Chapter B
Connection to the MV public distribution network

Contents

1 Power supply at medium voltage

The term «medium voltage» is commonly used for distribution systems with voltages above 1 kV and generally applied up to and including 52 kV(1). For technical and economic reasons, the nominal voltage of medium-voltage distribution networks rarely exceeds 35 kV.

In this chapter, networks which operate at 1000 V or less are referred to as low-voltage (LV) networks, whereas networks requiring a step-down transformer to feed LV networks are referred to as medium voltage (MV) networks.

The main characteristics of an MV power supply are:

- *The nominal voltage*
- *The short-circuit current*
- *The rated current used*
- *The earthing system*

1.1 Power supply characteristics of medium-voltage networks

The characteristics of the MV network determine which switchgear is used in the MV or MV/LV substation and are specific to individual countries. Familiarity with these characteristics is essential when defining and implementing connections.

1.2 Different types of MV power supply

The following power supply methods may be used as appropriate for the type of medium-voltage network.

Connection to an MV radial network: Single-line service

The substation is supplied by a tee-off from the MV radial network (overhead or cable), also known as a spur network. This type of network supports a single supply for loads (see **Fig. B1**).

The substation usually consists of an incoming panel, and overall protection is provided by a load-break switch and fuses with earthing switches as shown in Figure B1.

In some countries, the “substation” comprises a pole-mounted transformer without a load-break switch or fuses (installed on the pole). This type of distribution is very common in rural areas. Protection and switching devices are located remotely from the transformer. These usually control a main overhead line to which secondary overhead lines are connected.

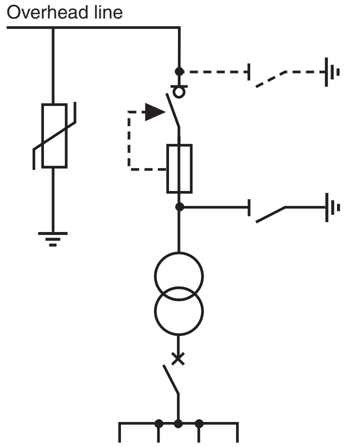

Fig. B1 : Single-line service (single supply)

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(1) According to the IEC there is no clear boundary between low and medium voltage; local and historical factors play a part, and limits are usually between 30 and 100 kV (see IEC 601-01-28).

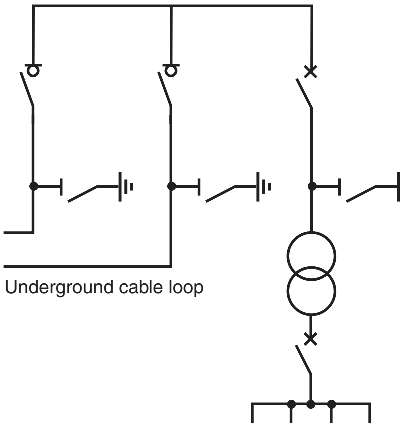

Fig. B2 : Ring-main service (double supply). The transformer is protected, in accordance with the applicable standards, by a circuit breaker or load-break switch as shown in Figure B1.

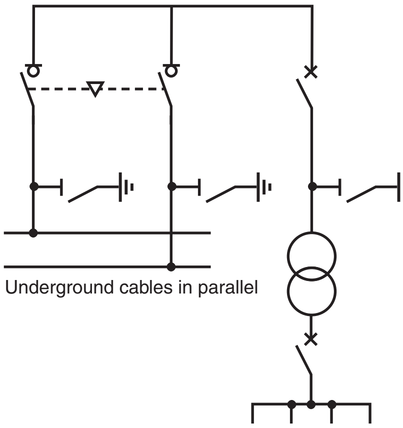

Fig. B3 : Parallel feeders service (double supply). The transformer is protected, in accordance with local standards, by a circuit breaker or load-break switch as shown in Figure B1.

Connection to an MV loop: Ring-main service

The power supply for the substation is connected in series to the power line of the medium-voltage distribution network to form a loop(1). This allows the line current to pass through a busbar, making it possible for loads to have two different power supplies (see **Fig. B2**).

The substation has three medium-voltage modular units or an integrated ring-main unit supporting the following functions:

- 2 incoming panels, each with a load-break switch. These are part of the loop and are connected to a busbar.
- 1 transformer feeder connected to the busbar. General protection is provided by load-break switches, a combined load-break/isolating switch or a circuit breaker.

All these types of switchgear are fitted with earthing switches.

All switches and earthing switches have a making capacity which enables them to close at the network's short-circuit current. Under this arrangement, the user benefits from a reliable power supply based on two MV feeders, with downtime kept to a minimum in the event of faults or work on the supplier network(1).

This method is used for the underground MV distribution networks found in urban areas.

Connection to two parallel MV cables: Parallel feeders service

If two parallel underground cables can be used to supply a substation, an MV switchboard similar to that of a ring-main station can be used (see **Fig. B3**).

The main difference to the ring-main station is that both load-break switches are interlocked. This means that only one of them can be closed at any one time (if one is closed, the other must be open).

In the event of the loss of supply, the associated incoming load-break switch must be open and the interlocking system must enable the switch which was open to close.

This sequence can be implemented either manually or automatically.

This method is used for networks in some densely-populated or expanding urban areas supplied by underground cables.

1.3 Some practical issues concerning MV distribution networks

Overhead networks

Weather conditions such as wind and frost may bring wires into contact and cause temporary (as opposed to permanent) short-circuits.

Ceramic or glass insulating materials may be broken by wind-borne debris or carelessly discharged firearms. Shorting to earth may also result when insulating material becomes heavily soiled.

Many of these faults are able to rectify themselves. For example, damaged insulating materials can continue functioning undetected in a dry environment, although heavy rain will probably cause flashover to earth (e.g. via a metallic support structure). Similarly, heavily soiled insulating material usually causes flashover to earth in damp conditions.

Almost invariably, fault current will take the form of an electric arc, whose intense heat dries the current's path and, to some extent, re-establishes insulating properties. During this time, protection devices will normally have proved effective in eliminating the fault (fuses will blow or the circuit breaker will trip).

Experience has shown that, in the vast majority of cases, the supply can be restored by replacing fuses or reclosing the circuit breaker.

As such, it is possible to improve the service continuity of overhead networks significantly by using circuit breakers with an automated reclosing facility on the relevant feeders.

These automated facilities support a set number of reclosing operations if a first attempt proves unsuccessful. The interval between successive attempts can be adjusted (to allow time for the air near the fault to deionise) before the circuit breaker finally locks out after all the attempts (usually three) have failed.

Remote control switches can be used on cable segments within networks to further improve service continuity. Load-break switches can also be teamed with a reclosing circuit breaker to isolate individual sections.

(1) A medium-voltage loop is an underground distribution network based on cables from two MV substation feeders. The two feeders are the two 'ends' of the loop and each is protected by an MV circuit breaker.

The loop is usually open, i.e. divided into two sections (half-loops), each of which is supplied by a feeder. To support this arrangement, the two incoming load-break switches on the substations in the loop are closed, allowing current to circulate around the loop. On one of the stations one switch is normally left open, determining the start of the loop.

A fault on one of the half-loops will trigger the protection device on the associated feeder, de-energising all substations within that half loop. Once the fault on the affected cable segment (between two adjacent substations) has been located, the supply to these substations can be restored from the other feeder.

This requires some reconfiguration of the loop, with the load-break switches being switched in order to move the start of the loop to the substation immediately downstream of the fault and open the switch on the substation immediately upstream of the fault on the loop. These measures isolate the cable segment where the fault has occurred and restore the supply to the whole loop, or to most of it if the switches that have been switched are not on substations on either side of the sole cable segment affected by the fault.

Systems for fault location and loop reconfiguration with remote control switches allow these processes to be automated.

Underground networks

Cable faults on underground networks can sometimes be caused by poorly arranged cable boxes or badly laid cables. For the most part, however, faults are the result of damage caused by tools such as pickaxes and pneumatic drills or by earthmoving plant used by other public utilities.

Insulation faults sometimes occur in connection boxes as a result of overvoltage, particularly at locations where an MV network is connected to an underground cable network. In such cases, overvoltage is usually caused by atmospheric conditions, and the reflection effects of electromagnetic waves at the junction box (where circuit impedance changes sharply) may generate sufficient strain on the cable box insulation for a fault to occur.

Devices to protect against overvoltages, such as lightning arresters, are often installed at these locations.

Underground cable networks suffer from fewer faults than overhead networks, but those which do occur are invariably permanent and take longer to locate and resolve.

In the event of a fault affecting an MV loop cable, the supply can be quickly restored to users once the cable segment where the fault occurred has been located.

Having said this, if the fault occurs at a feeder for a radial supply, it can take several hours to locate and resolve the fault, and all the users connected in a single branch arrangement downstream of the fault will be affected.

In cases where service continuity is essential for all or part of the installation concerned, provision must be made for an auxiliary supply.

The use of centralised remote control and monitoring based on SCADA (Supervisory Control And Data Acquisition) systems and recent developments in digital communication technology is increasingly common in countries where the complexity associated with highly interconnected networks justifies the investment required.

Remote control and monitoring for MV networks

Remote control and monitoring of MV feeders makes it possible to reduce loss of supply resulting from cable faults by supporting fast and effective loop reconfiguration. This facility relies on switches with electric controls which are fitted on a number of substations in the loop and linked to modified remote-control units. All stations containing this equipment can have their supply restored remotely, whereas other stations will require additional manual operations

Values of earth fault currents for MV power supply

The values of earth fault currents on distribution networks depend on the MV substation's earthing system (or neutral earthing system). They must be limited to reduce their impact on the network and restrict possible increased potential on user substation frames caused by the coupling of earth switches (overhead networks), and to reduce flashover with the station's LV circuits capable of generating dangerous levels of potential in the low voltage installation.

Where networks have both overhead and underground elements, an increased cable earthing capacitance value may cause the earth fault current value to rise and require measures to compensate this phenomenon. Earthing impedance will then involve reactance (a resistor in parallel with an inductor) in line with the leakage rate: the neutral earthing system is compensated. Compensatory impedance makes it possible to both:

- Control earth fault current values, regardless of the amount of cabling within the network, and
- Eliminate most temporary and semi-permanent single-phase faults naturally by facilitating self rectification, thereby avoiding many short-term losses

2 Procedure for the establishment of a new substation

Large consumers of electricity are invariably supplied at MV.

On LV systems operating at 120/208 V (3-phase 4-wires), a load of 50 kVA might be considered to be "large", while on a 240/415 V 3-phase system a "large" consumer could have a load in excess of 100 kVA. Both systems of LV distribution are common in many parts of the world.
As a matter of interest, the IEC recommends a "world" standard of 230/400 V for 3-phase 4-wire systems. This is a compromise level and will allow existing systems which operate at 220/380 V and at 240/415 V, or close to these values, to comply with the proposed standard simply by adjusting the off-circuit tapping switches of standard distribution transformers.

The distance over which the energy has to be transmitted is a further factor in considering an MV or LV service. Services to small but isolated rural consumers are obvious examples.

The decision of a MV or LV supply will depend on local circumstances and considerations such as those mentioned above, and will generally be imposed by the utility for the district concerned.

When a decision to supply power at MV has been made, there are two widely-followed methods of proceeding:

1 - The power-supplier constructs a standard substation close to the consumer's premises, but the MV/LV transformer(s) is (are) located in transformer chamber(s) inside the premises, close to the load centre

2 - The consumer constructs and equips his own substation on his own premises, to which the power supplier makes the MV connection

In method no. **1** the power supplier owns the substation, the cable(s) to the transformer(s), the transformer(s) and the transformer chamber(s), to which he has unrestricted access.
The transformer chamber(s) is (are) constructed by the consumer (to plans and regulations provided by the supplier) and include plinths, oil drains, fire walls and ceilings, ventilation, lighting, and earthing systems, all to be approved by the supply authority.
The tariff structure will cover an agreed part of the expenditure required to provide the service.

