g relay 21 under-impedance protection (as an alternative to overcurrent protection for voltage control when a unit transformer exists);
h relay 50V overcurrent protection with voltage control (as an alternative to protection against under-impedance when there is no unit transformer);
i relay 27 undervoltage protection;
j relay 59 overvoltage protection;
k relay 81 over and underfrequency protection;
l relay 24 overflux protection;
m relay 64R rotor ground protection;
n relay 64S stator ground protection (a function of the type of neutral status).

Other protection functions exist which are used for alternator protection, such as:
– 5 accidental energization;
– 37 underpower relay;
– 49R (51R) rotor overload;
– 60 voltage balance relay;
– 78 out of step relay;
but they are generally used applied to high power machines.

The typical protection functions for alternators are described briefly below and the basic criteria for their application are given.



Generator with grounded neutral

Generator with isolated neutral

9.1.1 '87G' differential protection

The main stator winding protection is entrusted to a differential relay with restraint characteristic. This relay compares the current values at the terminals of each phase of the winding and trips when the differential exceeds the relay setting value. It also ensures protection against phase-phase faults inside the stator winding.
In order to obtain better stability for external faults, the relay is normally of compensated type to increase the trip value in the case of a through fault.
Use of the differential protection can allow identification of ground faults inside of the protected zone as well, but its sensitivity is limited by the value of the ground fault current.

9.1.2 '49' thermal protection against stator overload

All overloads cause abnormal heating conditions of the stator winding which must be eliminated before the temperature reaches dangerous values for the machine. The protections also take into account the thermal condition of the machine before the overload occurs.

9.1.3 '51' overcurrent protection

This protection function is not strictly necessary for alternators since operation under overload also requires the turbine to be able to deliver more power or for the excitation system to be able to increase the field in the machine above the rated value. These conditions are rather difficult to produce and consequently this protection generally operates for external faults and for this reason must be delayed to prevent false trips.

9.1.4 '40' protection against excitation faults (loss of field)

The protection against loss of excitation is entrusted to relay 40 which controls the excitation state at the stator terminals. In practice, this relay measures the current which changes from 'capacitive' to 'inductive' as a consequence of lack of excitation.
Under normal operating conditions, the generator supplies reactive capacitive power and its impedance is therefore of capacitive type (over-excitation of the capacity curve).
When there is loss of excitation, the generator behaves like an asynchronous generator which absorbs reactive power from the network and its impedance is consequently of inductive type (underexcitation of the capacity curve). The setting of the

protection must be calculated not to cause unwanted trips in transient conditions, such as putting the machine in parallel with other sources. It is obvious that the protection only operates when the generator operates in parallel with other sources (or power factor correction banks).

9.1.5 '32' protection against reverse power (return of energy)

When the power source which moves the turbine fails, the generator (with the turbine always connected to the axle) operates like a motor and the active power necessary to keep the machine rotating is taken from the network.
The minimum drawing power required of the network by a coupled generator is a function of the type of turbine and can vary between less than 1% (steam turbine) up to very high values for generators coupled to diesel motors.
Code 32 protection function identifies reverse power, i.e. the flow of active power which goes from the network towards the generator. The protection setting must be calculated not to cause false trips in transient conditions, such as putting into parallel. As for protection against loss of field, it is obvious that the protection only operates when the generator operates in parallel with other sources.

9.1.6 '46' overcurrent protection against negative sequence

Balanced three-phase loads produce a field reaction in the stator which rotates in synchronism with the rotor. When there are unbalanced loads, the negative sequence component in the stator current induces a current in the rotor with double the rated frequency. This current which flows through the rotor winding causes serious heat rises in the rotor.
Unbalanced load conditions can be imposed by the network outside the generator, for example by:
- single-phase loads;
- different impedances between the phases (e.g.: different phase terminal tightening);
- open circuit on a transmission line;
- lack of transposition between the phases;
- faults between the turns;
- fault at a circuit-breaker pole on closing;
- trip of only one phase of a fuse bank;
- prolonged unbalanced operation, such as phase-phase fault or phase to ground fault;
- negative sequence harmonics.

For the reasons indicated, tripping under unbalanced load conditions must be delayed to allow the other plant protections, or the operator, to eliminate the fault selectively.
The protection settings must be calculated so that the time-current trip characteristic is as close as possible to the thermal tolerability curve of the generator and at the permanent limit of tolerability for unbalanced load.

9.1.7 '21' under-impedance protection

This protection is necessary to identify the faults outside the machine and take the generator out of service in the case where they are not eliminated by their own protections. This protection is generally applied to generators with unit transformer. The settings are calculated to identify faults inside the transformer with a first threshold (in short times) and faults in the network on the supply side of the unit transformer with a second threshold (long times).
The protection measures the impedance (ratio V/I) and trips when this is lower than the set values. A relay with circular characteristic with centre in the origin of the R-X plane is generally used for alternator protection.

9.1.8 '50V' overcurrent protection with voltage control

This protection is similar to the under-impedance protection (in some models it measures the V/I ratio) and serves to identify faults outside the generator. The overcurrent threshold varies according to the voltage value (of latching). The more the network voltage is lowered the lower the current trip threshold is. This characteristic prevents the risk of failed operation due to a rapid decrease in the fault current linked to a rapid decrease in the voltage and adds the advantage of making the relay sensitive to normal overload conditions when the voltage is kept at the rated value. Generally, the voltage latching characteristic recommends use of this relay to identify faults when, for any reason, the generator operates without the automatic voltage regulator.
Since this is a back-up protection, it must be coordinated with the other network protections to guarantee selective tripping.

9.1.9 '27' undervoltage protection

This function protects the generator and the users against excessive voltage drops which can occur when large users are started, when the voltage regulator does not work correctly or when there is a voltage drop due to fault not identified by other protections. This relay must be regulated at the minimum value allowed for network operation and with a delay time which allows re-establishment of the transient voltage values originated by these phenomena. The delay time must take the response times of the voltage regulator and excitation circuit into consideration.

9.1.10 '59' overvoltage protection

This function protects generators and users against overvoltages which can occur due to sudden disconnection of the loads or due to a malfunction of the voltage regulator. Generally, the protection is provided with two trip thresholds since it must be extremely rapid for large overvoltages which can cause insulation faults, whereas it must have long times for small overvoltages which can be solved by the voltage regulator.

9.1.11 '81' over- and under-frequency protection

The over- and under- frequency relay is used to identify variations in frequency generated by load fluctuations or bad operation of the speed regulator of the prime motor.
The relay setting threshold must be calculated to allow transient situations to be overcome and prevent damage to the turbine-generator unit. The threshold setting must be calculated at a frequency level equivalent to the maximum/minimum speed tolerated by the turbine and generator with continuity or for short periods (regulation is possible using several frequency thresholds).

9.1.12 '24' overflux protection

This protection function measures the voltage/frequency ratio (V/f) and allows monitoring so that the magnetic circuit does not go into saturation. The result of an overflow condition is heating of the machine with consequent reduction in life, therefore the characteristic normally used is of thermal type (with inverse time). Attention must be paid to the setting since at rated frequency, this protection operates exactly like an overvoltage protection with which it must therefore be coordinated.

9.1.13 '64R' protection against rotor ground fault

The field circuit of an alternator is generally isolated from ground. Therefore in the presence of an initial ground fault it is not necessary to stop the generator and just an alarm is possible. To be able to monitor the field circuit, it must be possible to overlay a low frequency signal (typically about 20 Hz) on the direct current circuit which, when suitably monitored, allows the level of machine insulation to be shown. The protection is therefore associated with a generator at low frequency to form a single measuring system.