Whichever procedure is followed, the same principles apply in the conception and realization of the project. The following notes refer to procedure no. **2**.

The consumer must provide certain data to the utility at the earliest stage of the project.

2.1 Preliminary information

Before any negotiations or discussions can be initiated with the supply authorities, the following basic elements must be established:

Maximum anticipated power (kVA) demand

Determination of this parameter is described in Chapter A, and must take into account the possibility of future additional load requirements. Factors to evaluate at this stage are:

- The utilization factor (ku)
- The simultaneity factor (ks)

Layout plans and elevations showing location of proposed substation

Plans should indicate clearly the means of access to the proposed substation, with dimensions of possible restrictions, e.g. entrances corridors and ceiling height, together with possible load (weight) bearing limits, and so on, keeping in mind that:

- The power-supply personnel must have free and unrestricted access to the MV equipment in the substation at all times
- Only qualified and authorized consumer's personnel are allowed access to the substation
- Some supply authorities or regulations require that the part of the installation operated by the authority is located in a separated room from the part operated by the customer.

Degree of supply continuity required

The consumer must estimate the consequences of a supply failure in terms of its duration:

- Loss of production
- Safety of personnel and equipment

The utility must give specific information to the prospective consumer.

2.2 Project studies

From the information provided by the consumer, the power-supplier must indicate:

The type of power supply proposed, and define:

- The kind of power-supply system: overheadline or underground-cable network
- Service connection details: single-line service, ring-main installation, or parallel feeders, etc.
- Power (kVA) limit and fault current level

The nominal voltage and rated voltage (Highest voltage for equipment)

Existing or future, depending on the development of the system.

Metering details which define:

- The cost of connection to the power network
- Tariff details (consumption and standing charges)

The utility must give official approval of the equipment to be installed in the substation, and of proposed methods of installation.

2.3 Implementation

Before any installation work is started, the official agreement of the power-supplier must be obtained. The request for approval must include the following information, largely based on the preliminary exchanges noted above:

- Location of the proposed substation
- Single-line diagram of power circuits and connections, together with earthing-circuit proposals
- Full details of electrical equipment to be installed, including performance characteristics
- Layout of equipment and provision for metering components
- Arrangements for power-factor improvement if required
- Arrangements provided for emergency standby power plant (MV or LV) if eventually required

After testing and checking of the installation by an independent test authority, a certificate is granted which permits the substation to be put into service.

2.4 Commissioning

When required by the authority, commissioning tests must be successfully completed before authority is given to energize the installation from the power supply system. Even if no test is required by the authority it is better to do the following verification tests:

- Measurement of earth-electrode resistances
- Continuity of all equipotential earth-and safety bonding conductors
- Inspection and functional testing of all MV components
- Insulation checks of MV equipment
- Dielectric strength test of transformer oil (and switchgear oil if appropriate), if applicable
- Inspection and testing of the LV installation in the substation
- Checks on all interlocks (mechanical key and electrical) and on all automatic sequences
- Checks on correct protective-relay operation and settings

It is also imperative to check that all equipment is provided, such that any properly executed operation can be carried out in complete safety. On receipt of the certificate of conformity (if required):

- Personnel of the power-supply authority will energize the MV equipment and check for correct operation of the metering
- The installation contractor is responsible for testing and connection of the LV installation

When finally the substation is operational:

- The substation and all equipment belongs to the consumer
- The power-supply authority has operational control over all MV switchgear in the substation, e.g. the two incoming load-break switches and the transformer MV switch (or CB) in the case of a RingMainUnit, together with all associated MV earthing switches
- The power-supply personnel has unrestricted access to the MV equipment
- The consumer has independent control of the MV switch (or CB) of the transformer(s) only, the consumer is responsible for the maintenance of all substation equipment, and must request the power-supply authority to isolate and earth the switchgear to allow maintenance work to proceed. The power supplier must issue a signed permit-to-work to the consumers maintenance personnel, together with keys of locked-off isolators, etc. at which the isolation has been carried out.

3 Protection aspect

The subject of protection in the electrical power industry is vast: it covers all aspects of safety for personnel, and protection against damage or destruction of property, plant, and equipment.

These different aspects of protection can be broadly classified according to the following objectives:

- Protection of personnel and animals against the dangers of overvoltages and electric shock, fire, explosions, and toxic gases, etc.
- Protection of the plant, equipment and components of a power system against the stresses of short-circuit faults, atmospheric surges (lightning) and power-system instability (loss of synchronism) etc.
- Protection of personnel and plant from the dangers of incorrect power-system operation, by the use of electrical and mechanical interlocking. All classes of switchgear (including, for example, tap-position selector switches on transformers, and so on...) have well-defined operating limits. This means that the order in which the different kinds of switching device can be safely closed or opened is vitally important. Interlocking keys and analogous electrical control circuits are frequently used to ensure strict compliance with correct operating sequences.

It is beyond the scope of a guide to describe in full technical detail the numerous schemes of protection available to power-systems engineers, but it is hoped that the following sections will prove to be useful through a discussion of general principles. While some of the protective devices mentioned are of universal application, descriptions generally will be confined to those in common use on MV and LV systems only, as defined in Sub-clause 1.1 of this Chapter.

Protection against electric shocks and overvoltages is closely related to the achievement of efficient (low resistance) earthing and effective application of the principles of equipotential environments.

3.1 Protection against electric shocks

Protective measures against electric shock are based on two common dangers:

- Contact with an active conductor, i.e. which is live with respect to earth in normal circumstances. This is referred to as a “direct contact” hazard.
- Contact with a conductive part of an apparatus which is normally dead, but which has become live due to insulation failure in the apparatus. This is referred to as an “indirect contact” hazard.

It may be noted that a third type of shock hazard can exist in the proximity of MV or LV (or mixed) earth electrodes which are passing earth-fault currents. This hazard is due to potential gradients on the surface of the ground and is referred to as a “step-voltage” hazard; shock current enters one foot and leaves by the other foot, and is particular dangerous for four-legged animals. A variation of this danger, known as a “touch voltage” hazard can occur, for instance, when an earthed metallic part is situated in an area in which potential gradients exist.

Touching the part would cause current to pass through the hand and both feet.

Animals with a relatively long front-to-hind legs span are particularly sensitive to step-voltage hazards and cattle have been killed by the potential gradients caused by a low voltage (230/400 V) neutral earth electrode of insufficiently low resistance.

Potential-gradient problems of the kind mentioned above are not normally encountered in electrical installations of buildings, providing that equipotential conductors properly bond all exposed metal parts of equipment and all extraneous metal (i.e. not part of an electrical apparatus or the installation - for example structural steelwork, etc.) to the protective-earthing conductor.

Direct-contact protection or basic protection

The main form of protection against direct contact hazards is to contain all live parts in housings of insulating material or in metallic earthed housings, by placing out of reach (behind insulated barriers or at the top of poles) or by means of obstacles.

Where insulated live parts are housed in a metal envelope, for example transformers, electric motors and many domestic appliances, the metal envelope is connected to the installation protective earthing system.

For MV switchgear, the IEC standard 62271-200 (Prefabricated Metal Enclosed switchgear and controlgear for voltages up to 52 kV) specifies a minimum Protection Index (IP coding) of IP2X which ensures the direct-contact protection. Furthermore, the metallic enclosure has to demonstrate an electrical continuity, then establishing a good segregation between inside and ouside of the enclosure. Proper grounding of the enclosure further participates to the electrical protection of the operators under normal operating conditions.

For LV appliances this is achieved through the third pin of a 3-pin plug and socket. Total or even partial failure of insulation to the metal, can raise the voltage of the envelope to a dangerous level (depending on the ratio of the resistance of the leakage path through the insulation, to the resistance from the metal envelope to earth).

Indirect-contact protection or fault protection

A person touching the metal envelope of an apparatus with a faulty insulation, as described above, is said to be making an indirect contact.

An indirect contact is characterized by the fact that a current path to earth exists (through the protective earthing (PE) conductor) in parallel with the shock current through the person concerned.

Case of fault on L.V. system

Extensive tests have shown that, providing the potential of the metal envelope is not greater than 50 V with respect to earth, or to any conductive material within reaching distance, no danger exists.

Indirect-contact hazard in the case of a MV fault

If the insulation failure in an apparatus is between a MV conductor and the metal envelope, it is not generally possible to limit the rise of voltage of the envelope to 50 V or less, simply by reducing the earthing resistance to a low value. The solution in this case is to create an equipotential situation, as described in Sub-clause 1.1 “Earthing systems”.

Earth connection resistance

Insulation faults affecting the MV substation’s equipment (internal) or resulting from atmospheric overvoltages (external) may generate earth currents capable of causing physical injury or damage to equipment.

Preventive measures essentially consist of:
- Interconnecting all substation frames and connecting them to the earth bar
- Minimising earth resistance

3.2 Protection of transformer and circuits

General

The electrical equipment and circuits in a substation must be protected in order to avoid or to control damage due to abnormal currents and/or voltages. All equipment normally used in power system installations have standardized short-time withstand ratings for overcurrent and overvoltage. The role of protective scheme is to ensure that this withstand limits can never be exceeded. In general, this means that fault conditions must be cleared as fast as possible without missing to ensure coordination between protective devices upstream and downstream the equipement to be protected. This means, when there is a fault in a network, generally several protective devices see the fault at the same time but only one must act.

These devices may be:

- Fuses which clear the faulty circuit directly or together with a mechanical tripping attachment, which opens an associated three-phase load-break switch

- Relays which act indirectly on the circuit-breaker coil

Transformer protection

Stresses due to the supply network

Some voltage surges can occur on the network such as :

- Atmospheric voltage surges

Atmospheric voltage surges are caused by a stroke of lightning falling on or near an overhead line.

- Operating voltage surges

A sudden change in the established operating conditions in an electrical network causes transient phenomena to occur. This is generally a high frequency or damped oscillation voltage surge wave.

For both voltage surges, the overvoltage protection device generally used is a varistor (Zinc Oxide).

In most cases, voltage surges protection has no action on switchgear.

Stresses due to the load

Overloading is frequently due to the coincidental demand of a number of small loads, or to an increase in the apparent power (kVA) demand of the installation, due to expansion in a factory, with consequent building extensions, and so on. Load increases raise the temperature of the wirings and of the insulation material. As a result, temperature increases involve a reduction of the equipment working life. Overload protection devices can be located on primary or secondary side of the transformer.

The protection against overloading of a transformer is now provided by a digital relay which acts to trip the circuit-breaker on the secondary side of the transformer. Such relay, generally called thermal overload relay, artificially simulates the temperature, taking into account the time constant of the transformer. Some of them are able to take into account the effect of harmonic currents due to non linear loads (rectifiers, computer equipment, variable speed drives…).This type of relay is also able to predict the time before overload tripping and the waiting time after tripping. So, this information is very helpful to control load shedding operation.

In addition, larger oil-immersed transformers frequently have thermostats with two settings, one for alarm purposes and the other for tripping.

Dry-type transformers use heat sensors embedded in the hottest part of the windings insulation for alarm and tripping.