9. Selection of the protection system for machines and plants

9.1.14 '64S' protection against stator ground fault

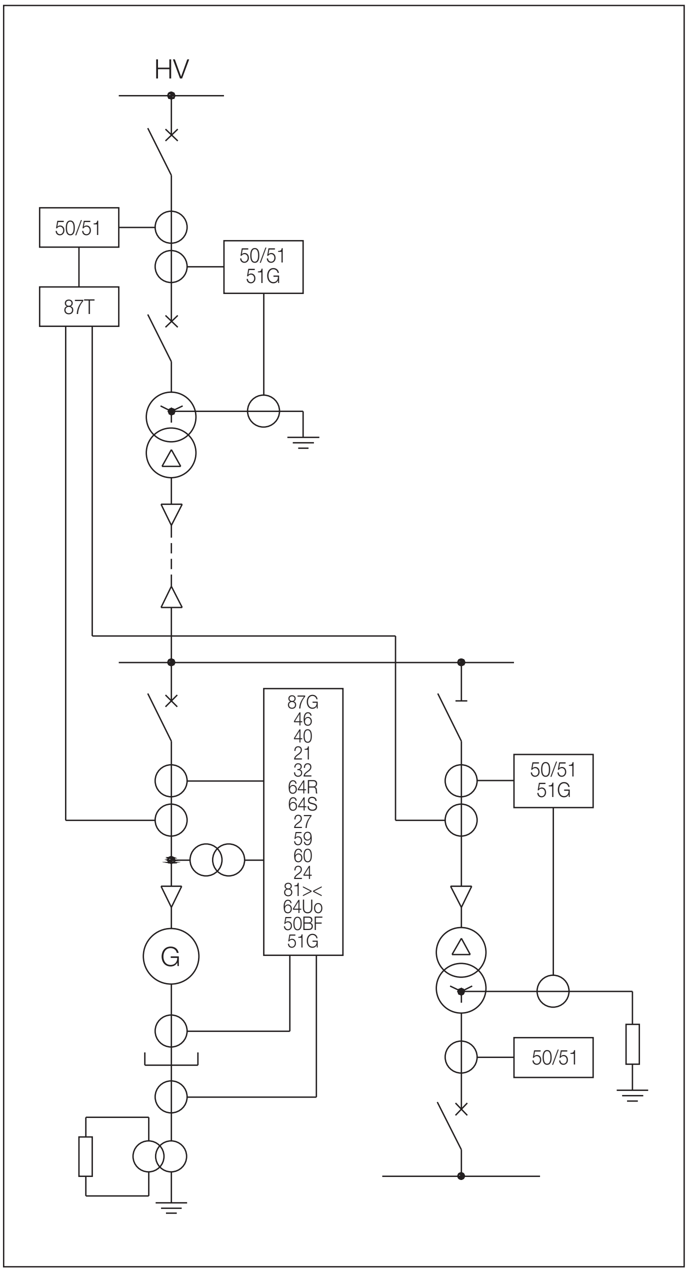
Identification of ground faults in a generator is a function of the way in which the neutral is run. In medium voltage generators there are practically only two types:

- isolated neutral;
- neutral grounded by a resistance and fault current value generally a few Amperes (typically 5-10 A).

For networks with isolated neutral, a homopolar overvoltage protection must be provided which is the only one to ensure a definite identification of the fault. Associated with this protection (if there is a minimum of capacitive current in the network) is directional homopolar overcurrent protections are installed which only and exclusively operate for faults inside the machine, allowing selective identification of the fault.
For networks with neutral grounded by means of resistance (typically on the star point of the alternator), it is necessary to provide a protection on the grounding (either voltage or current) and, furthermore, in the case where there are several grounding in the network at the same voltage level (metallically interconnected networks), it is necessary to provide a directional ground overcurrent protection on the line side (MV compartment) as well, with trip direction from the network towards the generator. The directional overcurrent protection (67G) only identifies ground faults in the generator and is therefore the first step in selectivity also being able to turn out very rapid.
On the other hand, the protection on the grounding (star point) (51G) identifies faults in any point of the network and therefore represents the last step of selectivity and must be delayed.

9.1.15 Protection trip matrix

It is not sufficient to provide protections to guarantee safety and a high level of service continuity in the plant, but it must also be ensured that the protections operate and act on the most appropriate operating parts. The single-line diagram and table are the example of a generator riser where the protection functions provided are detailed and the example of a possible trip matrix is given, with indications as to the possible actions that the various protection functions must carry out.



Relay code	Relay description	Step	86 GE	86 GI	52	41	152	Turbine stop	Alarm	52-LV
87G	Generator phase differential			X	X	X		X		
46-1	Unbalanced currents	1							X	
46-2		2		X						
40	Loss of field			X						
21-1	Under-impedance	1	X							
21-2		2	X							
32	Reverse power			X						
64S	Stator ground			X						
27	Undervoltage						X			
59-1	Overvoltage	1		X						
59-2		2		X						
24	Overflux	1							X	
		2		X						
81<-1	Under-frequency	1					X			
81<-2		2		X						
81>	Over-frequency			X						
64R-1	Rotor ground	1							X	
64R-2		2		X						
51	Transformer unit overcurrent	1	X							X
50		2	X							X
51G	Transformer unit overcurrent		X							X
64Uo	Homopolar overvoltage						X			X
50BF	Circuit-breaker failure				X		X			X
86GI	Internal fault lock-out relay				X	X		X	X	
86GE	External fault lock-out relay				X	X	X	X	X	
	Auxiliary power supply fault								X	

Relay 60 (VT fault) inhibits relay operation:

27 – undervoltage;
40 – loss of field;
21 – under-impedance.

Key:

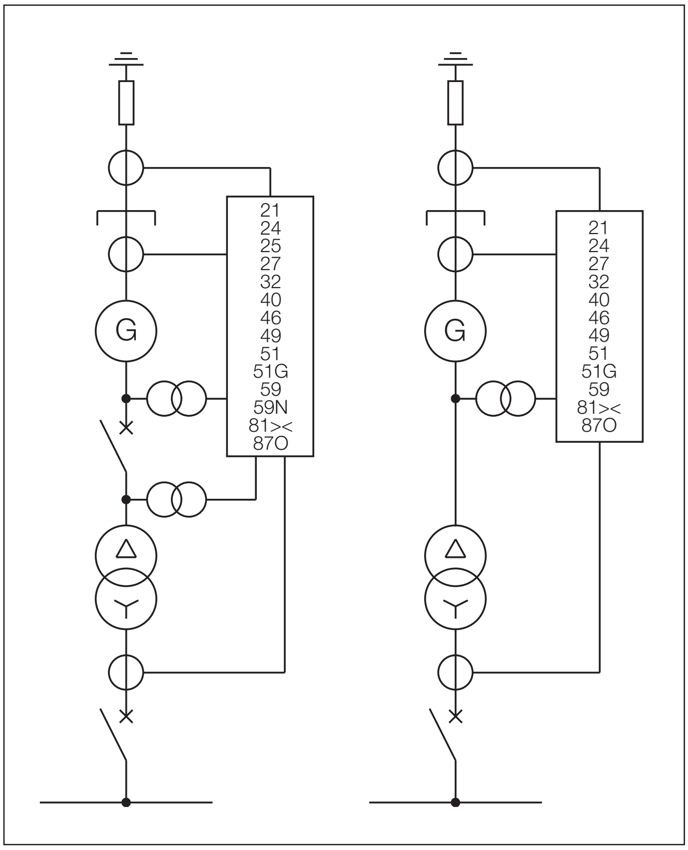
86GE	lock-out relay for external faults;
86GI	lock-out relay for internal faults;
152	HV side circuit-breaker (High Voltage);
52	machine circuit-breaker (generator);
41	generator field circuit-breaker;
STOP TURB	turbine stopping.

Relay recommended:
– REG 630

9. Selection of the protection system for machines and plants

9.2 Protections for generator transformer units

When a generator is connected directly to the network by means of a transformer without carrying out distribution to its terminals, the differential protection of the alternator can be replaced with a single differential riser protection (generator + transformer 87O overall) connected between the star point CTs of the alternator and the CTs on the incoming switchgear to the primary of the transformer. In this case, a differential transformer protection must be used and not a generator one as it is necessary to correct angle and ratio errors.
The main protection for the generator-transformer unit therefore becomes a compensated differential relay which must have filters to prevent false trips due to the presence of the second harmonic component originated by the magnetisation current at the connection of the transformer.
The characteristics of the current transformers, which must have suitable knee voltage and keep their precision even for external faults, are extremely important for correct operation of the protection.