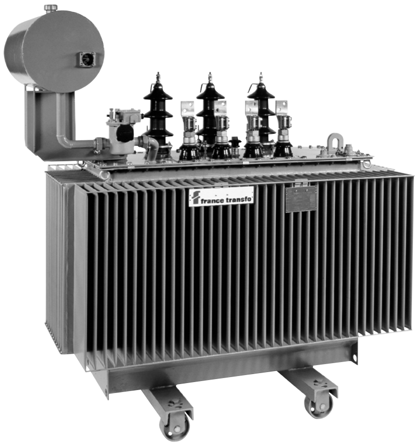

Fig. B4 : *Transformer with conservator tank*

Internal faults

The protection of transformers by transformer-mounted devices, against the effects of internal faults, is provided on transformers which are fitted with airbreathing conservator tanks by the classical Buchholz mechanical relay (see **Fig. B4**). These relays can detect a slow accumulation of gases which results from the arcing of incipient faults in the winding insulation or from the ingress of air due to an oil leak. This first level of detection generally gives an alarm, but if the condition deteriorates further, a second level of detection will trip the upstream circuit-breaker.

An oil-surge detection feature of the Buchholz relay will trip the upstream circuit-breaker “instantaneously” if a surge of oil occurs in the pipe connecting the main tank with the conservator tank.

Such a surge can only occur due to the displacement of oil caused by a rapidly formed bubble of gas, generated by an arc of short-circuit current in the oil.

By specially designing the cooling-oil radiator elements to perform a concerting action, “totally filled” types of transformer as large as 10 MVA are now currently available.

Fig. B5 : *Totally filled transformer*

Expansion of the oil is accommodated without an excessive rise in pressure by the “bellows” effect of the radiator elements. A full description of these transformers is given in Sub-clause 4.4 (see **Fig. B5**).

Evidently the Buchholz devices mentioned above cannot be applied to this design; a modern counterpart has been developed however, which measures:

- The accumulation of gas
- Overpressure
- Overtemperature

The first two conditions trip the upstream circuit-breaker, and the third condition trips the downstream circuit-breaker of the transformer.

Internal phase-to-phase short-circuit

Internal phase-to-phase short-circuit must be detected and cleared by:

- 3 fuses on the primary side of the tranformer or
- An overcurrent relay that trips a circuit-breaker upstream of the transformer

Internal phase-to-earth short-circuit

This is the most common type of internal fault. It must be detected by an earth fault relay. Earth fault current can be calculated with the sum of the 3 primary phase currents (if 3 current transformers are used) or by a specific core current transformer. If a great sensitivity is needed, specific core current transformer will be prefered. In such a case, a two current transformers set is sufficient (see **Fig. B6**).

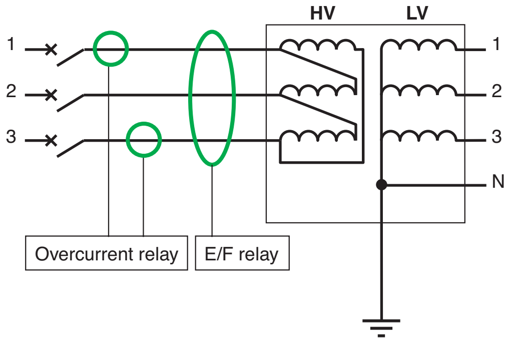

Fig. B6 : *Protection against earth fault on the MV winding*

Protection of circuits

The protection of the circuits downstream of the transformer must comply with the IEC 60364 requirements.

Discrimination between the protective devices upstream and downstream of the transformer

The consumer-type substation with LV metering requires discriminative operation between the MV fuses or MV circuit-breaker and the LV circuit-breaker or fuses. The rating of the MV fuses will be chosen according to the characteristics of the transformer.

The tripping characteristics of the LV circuit-breaker must be such that, for an overload or short-circuit condition downstream of its location, the breaker will trip sufficiently quickly to ensure that the MV fuses or the MV circuit-breaker will not be adversely affected by the passage of overcurrent through them.

The tripping performance curves for MV fuses or MV circuit-breaker and LV circuit-breakers are given by graphs of time-to-operate against current passing through them. Both curves have the general inverse-time/current form (with an abrupt discontinuity in the CB curve at the current value above which “instantaneous” tripping occurs).

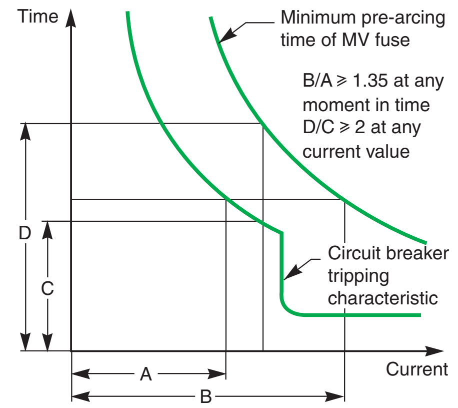

Fig. B7 : Discrimination between MV fuse operation and LV circuit-breaker tripping, for transformer protection

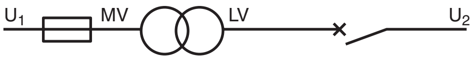

Fig. B8 : MV fuse and LV circuit-breaker configuration

These curves are shown typically in **Figure B7**.

- In order to achieve discrimination (see **Fig. B8**):

All parts of the fuse or MV circuit-breaker curve must be above and to the right of the CB curve.

- In order to leave the fuses unaffected (i.e. undamaged):

All parts of the minimum pre-arcing fuse curve must be located to the right of the CB curve by a factor of 1.35 or more (e.g. where, at time T, the CB curve passes through a point corresponding to 100 A, the fuse curve at the same time T must pass through a point corresponding to 135 A, or more, and so on...) and, all parts of the fuse curve must be above the CB curve by a factor of 2 or more (e.g. where, at a current level I the CB curve passes through a point corresponding to 1.5 seconds, the fuse curve at the same current level I must pass through a point corresponding to 3 seconds, or more, etc.).

The factors 1.35 and 2 are based on standard maximum manufacturing tolerances for MV fuses and LV circuit-breakers.

In order to compare the two curves, the MV currents must be converted to the equivalent LV currents, or vice-versa.

Where a LV fuse-switch is used, similar separation of the characteristic curves of the MV and LV fuses must be respected.

- In order to leave the MV circuit-breaker protection untripped:

All parts of the minimum pre-arcing fuse curve must be located to the right of the CB curve by a factor of 1.35 or more (e.g. where, at time T, the LV CB curve passes through a point corresponding to 100 A, the MV CB curve at the same time T must pass through a point corresponding to 135 A, or more, and so on...) and, all parts of the MV CB curve must be above the LV CB curve (time of LV CB curve must be less or equal than MV CB curves minus 0.3 s)

The factors 1.35 and 0.3 s are based on standard maximum manufacturing tolerances for MV current transformers, MV protection relay and LV circuit-breakers.

In order to compare the two curves, the MV currents must be converted to the equivalent LV currents, or vice-versa.

Choice of protective device on the primary side of the transformer

As explained before, for low reference current, the protection may be by fuses or by circuit-breaker.

When the reference current is high, the protection will be achieved by circuit-breaker.

Protection by circuit-breaker provides a more sensitive transformer protection compared with fuses. The implementation of additional protections (earth fault protection, thermal overload protection) is easier with circuit-breakers.

3.3 Interlocks and conditioned operations

Mechanical and electrical interlocks are included on mechanisms and in the control circuits of apparatus installed in substations, as a measure of protection against an incorrect sequence of manœuvres by operating personnel.

Mechanical protection between functions located on separate equipment (e.g. switchboard and transformer) is provided by key-transfer interlocking.

An interlocking scheme is intended to prevent any abnormal operational manœuvre. Some of such operations would expose operating personnel to danger, some others would only lead to an electrical incident.

Basic interlocking

Basic interlocking functions can be introduced in one given functionnal unit; some of these functions are made mandatory by the IEC 62271-200, for metal-enclosed MV switchgear, but some others are the result of a choice from the user.

Considering access to a MV panel, it requires a certain number of operations which shall be carried out in a pre-determined order. It is necessary to carry out operations in the reverse order to restore the system to its former condition. Either proper procedures, or dedicated interlocks, can ensure that the required operations are performed in the right sequence. Then such accessible compartment will be classified as “accessible and interlocked” or “accessible by procedure”. Even for users with proper rigorous procedures, use of interlocks can provide a further help for safety of the operators.

Key interlocking

Beyond the interlocks available within a given functionnal unit (see also 4.2), the most widely-used form of locking/interlocking depends on the principle of key transfer.

The principle is based on the possibility of freeing or trapping one or several keys, according to whether or not the required conditions are satisfied.

These conditions can be combined in unique and obligatory sequences, thereby guaranteeing the safety of personnel and installation by the avoidance of an incorrect operational procedure.

Non-observance of the correct sequence of operations in either case may have extremely serious consequences for the operating personnel, as well as for the equipment concerned.

Note: It is important to provide for a scheme of interlocking in the basic design stage of planning a MV/LV substation. In this way, the apparatuses concerned will be equipped during manufacture in a coherent manner, with assured compatibility of keys and locking devices.

Service continuity

For a given MV switchboard, the definition of the accessible compartments as well as their access conditions provide the basis of the “Loss of Service Continuity” classification defined in the standard IEC 62271-200. Use of interlocks or only proper procedure does not have any influence on the service continuity. Only the request for accessing a given part of the switchboard, under normal operation conditions, results in limiting conditions which can be more or less severe regarding the continuity of the electrical distribution process.

Interlocks in substations

In a MV/LV distribution substation which includes:

- A single incoming MV panel or two incoming panels (from parallel feeders) or two incoming/outgoing ring-main panels
- A transformer switchgear-and-protection panel, which can include a load-break/disconnecting switch with MV fuses and an earthing switch, or a circuit-breaker and line disconnecting switch together with an earthing switch
- A transformer compartment

Interlocks allow manœuvres and access to different panels in the following conditions:

Basic interlocks, embedded in single functionnal units

- Operation of the load-break/isolating switch
  - If the panel door is closed and the associated earthing switch is open
- Operation of the line-disconnecting switch of the transformer switchgear - and - protection panel
  - If the door of the panel is closed, and
  - If the circuit-breaker is open, and the earthing switch(es) is (are) open
- Closure of an earthing switch
  - If the associated isolating switch(es) is (are) open(1)
- Access to an accessible compartment of each panel, if interlocks have been specified
  - If the isolating switch for the compartment is open and the earthing switch(es) for the compartment is (are) closed
- Closure of the door of each accessible compartment, if interlocks have been specified
  - If the earthing switch(es) for the compartment is (are) closed

Functional interlocks involving several functional units or separate equipment

- Access to the terminals of a MV/LV transformer
  - If the tee-off functional unit has its switch open and its earthing switch closed. According to the possibility of back-feed from the LV side, a condition on the LV main breaker can be necessary.

Practical example

In a consumer-type substation with LV metering, the interlocking scheme most commonly used is MV/LV/TR (high voltage/ low voltage/transformer).

The aim of the interlocking is:

- To prevent access to the transformer compartment if the earthing switch has not been previously closed
- To prevent the closure of the earthing switch in a transformer switchgear-and-protection panel, if the LV circuit-breaker of the transformer has not been previously locked “open” or “withdrawn”

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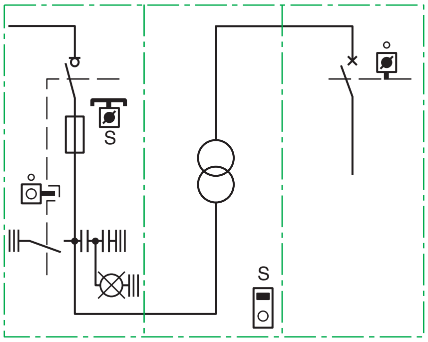
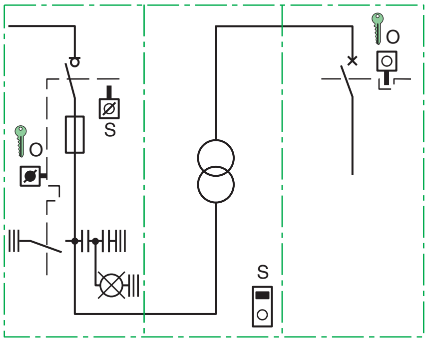
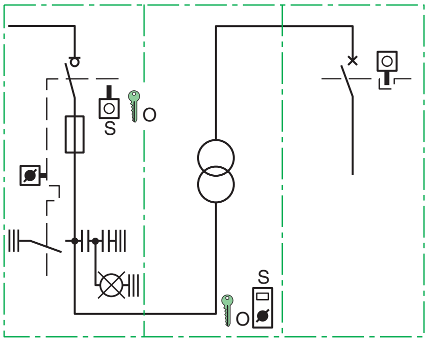
(1) If the earthing switch is on an incoming circuit, the associated isolating switches are those at both ends of the circuit, and these should be suitably interlocked. In such situation, the interlocking function becomes a multi-units key interlock.



MV switch and LV CB closed



MV fuses accessible



Transformer MV terminals accessible

Legend

Key absent

Key free

Key trapped

Panel or door

Fig. B9 : Example of MV/LV/TR interlocking

Access to the MV or LV terminals of a transformer, (protected upstream by a MV switchgear-and-protection panel, containing a MV load-break / isolating switch, MV fuses, and a MV earthing switch) must comply with the strict procedure described below, and is illustrated by the diagrams of **Figure B9**.

Note: The transformer in this example is provided with plug-in type MV terminal connectors which can only be removed by unlocking a retaining device common to all three phase connectors(1).

The MV load-break / disconnecting switch is mechanically linked with the MV earthing switch such that only one of the switches can be closed, i.e. closure of one switch automatically locks the closure of the other.

Procedure for the isolation and earthing of the power transformer, and removal of the MV plug-type shrouded terminal connections (or protective cover)

Initial conditions

- MV load-break/disconnection switch and LV circuit-breaker are closed
- MV earthing switch locked in the open position by key “O”
- Key “O” is trapped in the LV circuit-breaker as long as that circuit-breaker is closed

Step 1

- Open LV CB and lock it open with key “O”
- Key “O” is then released

Step 2

- Open the MV switch
- Check that the “voltage presence” indicators extinguish when the MV switch is opened

Step 3

- Unlock the MV earthing switch with key “O” and close the earthing switch
- Key “O” is now trapped

Step 4

The access panel to the MV fuses can now be removed (i.e. is released by closure of the MV earthing switch). Key “S” is located in this panel, and is trapped when the MV switch is closed

- Turn key “S” to lock the MV switch in the open position
- Key “S” is now released

Step 5

Key “S” allows removal of the common locking device of the plug-type MV terminal connectors on the transformer or of the common protective cover over the terminals, as the case may be.
In either case, exposure of one or more terminals will trap key “S” in the interlock.

The result of the foregoing procedure is that:

- The MV switch is locked in the open position by key “S”.

Key “S” is trapped at the transformer terminals interlock as long as the terminals are exposed.

- The MV earthing switch is in the closed position but not locked, i.e. may be opened or closed. When carrying out maintenance work, a padlock is generally used to lock the earthing switch in the closed position, the key of the padlock being held by the engineer supervizing the work.
- The LV CB is locked open by key “O”, which is trapped by the closed MV earthing switch. The transformer is therefore safely isolated and earthed.

It may be noted that the upstream terminal of the load-break disconnecting switch may remain live in the procedure described as the terminals in question are located in a separate non accessible compartment in the particular switchgear under discussion. Any other technical solution with exposed terminals in the accessed compartment would need further de-energisation and interlocks.

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(1) Or may be provided with a common protective cover over the three terminals.

4 The consumer substation with LV metering

4.1 General

A consumer substation with LV metering is an electrical installation connected to a utility supply system at a nominal voltage of 1 kV - 35 kV, and includes a single MV/LV transformer generally not exceeding 1,250 kVA.

Functions

The substation

All component parts of the substation are located in one room, either in an existing building, or in the form of a prefabricated housing exterior to the building.

Connection to the MV network

Connection at MV can be:

- Either by a single service cable or overhead line, or
- Via two mechanically interlocked load-break switches with two service cables from duplicate supply feeders, or
- Via two load-break switches of a ring-main unit

The transformer

Since the use of PCB[1]-filled transformers is prohibited in most countries, the preferred available technologies are:

- Oil-immersed transformers for substations located outside premises
- Dry-type, vacuum-cast-resin transformers for locations inside premises, e.g. multistoreyed buildings, buildings receiving the public, and so on...

Metering

Metering at low voltage allows the use of small metering transformers at modest cost. Most tariff structures take account of MV/LV transformer losses.

LV installation circuits

A low-voltage circuit-breaker, suitable for isolation duty and locking off facilities, to:

- Supply a distribution board
- Protect the transformer against overloading and the downstream circuits against short-circuit faults.

Simplified electrical network diagram

The diagram on the following page (**Figure B10**) shows:

- Methods for connecting to the network (4 options):
  - ☐ Spur network or single-line service
  - ☐ Provisional network (can be transformed into a loop)
  - ☐ Parallel feeders service
  - ☐ Loop or ring-main service
- MV protection and MV/LV transformation methods
- LV metering and LV general isolation methods
- LV protection and distribution methods
- Zones accessible to different parties

Fig. B11 : SM6 modular unit

4.2 Choosing MV equipment

Standards and specifications

Switchgear and equipment shall conform to the following international standards: IEC 62271-1, 62271-200, 60265-1, 62271-102, 62271-100, 62271-105

Local regulations may also demand conformance to national standards. These include:

- France: UTE
- United Kingdom: BS
- Germany: VDE
- USA: ANSI

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[1] Polychlorinated biphenyl

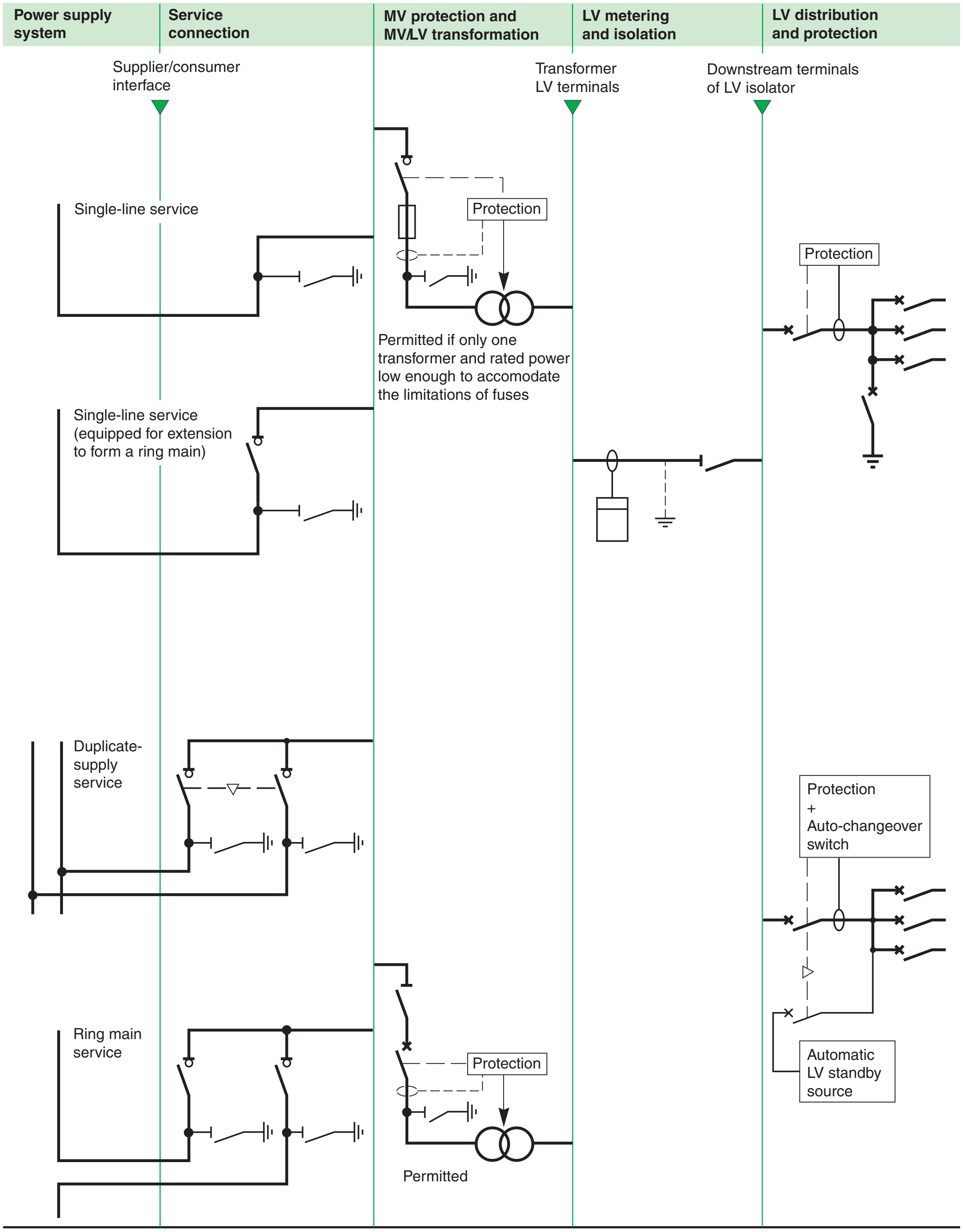


Fig. B10 : Consumer substation with LV metering

Choosing types of equipment

Substations can be implemented in line with local standards and practices using equipment such as:

- Modular units to support all types of layout and any subsequent expansion work (whilst ensuring there is sufficient space)
- Compact arrangements based on the ring-main unit where the supply is provided via a loop (single assembly comprising 3 functions). These are particularly suitable where:
  - Climatic conditions and/or pollution are very bad (integrated insulation)
  - There is not enough space for a modular solution

Compartmentalised modular units in metallic enclosures

IEC 62271-200 standard

The IEC 62271-200 standard specifies «AC metal-enclosed switchgear and controlgear for rated voltages above 1 kV and up to and including 52 kV».

The main precepts of the standard relate to:

- Switchgear types:
  - AIS (Air Insulated Switchgear)
  - GIS (Gas Insulated Switchgear)
- Functional units: «a switchgear component contained in a metallic enclosure and incorporating all the main and auxiliary circuit equipment required to perform a single function» - usually a modular unit
- Compartments: «a switchgear component contained in a closed metallic enclosure (apart from the openings required for interconnection, control or ventilation)». The manufacturer defines the content (e.g. busbar, cables, switchgear, etc.) and the number of compartments able to house the following types of switchgear:
  - Fixed
  - Removable
- Accessibility of individual compartments:
  - Controlled by interlocking or in accordance with procedures; for compartments which can be opened during normal operation
  - Using tools; for compartments which should not be opened during normal operation
  - Zero; for compartments which must not be opened
- The LSC (Loss of Service Continuity) defining the extent to which other compartments can remain energised when one compartment is open
  - LSC1, when opening a compartment requires the other functional units to be de-energised
  - LSC2 A, when the other functional units can remain energised
  - LSC2 B, when the other functional units and all the cable compartments can remain energised
  - The partition class between energised components and an open compartment, based on the type of partition: «a switchgear component contained in a metallic enclosure and separating one compartment from another»:
  - PM: metallic partitions
  - PI: insulating partitions

4.3 Choice of MV switchgear panel for a transformer circuit

Three types of MV switchgear panel are generally available:

- Load-break switch and separate MV fuses in the panel
- Load-break switch/MV fuses combination
- Circuit-breaker

Seven parameters influence the optimum choice:

- The primary current of the transformer
- The insulating medium of the transformer
- The position of the substation with respect to the load centre
- The kVA rating of the transformer
- The distance from switchgear to the transformer
- The use of separate protection relays (as opposed to direct-acting trip coils).