Relays recommended:
- REG 630
- RET 615
- RET 620
- RET 630

9.3 Line protections

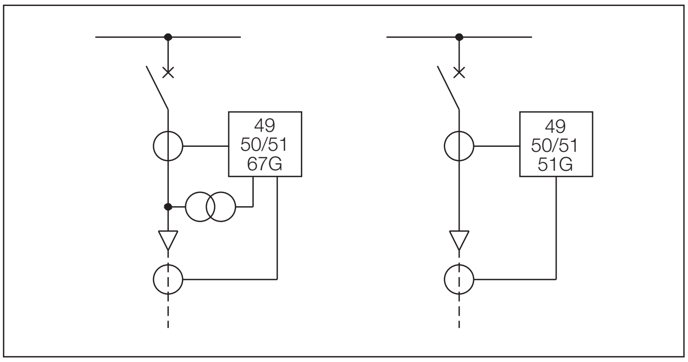
Protection of a line is adequate when protection against overloads is ensured and it is possible to identify polyphase short-circuit and single-phase ground faults. Therefore the protection is extremely simple and in general limited to the following protection functions:

a	relay 49	thermal protection against overload;
b	relay 51	overcurrent protection against high impedance faults;
c	relay 50	overcurrent protection against short-circuit;
d	relay 87L	differential line protection applicable when a selective protection is required in a particular zone of the distribution network. Protection 87L can be used in industrial plants with ring networks, meshed networks with or without the presence of decentralized power production;
e	relay 50N	protection against ground faults.

The thermal protection (49) was never provided in the past as it required installation of a particular relay with at considerable cost. With the advent of digital protections, this protection is generally provided in all relays and therefore allows good and adequate protection to be obtained, avoiding overtemperatures (with consequent reduction of life) of the lines. It is also often used only in alarm for monitoring the lines.

Protection functions 51/50 are against non-directional overcurrents and several thresholds are present in the relay (of which at least one with inverse time). These thresholds must be set for currents lower than the minimum fault current and be selective with the load side protections.
The ground protection is generally against overcurrent supplied by type ring CTs to guarantee great sensitivity and be able to identify ground faults even of resistive type. Two types of protections can be used:

- 51G: non-directional ground overcurrent: applicable when the capacitive contribution of the network load side is lower than the setting to be set on the protection;
- 67G: directional ground overcurrent: applicable to any network but with the caution that a set of three VTs with star connection must be present on the switchgear to be able to have the homopolar voltage which allows a reference for the direction of the fault current to be established.



Relays recommended:
- REF 601
- REF 611
- REF 615
- REF 620
- REF 630
- RED 615

9. Selection of the protection system for machines and plants

9.4 Transformer protections

A transformer is a two-way type of machine, i.e. the flow of energy can be in two directions without distinction. This clarification is very important since in plants where there can be power which flows without distinction from the primary to the secondary or vice versa, it is necessary to prepare protections on both sides. If, on the other hand, the transformer is only used with power flow in one direction, the protection system against phase faults may only be provided on the power supply side. What has been stated is only valid for the protections against phase faults and is not valid for ground protections as the two homopolar circuits are generally independent and each one needs dedicated protection against ground faults.
The faults or abnormal operating conditions in transformers can be traced back to (and consequently the protection must recognise) the following:

– Overload;
– Short-circuit;
– Primary side ground fault;
– Secondary side ground fault.

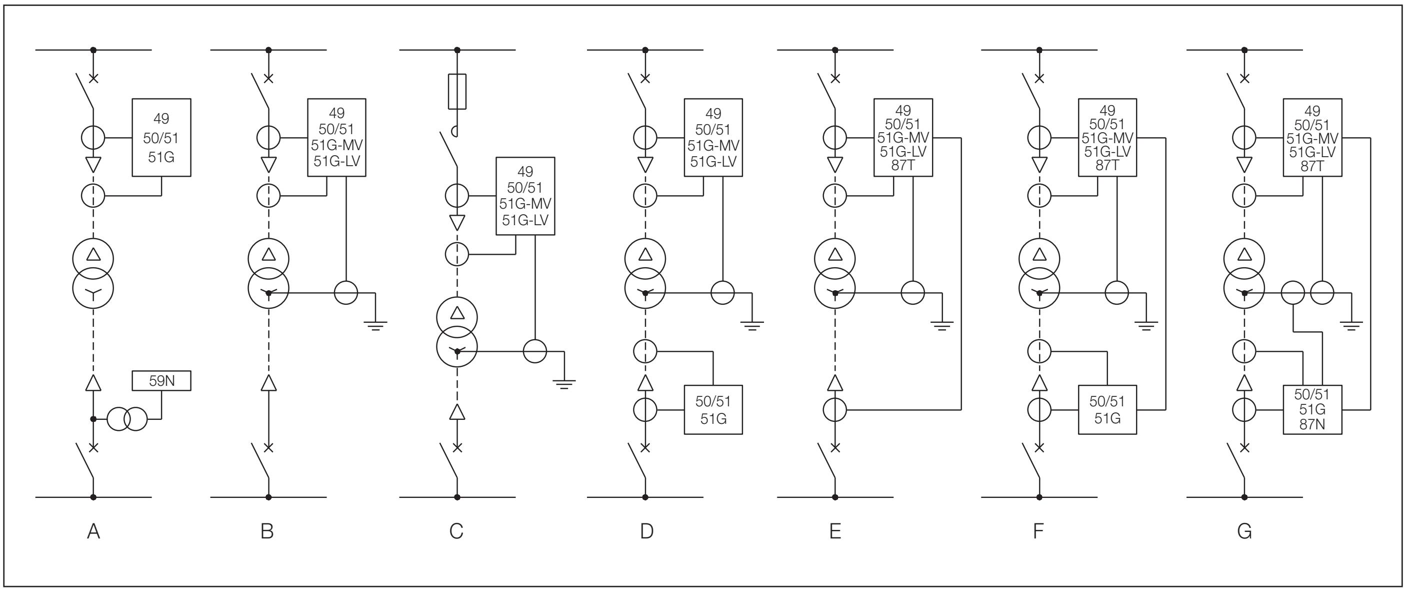
In their turn, these abnormal operating conditions can be identified using different protection functions which can also be a reserve for each other, for example, short-circuit can be identified using overcurrent protections and/or differential protections.
The protection functions to be provided for a transformer are:

a	relay 49	thermal overload protection;
b	relay 51	overcurrent protection with inverse time;
c	relay 51 or 50t	secondary side short-circuit overcurrent protection;
d	relay 50	primary side overcurrent short-circuit protection;
e	relay 87T	differential transformer protection;
f	relay 51G	primary side overcurrent ground fault protection;
g	relay 51G	secondary side overcurrent ground fault protection;
h	relay 26	overtemperature protection;
i	relay 63	overpressure protection (only for oil transformers).

Other protections can be provided for particular applications or for high-power machines. These protection functions are:

j	relay 24	overflux protection;
k	relay 46	negative sequence overcurrent protection;
l	relay 87N	restricted differential ground fault protection (for one or both windings);
m	relay 51G	tank protection.

In selecting the protection system, thermal protection has been indicated as both function 49 obtained by means of measuring the current absorbed by the transformer, and function 26 obtained by temperature measurements taken directly inside the machine.
Where installed, the temperature probes (code 26). which allow more effective and safe thermal protection and are preferable to thermal protection obtained by means of current measurements (code 49).
As shown in the list, several overcurrent protection thresholds are normally provided in order to be able to select settings which exploit both time type selectivity (functions 51 or 50t) and current type selectivity (50) and at the same time allow the machine an adequate overload and the possibility of obtaining good selectivity with the load side protections.
In the past, the differential protection was normally installed on machines with significant power (higher than 5 MVA).
Some types of protection relay (such as REF 54x) allow the differential protection to be activated already as a basis, and it can consequently be activated without extra costs even with small-sized machines.



The following figure shows some configurations of the protection system which can be selected according to the power of the machine, the connection unit and the status of the neutral.

The typical protection functions for a transformer are briefly described below.

9.4.1 '49' thermal overload protection

Overload of a transformer (and in general of all machines) corresponds to an increase in temperature inside the machine and as a consequence there is a reduction of life. The Standards give a general indication about how much the life of transformers is reduced according to the size of the overload and it can be noted that even significant overloads can be supported with small machine life reductions.
The possibility of having the real internal temperature of the machine could help better exploitation of the machine. In fact, the internal temperature of a transformer is, with the same power circulating, very different if the ambient temperature is 0° or 40° centigrade.

9.4.2 '51/50' overcurrent protection

Different overcurrent thresholds are used to guarantee good protection of the machine. In general, the first threshold has an inverse time characteristic and the type of characteristic is selected based on selectivity criteria. For example, when the protection has to be coordinated with low voltage releases, the extremely inverse time characteristic is normally used, whereas in medium voltage networks, if there are no motors with very long starting time, a very inverse time characteristic is generally chosen, etc. Then two thresholds with independent time (or definite time) characteristic are normally used to carry out the short-circuit protection with a delayed (selective) threshold for the secondary side faults and a threshold with instantaneous trip (time base) for primary side faults.

9.4.3 '87T' differential protection

The differential protection of the transformer is of the compensated type, i.e. it increases the trip threshold according to the line current. In practice, the higher the current is on the line, the higher the differential which serves to make the protection trip is. This solution allows great stability in the case of a through fault even in the presence of significant errors in the current transformers.
There are three peculiarities about a transformer differential protection:

- it makes a ratio correction (the currents which come from the two sets of three CTs are generally different);
- it makes angle correction to correct the angular unit of the transformer;
- it blocks the zero sequence which circulates in the star windings (without this precaution there could be false trips for external faults).

On connecting a transformer to the network, the inrush currents which supply the no-load transformer rise initially to peak values comparable with those of a short-circuit between phases at the secondary terminals to then decrease gradually, reducing down to the rated values of the no-load current. These currents would be detected by a normal differential protection as currents due to a fault inside the transformer causing an unwanted trip.
The inrush current is characterised by a high second harmonic component and the differential protections are fitted with a filter which, recognising the presence of the second harmonic, allows false trips to be prevented.
Both the differential protection and the overcurrent short-circuit protection normally operate on a time base (the difference in milliseconds is negligible when compared to the time which the circuit-breaker takes to open). The basic difference lies in the trip current threshold, which for the differential protection is a percentage of the rated current (indicatively 30%) whereas for the overcurrent protection it is a multiple (from 10 to 20 times) of the rated current. Therefore, where possible it is always useful to activate the differential protection which is much more sensitive and even allows faults with high resistance to be detected.

9.4.4 '51G' overcurrent protection against ground fault

As already noted, the ground protection must be provided for both the transformer secondaries. In general, transformers have an open circuit (if there is a delta-connected secondary) for passing zero sequence currents from load side to supply side (and vice versa). The two windings must therefore be protected independently against the ground faults and the relative protections are part of the selective protection system of the network.
The protection criterion against ground faults is a function of the type of winding connection:

- with delta windings:
  - with grounded neutral network, the machine is a user from the point of view of ground faults (even if the incoming feeder is from the power source). The ground protection is in this case very simple and can be entrusted to a homopolar overcurrent protection with setting at high sensitivity and extremely short time;
  - with isolated neutral, the only protection able to identify ground faults is the homopolar overvoltage protection which is not, however, of the selective type;

9. Selection of the protection system for machines and plants

- with star windings:
  - the star is isolated from ground: the situation is similar to the delta windings;
  - the star is connected a ground (directly to ground or by means of impedance): any ground fault in the metallically interconnected network (at the same voltage), reclosed on the star point and the homopolar current circulates in the faulted phase of the transformer. A protection on the star point allows identification of the fault current, but the setting must be selective with that of the other ground fault protections provided in the network. To end, it must be noted that in the absence of a fault, third harmonic currents reclose on the star points connected to ground and consequently, in order to prevent false trips, it is necessary for the protection to be fitted with suitable filters.

Often protection against low voltage ground faults on the grounded star points is not provided on the MV/LV transformers. In this case, for a fault in the transformer secondary, any protection provided on the main incoming low voltage does not detect any fault (the current circulates between the point of fault in the transformer and the star point of the transformer) and the only protection which can identify the fault is the phase overcurrent protection (for overloads) placed at the primary, but attention must be given that for delta-start transformers such as the MV/LV transformers typically are, the current which circulates in two phases at the primary (corresponding to the coil terminals where the fault current circulates to the secondary) is reduced by a root of three and therefore its identification could be obtained in long times not compatible with the tolerability of the transformer.

9.4.5 ‘87N’ restricted ground differential protection for a transformer winding

This protection is used for the transformers with neutral solidly grounded and therefore it is necessary to eliminate the faults which are of considerable value without waiting for the time needed to carry out selectivity.
The restricted differential ground protection can be made in two ways:

- by placing the four CTs (three line one and one on the star point) in parallel with the relay; the relay trips when the vectorial sum of the three line currents plus the neutral current is other than zero.
  This system is used when the relay has high consumption or when it is not possible to use ring transformers;
- using ring type current transformers. Two CTs (one which embraces the three line conductors and one on the star point) are connected in parallel and the resulting signal is sent to the relay. The ring CTs can have a transformation ratio different from that of the line CT and consequently allow greater sensitivity.

9.4.6 ‘63’ protection against internal anomalies for oil transformers (Bucholz relay)

The Bucholz relay is a protection generally used for oil transformers with tank fitted with conservator. It is a mechanical

Relays recommended:
- REF 601
- REF 615
- RET 615
- RET 620
- RET 630

type of device, whose operation is based on the fact that an electric arc in the oil causes localised heating with formation of bubbles of gas owing to fission of the hydrocarbon molecules making it up. This is a simple, economical, very effective and extremely reliable protection, with instantaneous trip (for important faults) and is only for faults inside the tank.

9.4.7 '26' overtemperature protection

This protection has the aim of preventing damage to the insulation of the windings caused by excessive heating due to overload currents which do not reach the trip threshold of the phase overcurrent protection, or which is caused by anomalies in plant cooling.
The protection is obtained by means of thermometric stations which detect the temperature of several heat probes, placed in particular points of the magnetic core and of the tank. It is always advisable to provide alarm thresholds set to reasonable margins in advance of the trip values.

9.4.8 '51G' tank protection

The tank protection is made up of an overcurrent relay connected to a C.T. inserted in the conductor which connects the transformer tank to ground. For a fault between phase and ground the current between the live conductors and ground flows through the above-mentioned conductor and makes the protection trip. For good operation of the tank protection, the ground fault current must be prevented from passing along other routes, other than the one the protection is inserted on, therefore it is necessary to take all the measures for isolating the transformer from ground.