Note: The fuses used in the load-break/switch fuses combination have striker-pins which ensure tripping of the 3-pole switch on the operation of one (or more) fuse(s).

4.4 Choice of MV/LV transformer

Characteristic parameters of a transformer

A transformer is characterized in part by its electrical parameters, but also by its technology and its conditions of use.

Electrical characteristics

- Rated power (Pn): the conventional apparent-power in kVA on which other design-parameter values and the construction of the transformer are based. Manufacturing tests and guarantees are referred to this rating
- Frequency: for power distribution systems of the kind discussed in this guide, the frequency will be 50 Hz or 60 Hz
- Rated primary and secondary voltages: For a primary winding capable of operating at more than one voltage level, a kVA rating corresponding to each level must be given. The secondary rated voltage is its open circuit value
- Rated insulation levels are given by overvoltage-withstand test values at power frequency, and by high voltage impulse tests values which simulate lightning discharges. At the voltage levels discussed in this guide, overvoltages caused by MV switching operations are generally less severe than those due to lightning, so that no separate tests for switching-surge withstand capability are made
- Off-circuit tap-selector switch generally allows a choice of up to ± 2.5% and ± 5% level about the rated voltage of the highest voltage winding. The transformer must be de-energized before this switch is operated
- Winding configurations are indicated in diagrammatic form by standard symbols for star, delta and inter-connected-star windings; (and combinations of these for special duty, e.g. six-or twelve-phase rectifier transformers, etc.) and in an IEC-recommended alphanumeric code. This code is read from left-to-right, the first letter refers to the highest voltage winding, the second letter to the next highest, and so on:

☐ Capital letters refer to the highest voltage winding

D = delta
Y = star
Z = interconnected-star (or zigzag)
N = neutral connection brought out to a terminal

☐ Lower-case letters are used for tertiary and secondary windings

d = delta
y = star
z = interconnected-star (or zigzag)
n = neutral connection brought out to a terminal

☐ A number from 0 to 11, corresponding to those, on a clock dial (“0” is used instead of “12”) follows any pair of letters to indicate the phase change (if any) which occurs during the transformation.

A very common winding configuration used for distribution transformers is that of a Dyn 11 transformer, which has a delta MV winding with a star-connected secondary winding the neutral point of which is brought out to a terminal. The phase change through the transformer is +30 degrees, i.e. phase 1 secondary voltage is at “11 o’clock” when phase 1 of the primary voltage is at “12 o’clock”, as shown in Figure B31 page B34. All combinations of delta, star and zigzag windings produce a phase change which (if not zero) is either 30 degrees or a multiple of 30 degrees. IEC 60076-4 describes the “clock code” in detail.

Characteristics related to the technology and utilization of the transformer

This list is not exhaustive:

- Choice of technology

The insulating medium is:

☐ Liquid (mineral oil) or
☐ Solid (epoxy resin and air)

- For indoor or outdoor installation
- Altitude (<= 1,000 m is standard)
- Temperature (IEC 60076-2)

☐ Maximum ambient air: 40 °C
☐ Daily maximum average ambient air: 30 °C
☐ Annual maximum average ambient air: 20 °C

For non-standard operating conditions, refer to “Influence of the Ambient temperature and altitude on the rated current” on page B7.

Description of insulation techniques

There are two basic classes of distribution transformer presently available:

- Dry type (cast in resin)
- Liquid filled (oil-immersed)

Fig. B12 : Dry-type transformer

Fig. B13 : Hermetically-sealed totally-filled tank

Fig. B14 : Air-breathing conservator-type tank at atmosphere pressure

Dry type transformers

The windings of these transformers are insulated by resin between turns and by resin and air to other windings and to frame. The resin is usually cast under vacuum process (which is patented by major manufacturers).

It is recommended that the transformer be chosen according to the IEC 60076-11, as follows:

- Environment class E2 (frequent condensation and/or high level of pollution)
- Climatic conditions class B2 (utilization, transport and stockage down to -25 °C)
- Fire resistance (transformers exposed to fire risk with low flammability and self extinguishing in a given time)

The following description refers to the process developed by a leading European manufacturer in this field.
The encapsulation of a winding uses three components:

- Epoxy-resin based on biphenol A with a viscosity that ensures complete impregnation of the windings
- Anhydride hardener modified to introduce a degree of resilience in the moulding, essential to avoid the development of cracks during the temperature cycles occurring in normal operation
- Pulverulent additive composed of trihydrated alumina Al (OH)3 and silica which enhances its mechanical and thermal properties, as well as giving exceptional intrinsic qualities to the insulation in the presence of heat.

This three-component system of encapsulation gives Class F insulation ($\Delta\theta$ = 100 K) with excellent fire-resisting qualities and immediate self-extinction. These transformers are therefore classified as nonflammable.

The mouldings of the windings contain no halogen compounds (chlorine, bromine, etc.) or other compounds capable of producing corrosive or toxic pollutants, thereby guaranteeing a high degree of safety to personnel in emergency situations, notably in the event of a fire.

It also performs exceptionally well in hostile industrial atmospheres of dust, humidity, etc. (see **Fig. B12**).

Liquid-filled transformers

The most common insulating/cooling liquid used in transformers is mineral oil. Mineral oils are specified in IEC 60296. Being flammable, safety measures are obligatory in many countries, especially for indoor substations. The DGPT unit (Detection of Gas, Pressure and Temperature) ensures the protection of oil-filled transformers. In the event of an anomaly, the DGPT causes the MV supply to the transformer to be cut off very rapidly, before the situation becomes dangerous.

Mineral oil is bio-degradable and does not contain PCB (polychlorinated biphenyl), which was the reason for banning askerel, i.e. Pyralène, Pyrolio, Pyroline...
On request, mineral oil can be replaced by an alternative insulating liquid, by adapting the transformer, as required, and taking appropriate additional precautions if necessary.

The insulating fluid also acts as a cooling medium; it expands as the load and/or the ambient temperature increases, so that all liquid-filled transformers must be designed to accommodate the extra volume of liquid without the pressure in the tank becoming excessive.

There are two ways in which this pressure limitation is commonly achieved:

- Hermetically-sealed totally-filled tank (up to 10 MVA at the present time)

Developed by a leading French manufacturer in 1963, this method was adopted by the national utility in 1972, and is now in world-wide service (see **Fig. B13**).
Expansion of the liquid is compensated by the elastic deformation of the oil-cooling passages attached to the tank.
The “total-fill” technique has many important advantages over other methods:

☐ Oxydation of the dielectric liquid (with atmospheric oxygen) is entirely precluded
☐ No need for an air-drying device, and so no consequent maintenance (inspection and changing of saturated dessicant)
☐ No need for dielectric-strength test of the liquid for at least 10 years
☐ Simplified protection against internal faults by means of a DGPT device is possible
☐ Simplicity of installation: lighter and lower profile (than tanks with a conservator) and access to the MV and LV terminals is unobstructed
☐ Immediate detection of (even small) oil leaks; water cannot enter the tank

- Air-breathing conservator-type tank at atmospheric pressure

Expansion of the insulating liquid is taken up by a change in the level of liquid in an expansion (conservator) tank, mounted above the transformer main tank, as shown in **Figure B14**. The space above the liquid in the conservator may be filled with air which is drawn in when the level of liquid falls, and is partially expelled when the level rises. When the air is drawn in from the surrounding atmosphere it is admitted through an oil seal, before passing through a dessicating device (generally containing silica-gel crystals) before entering the conservator. In some designs of larger transformers the space above the oil is occupied by an impermeable air bag so that the insulation liquid is never in contact with the atmosphere. The air enters and exits from the deformable bag through an oil seal and dessicator, as previously described. A conservator expansion tank is obligatory for transformers rated above 10 MVA (which is presently the upper limit for "total-fill" type transformers).

Choice of technology

As discussed above, the choice of transformer is between liquid-filled or dry type. For ratings up to 10 MVA, totally-filled units are available as an alternative to conservator-type transformers.

A choice depends on a number of considerations, including:

- Safety of persons in proximity to the transformer. Local regulations and official recommendations may have to be respected
- Economic considerations, taking account of the relative advantages of each technique

The regulations affecting the choice are:

- Dry-type transformer:
  - In some countries a dry-type transformer is obligatory in high apartment blocks
  - Dry-type transformers impose no constraints in other situations
- Transformers with liquid insulation:
  - This type of transformer is generally forbidden in high apartment blocks
  - For different kinds of insulation liquids, installation restrictions, or minimum protection against fire risk, vary according to the class of insulation used
  - Some countries in which the use of liquid dielectrics is highly developed, classify the several categories of liquid according to their fire performance. This latter is assessed according to two criteria: the flash-point temperature, and the minimum calorific power. The principal categories are shown in **Figure B15** in which a classification code is used for convenience.

Code	Dielectric fluid	Flash-point (°C)	Minimum calorific power (MJ/kg)
O1	Mineral oil	< 300	-
K1	High-density hydrocarbons	> 300	48
K2	Esters	> 300	34 - 37
K3	Silicones	> 300	27 - 28
L3	Insulating halogen liquids	-	12

Fig. B15 : Categories of dielectric fluids

The determination of optimal power

Oversizing a transformer

It results in:

- Excessive investment and unecessarily high no-load losses, but
- Lower on-load losses

Undersizing a transformer

It causes:

- A reduced efficiency when fully loaded, (the highest efficiency is attained in the range 50% - 70% full load) so that the optimum loading is not achieved
- On long-term overload, serious consequences for
  - The transformer, owing to the premature ageing of the windings insulation, and in extreme cases, resulting in failure of insulation and loss of the transformer
  - The installation, if overheating of the transformer causes protective relays to trip the controlling circuit-breaker.

Definition of optimal power

In order to select an optimal power (kVA) rating for a transformer, the following factors must be taken into account:

- List the power of installed power-consuming equipment as described in Chapter A
- Decide the utilization (or demand) factor for each individual item of load
- Determine the load cycle of the installation, noting the duration of loads and overloads
- Arrange for power-factor correction, if justified, in order to:
  - Reduce cost penalties in tariffs based, in part, on maximum kVA demand
  - Reduce the value of declared load (P(kVA) = P (kW)/cos φ)
- Select, among the range of standard transformer ratings available, taking into account all possible future extensions to the installation.

It is important to ensure that cooling arrangements for the transformer are adequate.

4.5 Instructions for use of MV equipment

The purpose of this chapter is to provide general guidelines on how to avoid or greatly reduce MV equipment degradation on sites exposed to humidity and pollution.

Normal service conditions for indoor MV equipment

All MV equipments comply with specific standards and with the IEC 62271-1 standard “Common specifications for high-voltage switchgear and controlgear”, which defines the normal conditions for the installation and use of such equipment.
For instance, regarding humidity, the standard mentions:
The conditions of humidity are as follows:

- The average value of the relative humidity, measured over a period of 24 h does not exceed 90%;
- The average value of the water vapour pressure, over a period of 24 h does not exceed 2.2 kPa;
- The average value of the relative humidity, over a period of one month does not exceed 90%;
- The average value of water vapour pressure, over a period of one month does not exceed 1.8 kPa;

Under these conditions, condensation may occasionally occur.

NOTE 1: Condensation can be expected where sudden temperature changes occur in period of high humidity.

NOTE 2: To withstand the effects of high humidity and condensation, such as a breakdown of insulation or corrosion of metallic parts, switchgear designed for such conditions and tested accordingly shoul be used.

NOTE 3: Condensation may be prevented by special design of the building or housing, by suitable ventilation and heating of the station or by use of dehumifying equipment.

As indicated in the standard, condensation may occasionally occur even under normal conditions. The standard goes on to indicate special measures concerning the substation premises that can be implemented to prevent condensation.