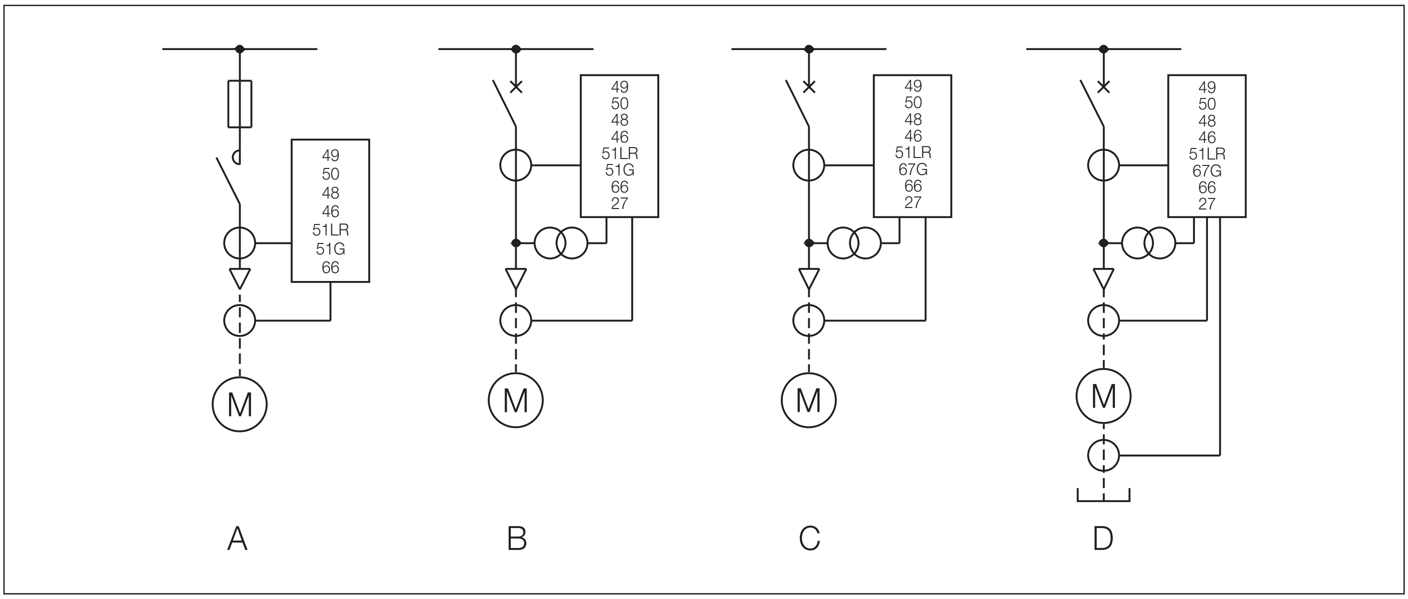
9.5 Protections for motors

When a motor protection is analysed, it must be remembered that in the starting phase the machine absorbs a current equal to about 6 times the rated one for a variable time according to the characteristics of the machine moved (from fractions of a second for small pumps up to tens of seconds for large fans).
In the presence of a network short-circuit, the motor behaves like a generator during the first instants and supplies the fault with a current theoretically equal to the starting current.
Both the starting condition as well as the contribution to the short-circuit are service conditions of the machine and the protections must be calculated to prevent false trips in these operating conditions.
Motor faults or abnormal operating conditions can be traced back to (and consequently the protection must recognise):

- Overload;
- Short-circuit;
- Ground fault;
- Too long starting;
- Locked rotor running;
- Unbalanced load;
- Excessive number of starts.

The anomalous operating conditions can be identified with different protection functions which can also be a reserve for each other, for example short-circuit can be identified using overcurrent protections and/or differential protections.
The protection functions to be provided for a motor are:

a	relay 49	thermal image protection against overload;
b	relay 50	overcurrent short-circuit protection (which can be in association with the fuses);
c	relay 87M	differential protection;



d	relay 51G	overcurrent ground fault protection;
e	relay 48	overcurrent protection against prolonged starting;
f	relay 51LR	overcurrent protection against locked rotor during running;
g	relay 46	negative sequence overcurrent protection;
h	relay 66	number of starts control protection.

Other protection functions can be provided for particular applications and these are:

i	relay 27	undervoltage protection against motor disconnection;
j	relay 37	undercurrent protection (typical for submerged pumps);
k	relay 78	protection against out of step for synchronous motors.

The motor represents a user 'terminal' of the electric system and therefore the protection system setting is not conditioned by other network protections.
With regard to the differential protection, its use can be very important for motors, unlike for the other electric machines, when the short-circuit currents are low and because the trip time compared to a normal overcurrent protection can also be greatly reduced (20 ms instead of 70-80 ms). The short-circuit protection of the overcurrent type must be delayed to avoid unwanted trips in the first instants of the motor starting phase (connection or inrush current), therefore for motors with power higher than or equal to 1500 kW it is normally provided.
The main difficulty in applying the differential protection for motors consists in having to provide star point side CTs and therefore to sometimes provide special versions for the motor terminal box or even external cabinets for installation of the CT and formation of the star point.
The figure shows some configurations of the protection system which can be selected according to the power of the machine, the connection unit, and the neutral status.

The typical motor protection functions are described below.

9.5.1 '49' thermal image protection against overload

The thermal image protection, simulating the time constant of the motor, allows good and effective motor protection to be obtained in the case of an overload.
The characteristic trip curve of the protection is of exponential type in accordance with the Standard for thermal relays.
When setting the protection, if the motor is foreseen for 'hot' re-starting, it must be verified that the equivalent thermal curve is such as to allow passage of the starting current for the corresponding time.
For thermal protection it is normally possible to set both the heating time constant as well as the cooling time constant.

9.5.2 '46' overcurrent protection against negative sequence (unbalanced loads)

The balanced three-phase loads produce a field reaction in the stator which rotates in synchronism with the rotor. In the presence of unbalanced loads, the negative sequence component in the stator current induces a current in the r otor with double the frequency of the rated one. This current which flows through the rotor winding causes serious heating in the rotor.
This function sees to protection of the motor in the case of one or two missing phases of the power supply and for unbalanced currents of small amplitude. It is necessary for this protection to trip in long times for small currents which can be of transient type. The protection must have a definite time characteristic it being a question of heating the rotor circuit.

9.5.3 '50' short-circuit overcurrent protection

This function protects the motor with relative connection cable against serious phase-phase or three-phase faults.
For outgoing feeders equipped with contactor and fuse, the short-circuit protection is also entrusted to the fuse, but the short-circuit overcurrent protection is in any case necessary to identify the faults of small size which can be solved by means of opening the contactor.
In the latter case, the protection must have a delay such as to be able to be coordinated with the opening characteristics of the contactor and the fuse trip curve.
When the outgoing feeder is equipped with a circuit-breaker, a delay on the trip time is provided in any case to let the peak currents on starting pass.

9.5.4 '51G - 67G' overcurrent protection against ground fault

This is a homopolar overcurrent protection against ground fault and the only particular attention consists in checking the need or not to provide directionality. In particular, the protection must be of the directional type should the capacitive contribution of the motor and associated cable be higher than the threshold value to be set.
As already shown, the motor is a user terminal of the electric network and therefore this protection represents the first step of selectivity for ground faults.

9.5.5 '48' overcurrent protection against prolonged starting

This protection function is only activated during the starting phase (once the starting time is over it is put out of service).
The aim of this protection is to check that the motor starts within the foreseen time. If the starting time exceeds the value calculated, overheating of the windings occurs with serious jeopardy for the life of the machine.
An important datum to define the setting of this protection is the starting time, which is also and above all a function of the operating machine which is connected to the axle.

9.5.6 '51LR' overcurrent protection against locked running rotor

This protection function is out of service in the starting phase and is only activated on completion of starting.
This protection verifies the anomalous operating condition of the machine due to a lock, caused, for example, by failure of the bearings (more than 30% of faults in motors), or by a stall condition.
The protection therefore has a rapid time for currents which can be compared with the starting currents without waiting for the thermal protection threshold which has large delays.
In this way you can manages to operate in short times for motor locks which would jeopardise the life time, excessively overheating the stator windings.

9.5.7 '66' protection against repeated starts

This protection verifies that the number of consecutive starts (or within restricted times) is compatible with the motor characteristics.
During starting, the motor absorbs a multiple current of the rated current (5-6 times) with generally limited ventilation (fan propeller integral with the rotor). Therefore during starting there is considerable overheating of the machine without the heat being removed. If these starts are repeated over short times, they lead to a rise in the machine temperature with consequent reduction of its life.
This protection function must be wired to prevent the circuit-breaker closing and not opening as typically happens for the other protection functions.

9.5.8 '27' undervoltage protection

An undervoltage relay for motor protection has different applications:
- to check that voltage drops in the network are not critical taking the motors to the stall condition;
- to check that the voltage is sufficiently high on circuit-breaker closing to allow correct motor starting;
- to disconnect the motor when there is no voltage in the network in order to avoid simultaneous re-starting with other machines and consequently the network being put completely out of commission, due to collapse.

The protection setting changes, as well as the command the protection gives, depending on the function to be obtained.

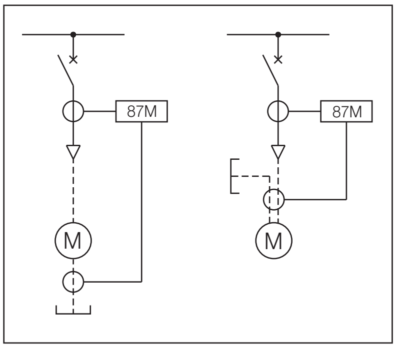
Relays recommended:
- REM 611
- REM 615
- REM 620
- REM 630

9. Selection of the protection system for machines and plants

9.5.9 ‘87M’ differential protection

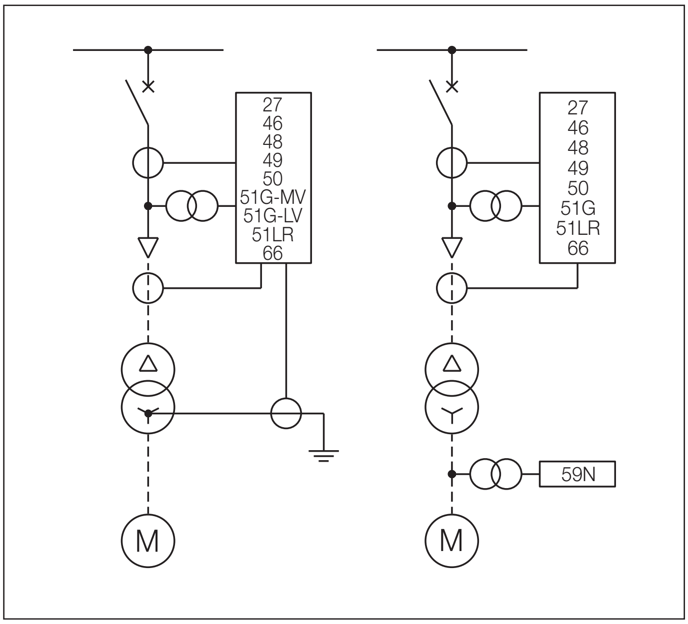
Two different protection techniques are used to carry out differential motor protection:

- compensated differential protection (as for the generators) which is supplied by a set of three line side and three star point side CTs. This protection has the serious problem that the CT on the star point side must have a considerable performance due to having to supply the connection cable between the CT and relay (distance between the switchgear and motor);
- self-balancing protection which is supplied by just one set of three star point side CTs. The CT of each phase embraces the two terminals of one phase of the motor, consequently measuring the vectorial sum of the current coming in and the current going out. If this value is other than zero there is a fault inside the machine. Using this protection function (simple overcurrent relay with an instantaneous threshold) there is the advantage that the CT for the differential protection can have even a much lower rated primary current than the rated current of the motor, thereby allowing great sensitivity of the protection (even higher than the classic differential protection).



9.6 Block transformer-motor protections

Motors which are provided with a rigid connection to the transformer require protections equivalent to what was described previously for motors supplied at the network voltage. The setting of the protections must be calculated on the basis of the characteristics of the machine with lower performances (the motor), since there is generally just one protection for the two machines transformer and motor.



Relays recommended:
– REM 611
– REM 615
– REM 620
– REM 630

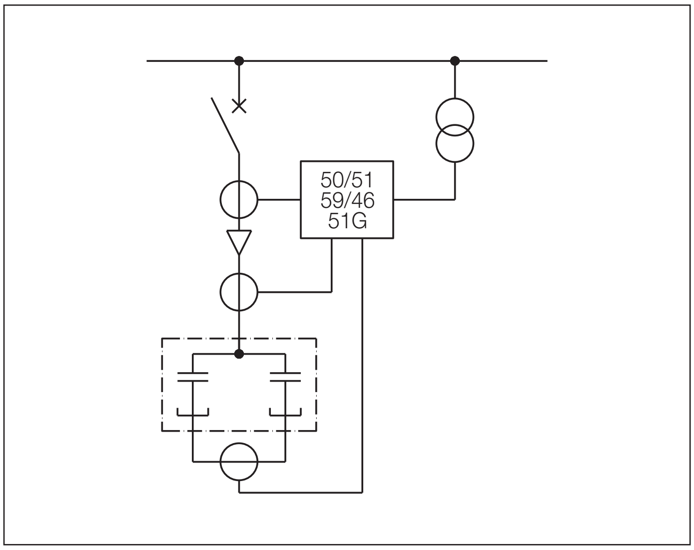
The only protection which has to be added is the protection against ground fault at the transformer secondary (motor side). The two networks (at the transformer primary and secondary) are independent from the point of view of ground faults. The protection can be of current type if the network is run with grounded neutral on the motor side, otherwise it must be provided with a homopolar overvoltage protection.

9.7 Protections for capacitors

The capacitors are a static load where the current absorbed is only a function of the network voltage. The capacitors are generators of reactive capacitive power, therefore they have the effect (apart from varying the network power factor of the) of increasing the voltage at the connection point. The capacitors also represent a critical point in networks with a high harmonic content since they can cause resonance phenomena with consequent high currents which can lead to damaging the capacitor.
At its connection, the power factor correction bank absorbs a transient current (very short time) which can even reach 10 times the rated current.
The faults or anomalous operating conditions of the capacitors can be due to (and consequently the protection must recognise):

- Currents higher than the rated current;
- Short-circuit;
- Ground fault;
- Overvoltage;
- Unbalanced impedance (fault on the elementary element making up the capacitor).

The anomalous operating conditions can be identified with the following protection functions:



a	relay 51	overcurrent protection;
b	relay 50	short-circuit overcurrent protection (which can be replaced by fuses);
c	relay 51G	overcurrent ground fault protection;
d	relay 59	overvoltage protection;
e	relay 46	negative sequence overcurrent protection.

The capacitor is a user 'terminal' of the electric system and therefore the setting of the protection system is not conditioned by other network protections.

9.7.1 '51' overcurrent protection

The tolerability of the capacitors for currents higher than the rated one is defined in the IEC 60871-1 2014 Standards: Shunt capacitors for a.c. power systems having a rated voltage above 1000 V - Part 1: General and IEEE Std 18-2012 Standards: IEEE Standard for Shunt Power Capacitors. This characteristic is very steep and there is no equivalent curve in the IEC 60255 (protections) Standards. An important datum to take into consideration in calculating the protection setting is the variation in voltage which can occur in the network, especially at low load, in the presence of the capacitor. This datum must be selected as a reference for calculating the trip threshold setting.

9.7.2 '50' overcurrent short-circuit protection

This function protects the capacitor with relative connection cable against serious phase-phase or three-phase faults. When selecting the setting, the transient phenomenon relative to supplying the bank with voltage must be taken into account. For outgoing feeders equipped with contactor and fuse, the protection of short-circuit is also entrusted to the fuse and therefore the overcurrent short-circuit protection can be omitted.

9.7.3 '51G -67G' overcurrent protection against ground fault

This is a normal homopolar ground fault protection and particular attention must only be paid to checking the need whether to provide directionality or not. In particular, the protection must be of the directional type when the capacitive contribution for single-phase ground fault of the associated cable is higher than the threshold value which is to be set. The star point of capacitor banks is never grounded and consequently the capacitor is the user terminal from the point of view of ground faults, so the protection can be set as the first step of selectivity.

9. Selection of the protection system for machines and plants

9.7.4 '59' overvoltage protection

The capacitor is a reactive power generator and, consequently, tends to raise the network voltage. For this reason, it is important to provide an overvoltage protection which puts it out of service so as to avoid high overvoltages of long duration both for the capacitor and for the connected electric network since, by putting the capacitor out of service, the contribution of reactive power is reduced and therefore the network voltage.

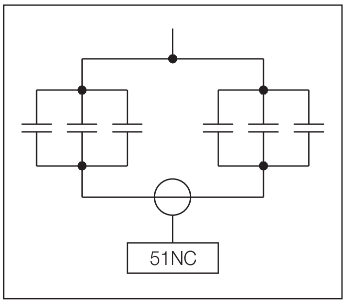
9.7.5 '46' overcurrent protection against negative sequence

Power factor correction banks are made up of a lot of capacitors to obtain the total capacity required. Perforation of the insulation of one of these basic capacitors modifies the impedance of that branch and consequently the power factor correction bank is un unbalanced load which with a three-phase symmetrical power supply absorbs unbalanced currents. Identification of an unbalanced current allows problems in the power factor correction bank to be detected and to operate before the fault evolves due to the increase in current due to the lower impedance.
The use of a negative sequence overcurrent relay on the power supply line to the power factor correction bank can therefore monitor this condition, but generally the sensitivity which can be obtained is not sufficient to guarantee protection against faults in the basic capacitor making up the power factor correction bank.
When power factor correction bank are installed in the plant, they are normally made with star connection (less voltage on each phase) and in general two star banks are provided in parallel with each other. The availability of the star points of two banks allows an extremely sensitive and reliable protection against unbalance.