Fig. B15 : SM6 metal enclosed indoor MV eqpuipment

Use under severe conditions

Under certain severe conditions concerning humidity and pollution, largely beyond the normal conditions of use mentioned above, correctly designed electrical equipment can be subject to damage by rapid corrosion of metal parts and surface degradation of insulating parts.

Remedial measures for condensation problems

- Carefully design or adapt substation ventilation.
- Avoid temperature variations.
- Eliminate sources of humidity in the substation environment.
- Install an air conditioning system.
- Make sure cabling is in accordance with applicable rules.

Remedial measures for pollution problems

- Equip substation ventilation openings with chevron-type baffles to reduce entry of dust and pollution.
- Keep substation ventilation to the minimum required for evacuation of transformer heat to reduce entry of pollution and dust.
- Use MV cubicles with a sufficiently high degree of protection (IP).
- Use air conditioning systems with filters to restrict entry of pollution and dust.
- Regularly clean all traces of pollution from metal and insulating parts.

Ventilation

Substation ventilation is generally required to dissipate the heat produced by transformers and to allow drying after particularly wet or humid periods.
However, a number of studies have shown that excessive ventilation can drastically increase condensation.
Ventilation should therefore be kept to the minimum level required.
Furthermore, ventilation should never generate sudden temperature variations that can cause the dew point to be reached.
For this reason:
Natural ventilation should be used whenever possible. If forced ventilation is necessary, the fans should operate continuously to avoid temperature fluctuations.

Guidelines for sizing the air entry and exit openings of substations are presented hereafter.

Calculation methods

A number of calculation methods are available to estimate the required size of substation ventilation openings, either for the design of new substations or the adaptation of existing substations for which condensation problems have occurred.
The basic method is based on transformer dissipation.
The required ventilation opening surface areas S and S' can be estimated using the following formulas:

$$S = \frac{1.8 \text{ x } 10^{-4} P}{\sqrt{H}} \text{ and } S' = 1.10 \text{ x } S$$

where:
S = Lower (air entry) ventilation opening area [m²] (grid surface deducted)
S'= Upper (air exit) ventilation opening area [m²] (grid surface deducted)
P = Total dissipated power [W]
P is the sum of the power dissipated by:

- The transformer (dissipation at no load and due to load)
- The LV switchgear
- The MV switchgear

H = Height between ventilation opening mid-points [m]
See **Fig. B16**

Note:

This formula is valid for a yearly average temperature of 20 °C and a maximum altitude of 1,000 m.

It must be noted that these formulae are able to determine only one order of magnitude of the sections S and S', which are qualified as thermal section, i.e. fully open and just necessary to evacuate the thermal energy generated inside the MV/LV substation.
The pratical sections are of course larger according ot the adopted technological solution.

Indeed, the real air flow is strongly dependant:

- on the openings shape and solutions adopted to ensure the cubicle protection index (IP): metal grid, stamped holes, chevron louvers,...
- on internal components size and their position compared to the openings: transformer and/or retention oil box position and dimensions, flow channel between the components, ...
- and on some physical and environmental parameters: outside ambient temperature, altitude, magnitude of the resulting temperature rise.

The understanding and the optimization of the attached physical phenomena are subject to precise flow studies, based on the fluid dynamics laws, and realized with specific analytic software.

Example:

Transformer dissipation = 7,970 W
LV switchgear dissipation = 750 W
MV switchgear dissipation = 300 W
The height between ventilation opening mid-points is 1.5 m.

Calculation:
Dissipated Power P = 7,970 + 750 + 300 = 9,020 W

$$S = \frac{1.8 \text{ x } 10^{-4} P}{\sqrt{1.5}} = 1.32 \text{ m}^2 \text{ and } S' = 1.1 \text{ x } 1.32 = 1.46 \text{ m}^2$$

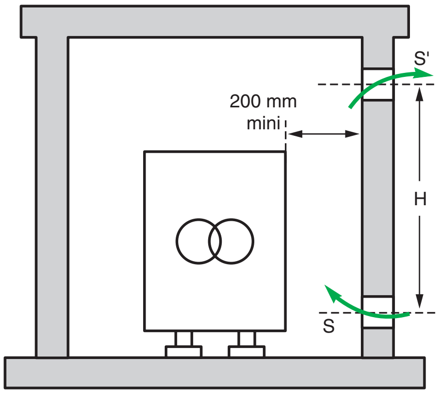


Fig. B16 : *Natural ventilation*

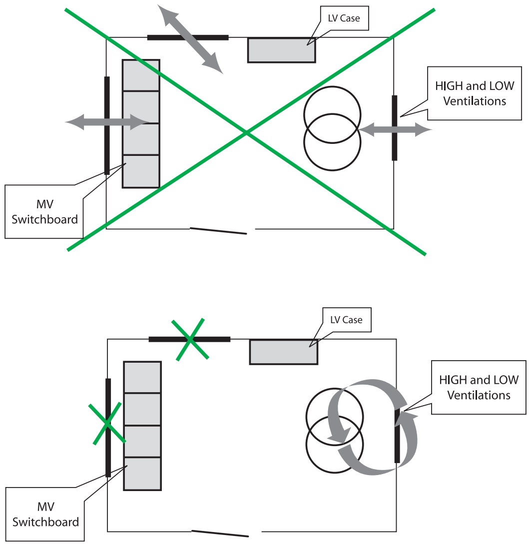


Fig. B17 : *Ventilation opening locations*

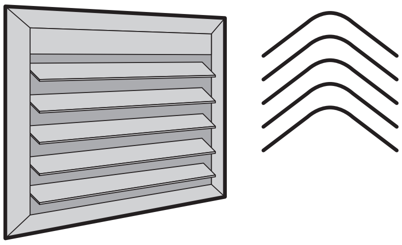


Fig. B18 : *Chevron-blade baffles*

Ventilation opening locations

To favour evacuation of the heat produced by the transformer via natural convection, ventilation openings should be located at the top and bottom of the wall near the transformer. The heat dissipated by the MV switchboard is negligible.

To avoid condensation problems, the substation ventilation openings should be located as far as possible from the switchboard (see **Fig. B 17**).

Type of ventilation openings

To reduce the entry of dust, pollution, mist, etc., the substation ventilation openings should be equipped with chevron-blade baffles.

Always make sure the baffles are oriented in the right direction (see **Fig. B18**).

Temperature variations inside cubicles

To reduce temperature variations, always install anti-condensation heaters inside MV cubicles if the average relative humidity can remain high over a long period of time. The heaters must operate continuously, 24 hours a day all year long.

Never connect them to a temperature control or regulation system as this could lead to temperature variations and condensation as well as a shorter service life for the heating elements. Make sure the heaters offer an adequate service life (standard versions are generally sufficient).

Temperature variations inside the substation

The following measures can be taken to reduce temperature variations inside the substation:

- Improve the thermal insulation of the substation to reduce the effects of outdoor temperature variations on the temperature inside the substation.
- Avoid substation heating if possible. If heating is required, make sure the regulation system and/or thermostat are sufficiently accurate and designed to avoid excessive temperature swings (e.g. no greater than 1 °C).

If a sufficiently accurate temperature regulation system is not available, leave the heating on continuously, 24 hours a day all year long.

- Eliminate cold air drafts from cable trenches under cubicles or from openings in the substation (under doors, roof joints, etc.).

Substation environment and humidity

Various factors outside the substation can affect the humidity inside.

- Plants

Avoid excessive plant growth around the substation.

- Substation waterproofing

The substation roof must not leak. Avoid flat roofs for which waterproofing is difficult to implement and maintain.

- Humidity from cable trenches

Make sure cable trenches are dry under all conditions.

A partial solution is to add sand to the bottom of the cable trench.

Pollution protection and cleaning

Excessive pollution favours leakage current, tracking and flashover on insulators.

To prevent MV equipment degradation by pollution, it is possible to either protect the equipment against pollution or regularly clean the resulting contamination.

Protection

Indoor MV switchgear can be protected by enclosures providing a sufficiently high degree of protection (IP).

Cleaning

If not fully protected, MV equipment must be cleaned regularly to prevent degradation by contamination from pollution.

Cleaning is a critical process. The use of unsuitable products can irreversibly damage the equipment.

For cleaning procedures, please contact your Schneider Electric correspondent.

5 The consumer substation with MV metering

A consumer substation with MV metering is an electrical installation connected to a utility supply system at a nominal voltage of 1 kV - 35 kV and generally includes a single MV/LV transformer which exceeds 1,250 kVA, or several smaller transformers.
The rated current of the MV switchgear does not normally exceed 400 A.

5.1 General

Functions

The substation

According to the complexity of the installation and the manner in which the load is divided, the substation:

- Might include one room containing the MV switchboard and metering panel(s), together with the transformer(s) and low-voltage main distribution board(s),
- Or might supply one or more transformer rooms, which include local LV distribution boards, supplied at MV from switchgear in a main substation, similar to that described above.

These substations may be installed, either:

- Inside a building, or
- Outdoors in prefabricated housings.

Connection to the MV network

Connection at MV can be:

- Either by a single service cable or overhead line, or
- Via two mechanically interlocked load-break switches with two service cables from duplicate supply feeders, or
- Via two load-break switches of a ring-main unit.

Metering

Before the installation project begins, the agreement of the power-supply utility regarding metering arrangements must be obtained.

A metering panel will be incorporated in the MV switchboard. Voltage transformers and current transformers, having the necessary metering accuracy, may be included in the main incoming circuit-breaker panel or (in the case of the voltage transformer) may be installed separately in the metering panel.

Transformer rooms

If the installation includes a number of transformer rooms, MV supplies from the main substation may be by simple radial feeders connected directly to the transformers, or by duplicate feeders to each room, or again, by a ring-main, according to the degree of supply availability desired.

In the two latter cases, 3-panel ring-main units will be required at each transformer room.

Local emergency generators

Emergency standby generators are intended to maintain a power supply to essential loads, in the event of failure of the power supply system.

Capacitors

Capacitors will be installed, according to requirements:

- In stepped MV banks at the main substation, or
- At LV in transformer rooms.

Transformers

For additional supply-security reasons, transformers may be arranged for automatic changeover operation, or for parallel operation.