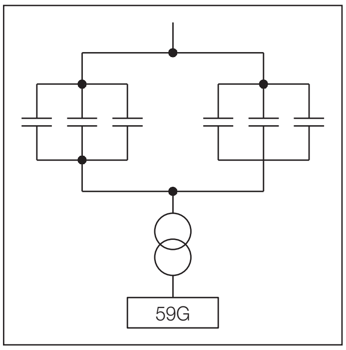
Relays recommended:
– REV 615

The true star points of the two power factor correction banks are coincident (with the theoretical star point) in the absence of a fault. Vice versa, in the presence of a fault in a basic capacitor of one of the two banks, there is movement of the real star point of the bank which is the seat of the fault (three different impedances).
Two different techniques can be used to identify the fault with great sensitivity:

– use of a single-phase overcurrent relays: in this case the star points of the two power factor correction banks are connected with each other and a CT is connected into this connection. A relay connected to the secondary measures the current which circulates over the connection - current which in the absence of a fault is equal to zero (two balanced three-phase banks), whereas it is different from zero in the presence of a fault; the code of the protection is 51NC (unbalance current for capacitor banks);



– use of single-phase overvoltage relays: in this case the star points of the two power factor correction banks are connected with each other and a VT. A relay connected to the secondary measures the voltage between the two star points. In the the absence of a fault this voltage is equal to zero (two balanced three-phase banks), whereas it is different from zero in the presence of a fault.



9.8 Protections for ring networks

The need to provide a reserve power supply for each substation with a lower investment than the one required for the double radial configuration lies at the base of selecting the ring configuration. The lower commitment in terms of cost has a negative aspect in the greater difficulty of building a protection system which guarantees trip selectivity, respect of the maximum trip time values required by the power Utility and rapid identification of the fault zone at the same time.
In distribution networks of the ring type, the direction of the fault currents in the feeders making up the ring is not predetermined, but depends both on localization of the fault point and on the network configuration at the time of the fault.

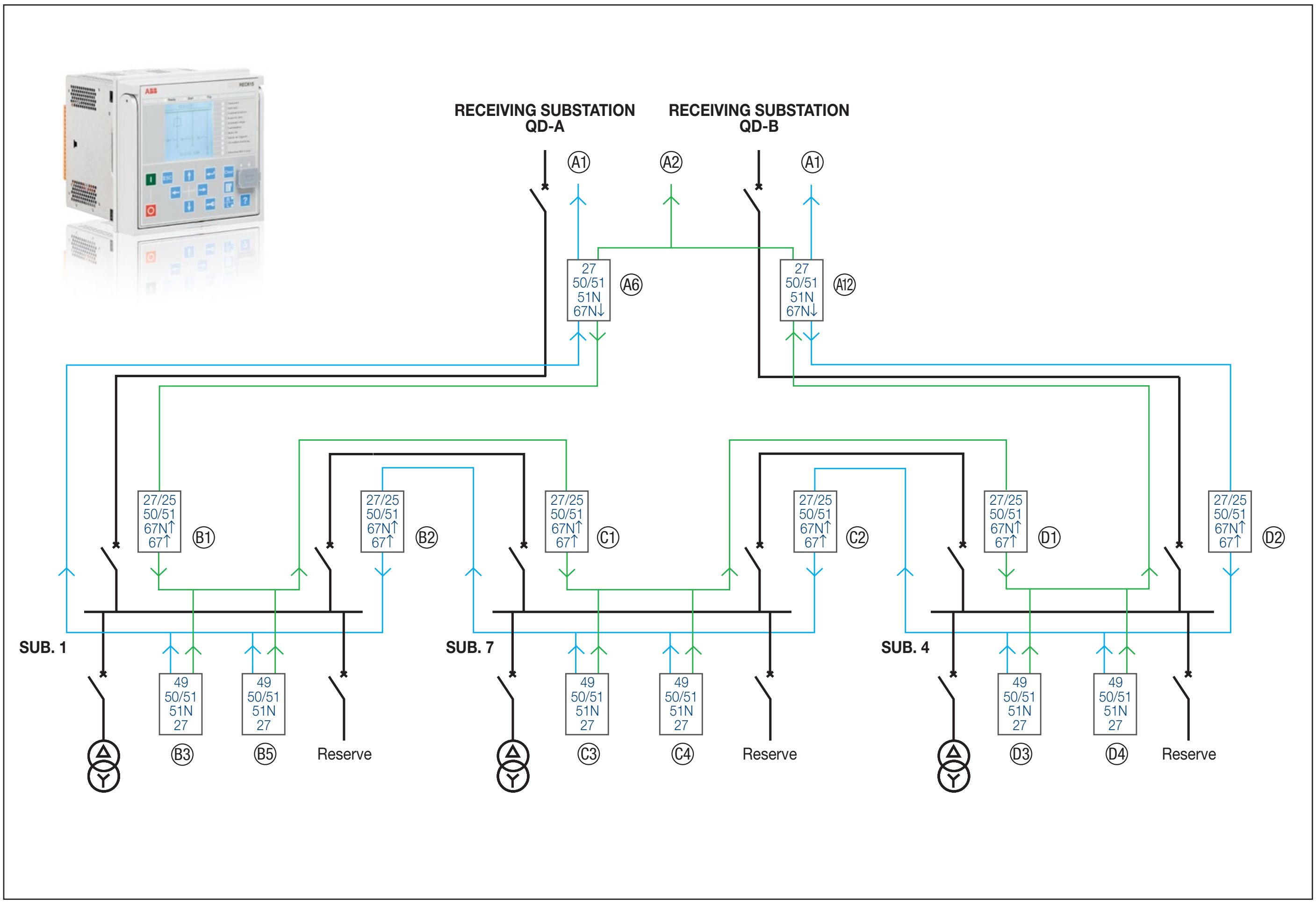
The protection systems normally used in a ring network are:

- if the ring is run open, it is a radial network and consequently time or logical selectivity using normal overcurrent protections can be used (possibly directional for ground fault if there is a high capacitive contribution);
- if the ring is run closed and there are circuit-breakers on the substation in-out and you want to put only the feeder or the faulty busbar out of service, it is necessary to provide directional of phase and ground protections with connection with pilot wire to carry out logical selectivity.

As an alternative to this solution, it is possible to use differential protections to identify and put only the line seat of the fault out of service on a time basis.

9.8.1 Block diagrams for logical selectivity

The figure gives a typical diagram of logical selectivity which can be made with ring networks. This block diagram is extremely simple and the result of eliminating the faulted part of the network selectively is obtained (perhaps even more than



the faulted part, but substations not affected by a fault are not stopped). It is, in any case, obvious that more complex systems can be made where, for example, even more sophisticated logical selectivity can be made (with only the busbar or cable fault out of service) and particular functions activated (important with small-sized transformers as ring networks typically are), such as failed circuit-breaker opening 50BF.

Relays recommended:
- REF 630
- REF 615

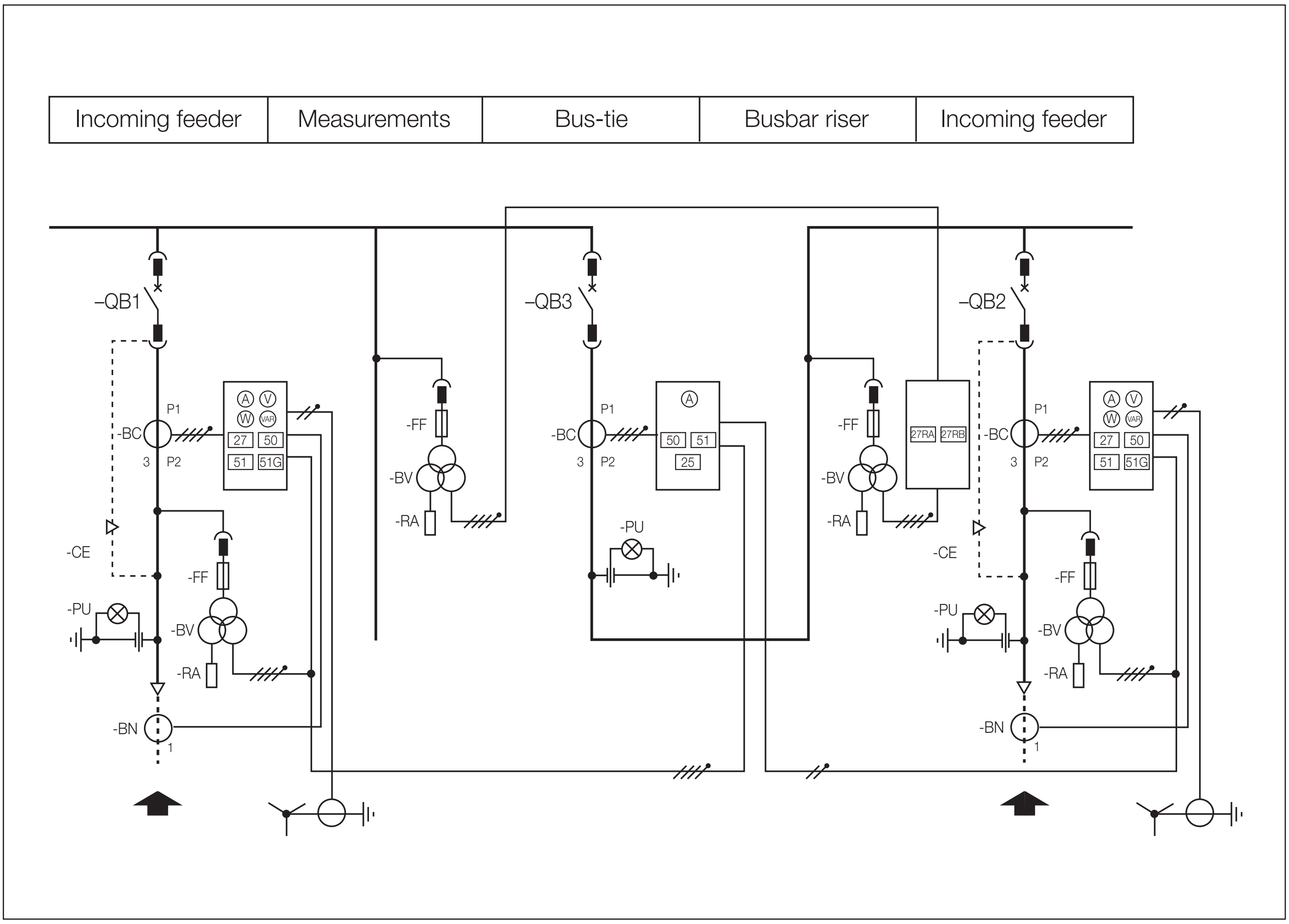
9.9 Automatic changeover

The automatic changeover systems do not come within the sphere of electrical protections. They are simply the ensemble of devices which automatically supply the power supply from an alternative source to some busbars or to single users when the normal power supply fails. This function is very important because it considerably improves service continuity.
It must be pointed out that different philosophies and different levels of complexity exist in carrying out the logics associated with automatic changeovers and consequently the protection systems must also adapt to these.
The use of automatic changeovers is not generalised: it is only justified for the most important users, in particular in continuous cycle plants, such as chemical or petrochemical plants and the auxiliary services of power stations.
There are two types of automatic changeovers (which are also completely different from each other from the point of view of complexity and cost):
- rapid changeovers without voltage gap (typical of feed water pumps supplying power stations);
- slow changeovers with voltage gap and temporary loss of the loads (typical of petrochemical plants).

The subject of automatic changeover is, in any case, closely linked to that of protections, because the latter provide the information and establish the conditions so that changeover can either take place or has to be locked.
In the presence of several changeovers in cascade (at the same or different voltage), the slow changeover waiting times must be coordinated so that they are carried out in order of time from the source towards the user substation (in any case, always selective with the overcurrent protections).
The measurement relay (of current and voltage) connected in the logics of automatic changeovers, does not carry out any protection functions.
Different network operating conditions must be analysed and combined to allow or prohibit automatic changeover. In particular:
- correct position of the circuit-breakers;
- permanent lack of voltage on an incoming feeder;
- presence of sound voltage on the other incoming feeder;
- busbar loads disconnected or suitable for re-acceleration during push-pull;
- low value of the busbar residual voltage in the case where the motors are not disconnected from the busbar or are not able to start again in push-pull;
- load side phase faults cleared up or not (consent/lock);
- load side ground faults cleared up or not (consent/lock).

During return to normal conditions, if the two sources cannot be in synchronism, a relay for verifying synchronism must be provided to enable momentary parallel.
The protection functions which are used to carry out automatic changeover are:

a	relay 27	undervoltage protection transfer start;
b	relay 27I (59)	undervoltage/voltage protection for consent (sound voltage on other riser);
c	relay 27R	residual undervoltage protection;
d	relay 27M	undervoltage protection against motor disconnection;
e	relay 50	overcurrent phase protection against lock on changeover in the presence of a load side fault;
f	relay 50G	overcurrent ground protection against lock on changeover in the presence of a load side fault;
g	relay 25	synchronism check relay (for parallel transit consent).



9.9.1 '27' undervoltage protection for starting changeover

This protection function is used to control the voltage drop on the incoming switchgear riser. In practice it gives the command to start the changeover.
The conditions which can occur in the network and which start from a trip of this protection are:

- lack of source voltage;
- fault in the transformer or in the power supply line;
- fault in the distribution switchgear busbars;
- fault in a load side user not cleared up by the relative circuit-breaker.

It is obvious that the latter two conditions mentioned must not give rise to automatic changeover (lock due to protections 50 and 50G). In calculating the settings of this protection, selectivity with the current protections inserted on the load side must be verified.

9.9.2 '27I/59' under/overvoltage protection for changeover consent

This relay is used to control the effectiveness of the voltage value of the opposite incoming switchgear riser and therefore to check that it is able to accept the loads of the busbar which has gone out of service.
This function must have a delay to be able to memorise any disturbances in the power supply source so as not to start automatic changeover if there is a lack of stability in the power supply voltage.

9. Selection of the protection system for machines and plants

9.9.3 ‘27M’ undervoltage protection against disconnection of motors

This function (where not already implemented on each motor) serves to disconnect all the rotating users from the switchgear in the case of a voltage drop.
In fact, all the circuit-breakers and MV contactors which have direct current control coils, remain closed during the lack of voltage and cause a serious overload on re-establishment of the voltage at the rated value due to restarting of all the motors, and are thus able to cause collapse of the system caused by the limited availability of power.

9.9.4 ‘27R’ residual undervoltage protection

This protection function is used to give consent for automatic changeover when the residual voltage generated by the motors which are decelerating drops below the set value.
Starting the changeover before the voltage is below this value can cause serious damage to the motors if these are not suitable for restarting in push-pull, or can create problems at the joints which are usually the weak points regarding the effects of shearing stresses.

9.9.5 ‘50-50G’ phase and ground overcurrent protection against locked changeover

In the case of a short-circuit (single-phase or polyphase) on the switchgear busbars or in a user not cleared up by its own circuit-breaker or contactor, there is a permanent voltage drop in the distribution network. In this situation, the conditions for automatic changeover are verified but remain locked by this protection.
The protection must be set above the overcurrent which can occur in the network without faults (for example: increase in current due to re-acceleration or to the contribution of motor short-circuit current due to a fault in the transformer).

9.9.6 ‘25’ synchronism check relay

The synchronism check relay checks that the voltages at the two ends of the parallel circuit-breaker have approximately the same modulus, the same phase and the same frequency.
This relay is used because, during re-establishment of normal conditions following an automatic changeover, a momentary parallel between the two sources is wanted to avoid going out of service again due to the voltage gap.
The parameters which are verified by the protection to either give or not give consent for parallel operation are the following:

– modules of the voltages;
– difference in the modulus between voltages;
– difference in the phase between voltages;
– frequency slip.

Relay recommended:
– REF 620

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