One-line diagrams

The diagrams shown in **Figure B19** next page represent:

- The different methods of MV service connection, which may be one of four types:
  - Single-line service
  - Single-line service (equipped for extension to form a ring main)
  - Duplicate supply service
  - Ring main service
- General protection at MV, and MV metering functions
- Protection of outgoing MV circuits
- Protection of LV distribution circuits

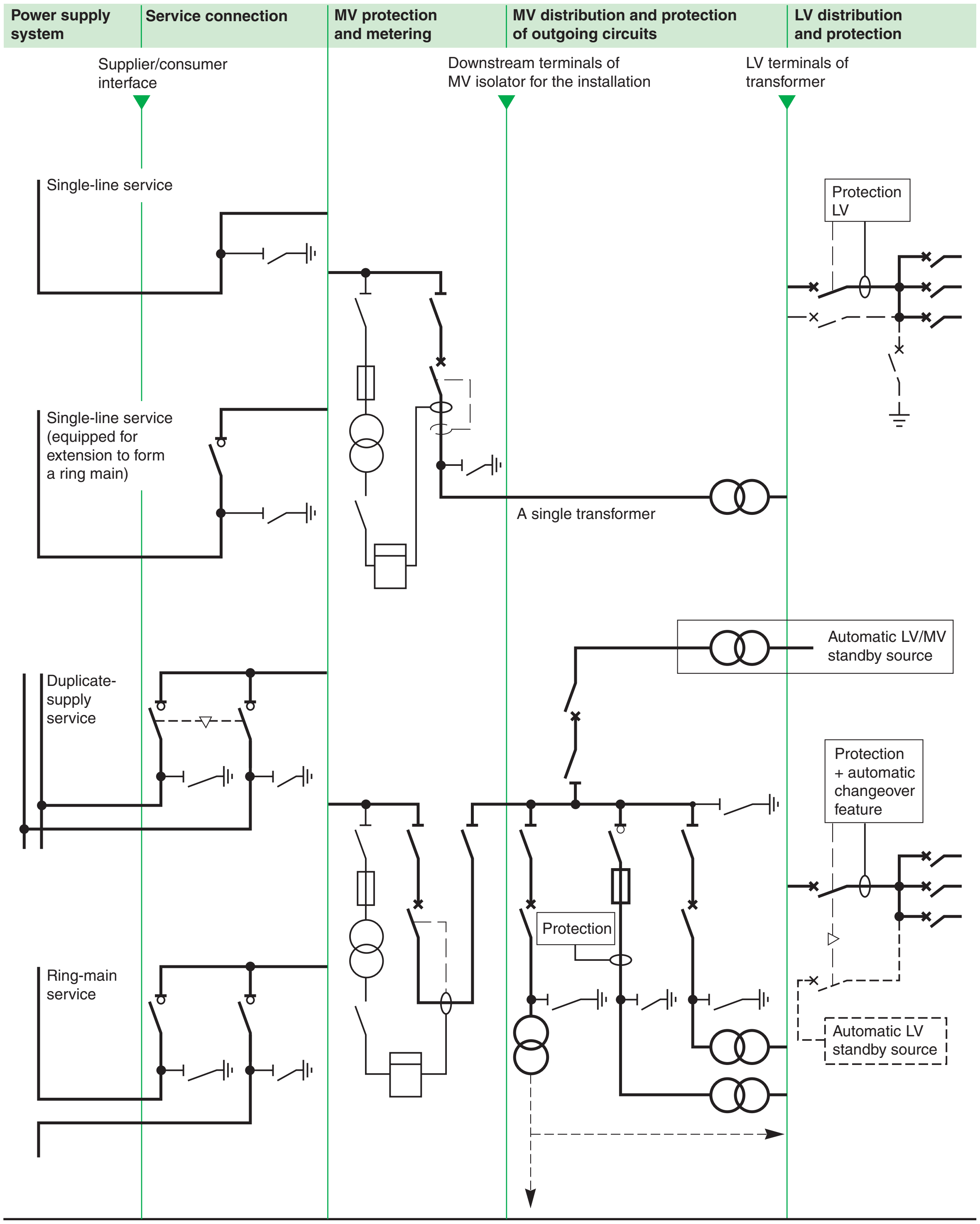


Fig. B19 : *Consumer substation with MV metering*

5.2 Choice of panels

A substation with MV metering includes, in addition to the panels described in 4.2, panels specifically designed for metering and, if required, for automatic or manual changeover from one source to another.

Metering and general protection

These two functions are achieved by the association of two panels:

- One panel containing the VT
- The main MV circuit-breaker panel containing the CTs for measurement and protection

The general protection is usually against overcurrent (overload and short-circuit) and earth faults. Both schemes use protective relays which are sealed by the power-supply utility.

Substation including generators

Generator in stand alone operation

If the installation needs great power supply availability, a MV standby generator set can be used. In such a case, the installation must include an automatic changeover. In order to avoid any posssibility of parallel operation of the generator with the power supply network, a specific panel with automatic changeover is needed (see **Fig. B20**).

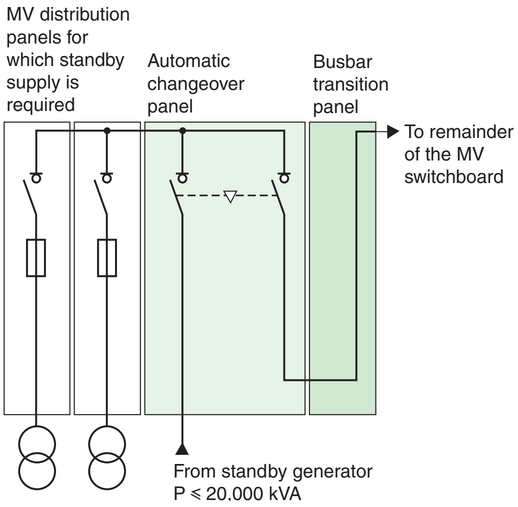


Fig. B20 *: Section of MV switchboard including standby supply panel*

- Protection

Specific protective devices are intended to protect the generator itself. It must be noted that, due to the very low short-circuit power of the generator comparing with the power supply network, a great attention must be paid to protection discrimination.

- Control

A voltage regulator controlling an alternator is generally arranged to respond to a reduction of voltage at its terminals by automatically increasing the excitation current of the alternator, until the voltage is restored to normal. When it is intended that the alternator should operate in parallel with others, the AVR (Automatic Voltage Regulator) is switched to “parallel operation” in which the AVR control circuit is slightly modified (compounded) to ensure satisfactory sharing of kvars with the other parallel machines.

When a number of alternators are operating in parallel under AVR control, an increase in the excitation current of one of them (for example, carried out manually after switching its AVR to Manual control) will have practically no effect on the voltage level. In fact, the alternator in question will simply operate at a lower power factor (more kVA, and therefore more current) than before.

The power factor of all the other machines will automatically improve, such that the load power factor requirements are satisfied, as before.

Generator operating in parallel with the utility supply network

To connect a generator set on the network, the agreement of the power supply utility is usually required. Generally the equipement (panels, protection relays) must be approved by the utility.
The following notes indicate some basic consideration to be taken into account for protection and control.

- Protection

To study the connection of generator set, the power supply utility needs some data as follows :

- ☐ Power injected on the network
- ☐ Connection mode
- ☐ Short-circuit current of the generator set
- ☐ Voltage unbalance of the generator
- ☐ etc.

Depending on the connection mode, dedicated uncoupling protection functions are required :

- ☐ Under-voltage and over-voltage protection
- ☐ Under-frequency and over-frequency protection
- ☐ Zero sequence overvoltage protection
- ☐ Maximum time of coupling (for momentary coupling)
- ☐ Reverse real power

For safety reasons, the switchgear used for uncoupling must also be provided with the characteristics of a disconnector (i.e total isolation of all active conductors between the generator set and the power supply network).

- Control

When generators at a consumer's substation operate in parallel with all the generation of the utility power supply system, supposing the power system voltage is reduced for operational reasons (it is common to operate MV systems within a range of ± 5% of nominal voltage, or even more, where load-flow patterns require it), an AVR set to maintain the voltage within ± 3% (for example) will immediately attempt to raise the voltage by increasing the excitation current of the alternator.

Instead of raising the voltage, the alternator will simply operate at a lower power factor than before, thereby increasing its current output, and will continue to do so, until it is eventually tripped out by its overcurrent protective relays. This is a well-known problem and is usually overcome by the provision of a "constant power-factor" control switch on the AVR unit.

By making this selection, the AVR will automatically adjust the excitation current to match whatever voltage exists on the power system, while at the same time maintaining the power factor of the alternator constant at the pre-set value (selected on the AVR control unit).

In the event that the alternator becomes decoupled from the power system, the AVR must be automatically (rapidly) switched back to "constant-voltage" control.

5.3 Parallel operation of transformers

The need for operation of two or more transformers in parallel often arises due to:

- Load growth, which exceeds the capactiy of an existing transformer
- Lack of space (height) for one large transformer
- A measure of security (the probability of two transformers failing at the same time is very small)
- The adoption of a standard size of transformer throughout an installation

Total power (kVA)

The total power (kVA) available when two or more transformers of the same kVA rating are connected in parallel, is equal to the sum of the individual ratings, providing that the percentage impedances are all equal and the voltage ratios are identical.

Transformers of unequal kVA ratings will share a load practically (but not exactly) in proportion to their ratings, providing that the voltage ratios are identical and the percentage impedances (at their own kVA rating) are identical, or very nearly so. In these cases, a total of more than 90% of the sum of the two ratings is normally available.

It is recommended that transformers, the kVA ratings of which differ by more than 2:1, should not be operated permanently in parallel.

Conditions necessary for parallel operation

All paralleled units must be supplied from the same network.

The inevitable circulating currents exchanged between the secondary circuits of paralleled transformers will be negligibly small providing that:

- Secondary cabling from the transformers to the point of paralleling have approximately equal lengths and characteristics
- The transformer manufacturer is fully informed of the duty intended for the transformers, so that:
  - The winding configurations (star, delta, zigzag star) of the several transformers have the same phase change between primary and secondary voltages
  - The short-circuit impedances are equal, or differ by less than 10%
  - Voltage differences between corresponding phases must not exceed 0.4%
  - All possible information on the conditions of use, expected load cycles, etc. should be given to the manufacturer with a view to optimizing load and no-load losses

Common winding arrangements

As described in 4.4 “Electrical characteristics-winding configurations” the relationships between primary, secondary, and tertiary windings depend on:

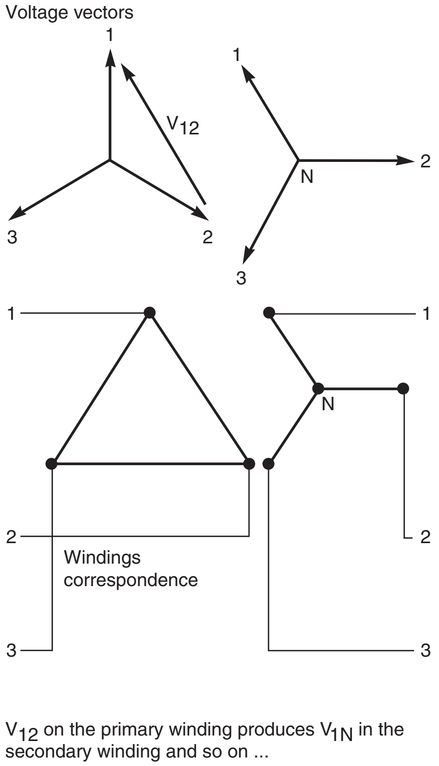
- Type of windings (delta, star, zigzag)
- Connection of the phase windings

Depending on which ends of the windings form the star point (for example), a star winding will produce voltages which are 180° displaced with respect to those produced if the opposite ends had been joined to form the star point. Similar 180° changes occur in the two possible ways of connecting phase-to-phase coils to form delta windings, while four different combinations of zigzag connections are possible.

- The phase displacement of the secondary phase voltages with respect to the corresponding primary phase voltages.

As previously noted, this displacement (if not zero) will always be a multiple of 30° and will depend on the two factors mentioned above, viz type of windings and connection (i.e. polarity) of the phase windings.

By far the most common type of distribution transformer winding configuration is the Dyn 11 connection (see **Fig. B21**).



V_{12} on the primary winding produces V_{1N} in the secondary winding and so on ...

Fig. B21 : Phase change through a Dyn 11 transformer

6 Constitution of MV/LV distribution substations

MV/LV substations are constructed according to the magnitude of the load and the kind of power system in question.

Substations may be built in public places, such as parks, residential districts, etc. or on private premises, in which case the power supply authority must have unrestricted access. This is normally assured by locating the substation, such that one of its walls, which includes an access door, coincides with the boundary of the consumers premises and the public way.

6.1 Different types of substation

Substations may be classified according to metering arrangements (MV or LV) and type of supply (overhead line or underground cable).
The substations may be installed:

- Either indoors in room specially built for the purpose, within a building, or
- An outdoor installation which could be :
  - Installed in a dedicated enclosure prefabricated or not, with indoor equipment (switchgear and transformer)
  - Ground mounted with outdoor equipment (switchgear and transformers)
  - Pole mounted with dedicated outdoor equipment (swithgear and transformers)

Prefabricated substations provide a particularly simple, rapid and competitive choice.

6.2 Indoor substation

Conception

Figure B22 shows a typical equipment layout recommended for a LV metering substation.
Remark: the use of a cast-resin dry-type transformer does not need a fireprotection oil sump. However, periodic cleaning is needed.

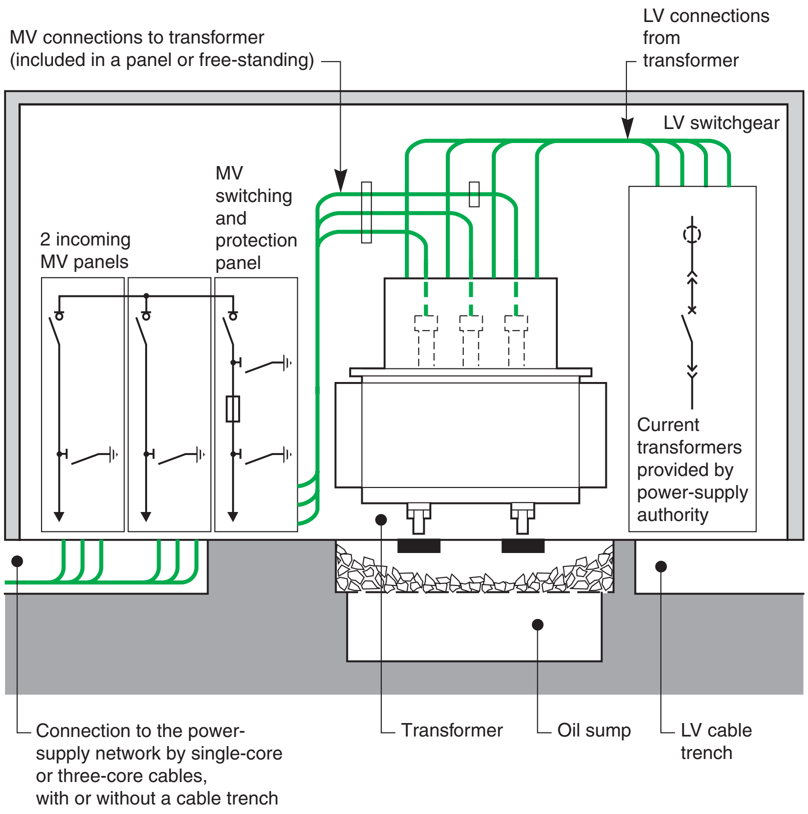


Fig. B22 : Typical arrangment of switchgear panels for LV metering

Service connections and equipment interconnections

At high voltage

- Connections to the MV system are made by, and are the responsibility of the utility
- Connections between the MV switchgear and the transformers may be:
  - By short copper bars where the transformer is housed in a panel forming part of the MV switchboard
  - By single-core screened cables with synthetic insulation, with possible use of plug-in type terminals at the transformer

At low voltage

- Connections between the LV terminals of the transformer and the LV switchgear may be:
  - Single-core cables
  - Solid copper bars (circular or rectangular section) with heat-shrinkable insulation

Metering (see **Fig. B23**)

- Metering current transformers are generally installed in the protective cover of the power transformer LV terminals, the cover being sealed by the supply utility
- Alternatively, the current transformers are installed in a sealed compartment within the main LV distribution cabinet
- The meters are mounted on a panel which is completely free from vibrations
- Placed as close to the current transformers as possible, and
- Are accessible only to the utility

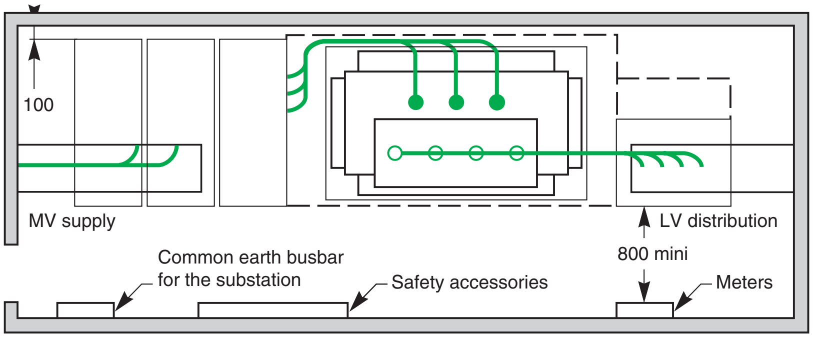


Fig. B23 : Plan view of typical substation with LV metering

Earthing circuits

The substation must include:

- An earth electrode for all exposed conductive parts of electrical equipment in the substation and exposed extraneous metal including:
  - Protective metal screens
  - Reinforcing rods in the concrete base of the substation

Substation lighting

Supply to the lighting circuits can be taken from a point upstream or downstream of the main incoming LV circuit-breaker. In either case, appropriate overcurrent protection must be provided. A separate automatic circuit (or circuits) is (are) recommended for emergency lighting purposes.

Operating switches, pushbuttons, etc. are normally located immediately adjacent to entrances.

Lighting fittings are arranged such that:

- Switchgear operating handles and position indication markings are adequately illuminated
- All metering dials and instruction plaques and so on, can be easily read

Materials for operation and safety

According to local safety rules, generally, the substation is provided with:

- Materials for assuring safe exploitation of the equipment including:
  - Insulating stool and/or an insulating mat (rubber or synthetic)
  - A pair of insulated gloves stored in an envelope provided for the purpose
  - A voltage-detecting device for use on the MV equipment
  - Earthing attachments (according to type of switchgear)
- Fire-extinguishing devices of the powder or CO2 type
- Warning signs, notices and safety alarms:
  - On the external face of all access doors, a DANGER warning plaque and prohibition of entry notice, together with instructions for first-aid care for victims of electrical accidents.

6.3 Outdoor substations

Outdoor substation with prefabricated enclosures

A prefabricated MV/LV substation complying with IEC 62271-202 standard includes :

- equipement in accordance with IEC standards
- a type tested enclosure, which means during its design, it has undergone a battery of tests (see **Fig. B24**):
  - Degree of protection
  - Functional tests
  - Temperature class
  - Non-flammable materials
  - Mechanical resistance of the enclosure
  - Sound level
  - Insulation level
  - Internal arc withstand
  - Earthing circuit test
  - Oil retention,…

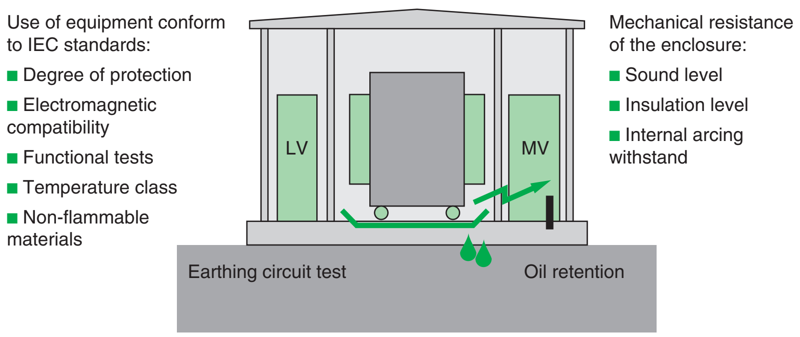


Fig. B24 : Type tested substation according to IEC 62271-202 standard

Main benefits are :

- Safety:
  - For public and operators thanks to a high reproducible quality level
- Cost effective:
  - Manufactured, equipped and tested in the factory
- Delivery time
  - Delivered ready to be connected.

IEC 62271-202 standard includes four main designs (see **Fig. B25**)

- Walk-in type substation :
  - Operation protected from bad weather conditions
- Non walk-in substation
  - Ground space savings, and outdoors operations
- Half buried substation
  - Limited visual impact
- Underground substation
  - Blends completely into the environment.

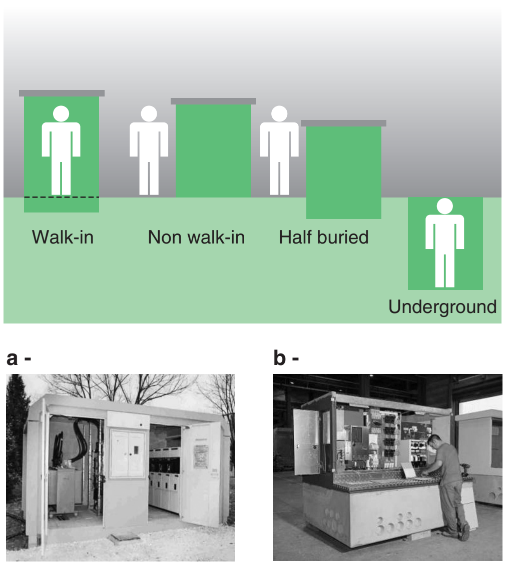


*Fig. B25 : The four designs according to IEC 62271-202 standard and two pictures **[a]** walk-in type MV/LV substation; **[b]** half buried type MV/LV substation*

6 Constitution of MV/LV distribution substations

Outdoor substations without enclosures (see **Fig. B26**)

These kinds of outdoor substation are common in some countries, based on weatherproof equipment exposed to the elements.

These substations comprise a fenced area in which three or more concrete plinths are installed for:

- A ring-main unit, or one or more switch-fuse or circuit-breaker unit(s)
- One or more transformer(s), and
- One or more LV distribution panel(s).

Pole mounted substations

Field of application

These substations are mainly used to supply isolated rural consumers from MV overhead line distribution systems.

Constitution

In this type of substation, most often, the MV transformer protection is provided by fuses.
Lightning arresters are provided, however, to protect the transformer and consumers as shown in **Figure B27**.

General arrangement of equipment

As previously noted the location of the substation must allow easy access, not only for personnel but for equipment handling (raising the transformer, for example) and the manœuvring of heavy vehicles.

Fig. B26 : Outdoor substations without enclosures

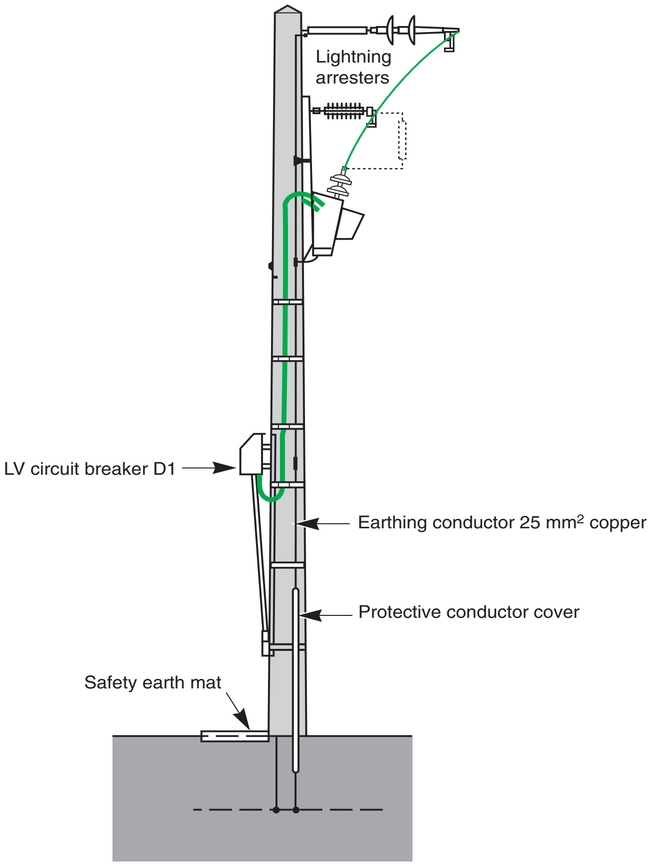


Fig. B27 : Pole-mounted transformer substation