ELECTRICITY

EARTH AND NEUTRAL

TRAINING MANUAL
Course EXP-MN-SE070
Revision 0

ELECTRICITY

EARTH AND NEUTRAL

CONTENTS

1. OBJECTIVES

At the end of this presentation, the electrician (or future electrician) will be able to:

- Differentiate the different neutral arrangements in LV and HV,
- Explain the reasons why the neutral must be connected (or not) to the earth,
- Associate the distribution protections according to the neutral arrangement used,
- Explain the equipotentiality of equipment grounds principle,
- Differentiate the techniques used to install earth connections,
- Choose/identify/select the cross-sectional area of the earth connectors,
- Differentiate the different distribution and earth connection principles,
- Establish the link or parallel between earth resistance and insulating resistance,
- Use the appropriate measuring instruments to measure earth and insulating resistance,
- Describe the earthing systems for lightning protection,
- Justify the interconnections between a site's different earthing systems.

2. INTRODUCTION

Earthing of equipment, the earthing network and the principles of earthing the neutral exist for two reasons:

- Protection of persons,
- Protection of property and equipment.

Let us describe/revise the risks.

2.1. DEFINITIONS

Active conductors

All conductors used for the transmission of electrical energy, including the neutral.

Equipment ground

Conductive part liable to be touched and normally insulated from the active parts but which can accidentally become energised with a hazardous voltage.

Direct contact

This is when someone touches or comes in contact with the active parts of electrical equipment (conductors or energised parts).

Figure 1: Direct contact

The NF C 15-100 standard defines direct contact as follows: "contact by persons or domestic or farm with active parts".

Indirect contact

Contact by persons with equipment grounds which have been accidentally energised following an insulation fault.

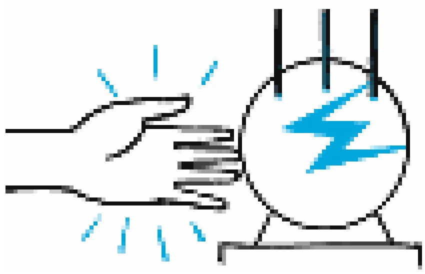


Figure 2: Indirect contact

The NF C 15-100 standard defines indirect contact as follows: "contact by persons or domestic or farm animals with equipment grounds energised following an insulation fault".

Fault current Id

Current resulting from an insulation fault.

Residual current

IΔn is the rms value of the vectoral sum of the current flowing through all the active conductors of a circuit at a point in the installation.

Residual operating current If

Value of the residual differential current causing the device or system to operate. In France, the construction standards define this current as follows:
at 20 °C, IΔn/2 ≤ If ≤ IΔn.

2.2. EFFECTS OF CURRENT FLOWING THROUGH THE HUMAN BODY

2.2.1. Impedance of the human body

The information given in this chapter is taken from the report resulting from the 1984 IEC 479-1 standard and the 1987 IEC 479-2 standard which concern the effects of current flowing through the human body. The risks run when an electric current flows through a person basically depend on its current value and the exposure time.

This current depends on the contact voltage (also known as "touch voltage") which affects this person, and on the impedance this current encounters when passing through the human body. This relationship is not linear because this impedance depends on the path taken through the body, the current frequency, the applied contact voltage and the dampness of the skin.

2.2.2. Effects of alternating current AC (between 15 and 100 Hz)

Perception threshold: minimum value of the current which causes a sensation for a person through which the current flows. 0.5 mA approx.

Non-release threshold: maximum current value for which a person holding electrodes can release them. Generally considered to be 10 mA.

Ventricular fibrillation threshold of the human heart: this threshold depends on the time the current takes to pass through the body. It is considered to be equal to 400 mA for an exposure time less than 0.1 s.

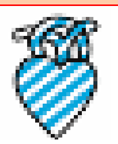
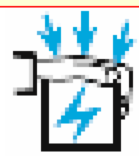
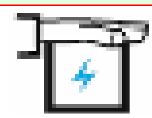
1 A	75 mA	30 mA	10 mA	0.5 mA
				
Cardiac arrest	Irreversible cardiac fibrillation threshold	Respiratory paralysis threshold	Muscular contraction (can't let go)	Very low sensation

Table 1: Summary of the consequences of current flowing through the human body

The physiological effects of electric current are summarised in the table in this paragraph.

2.2.3. Effects of AC at a frequency higher than 100 Hz

The higher the current frequency, the lower the risks of ventricular fibrillation; but the greater the risks of burns. However, the higher the current (between 200 and 400 Hz), the lower the impedance of the human body. It is generally considered that the conditions for protection against direct contacts are identical at 400 Hz and at 50/60 Hz.

2.2.4. Effects of direct current DC

DC appears to be less dangerous than AC; it is less difficult to release parts gripped with the hand than with AC. In DC, the ventricular fibrillation threshold is much higher.

2.2.5. Effects of currents with special waveforms

The development of electronic control systems risks creating, in the case of an insulating fault, currents the shape of which consists of AC with a DC component superimposed on it. The effects of these currents on the human body are midway between those of AC and those of DC.

2.2.6. Effects of short single-pulse currents

These result from capacitor discharges and can represent certain hazards for persons in the case of an insulation fault. The main factor which can cause ventricular fibrillation is the value of the quantity of electricity It or of energy I^2t for shock durations less than 10 ms. The pain threshold depends on the pulse load and its peak value. It is generally around 50 to 100 x 10^6 A2s.

2.2.7. Risk of burns

Another major risk linked with electricity is burns. These are very frequent with domestic accidents and particularly with industrial accidents (over 80 % of the electrical accidents observed at the EDF are burns). There are two types of burns:

- burns due to arcs: these are thermal burns due to the intense heat given off by an electric arc,
- electrothermal burns: these are the only true electrical burns, and they are due to the current flowing through the human body.

2.3. PROTECTION AGAINST DIRECT CONTACTS WHATEVER THE NEUTRAL POINT ARRANGEMENT

The active parts can be the active conductors, the windings of a motor or transformer, or the tracks of a printed circuit.

The current can flow either from one active conductor to another by passing through the human body, or from an active conductor to earth then to the source by passing through the human body. In the first case, the person must be considered as a single-phase load, and in the second case the person must be considered as an insulation fault.

In the analysis of the direct contact protections to be used, direct contact is characterised by the absence or non-effect of a protective conductor.

Whatever the neutral point arrangement is during a direct contact, the current which returns to the source is that which flows through the human body.

According to the NF C 15-100 standard there are several types of means to be put in place to protect persons against direct contacts.

2.3.1. Measures making direct contact non-hazardous

Very low voltage (VLSV, VLPV) limited to 25 V can be used (operating limitations, low powers carried). See course "Electrical Safety" SE180

2.3.2. Preventive measures

They are designed to place the energised active parts out of reach:

- insulation of the active parts: insulated casing of a circuit breaker, outer insulation of a cable, etc.
- barriers or enclosures (boxes or cubicles with minimum protection level IP 2x or IP xx.B). These enclosures can only be opened with a key or a tool, or after switching off the active parts, or even with the automatic interposition of a screen.
- separation distance or obstacles to ensure hazardous parts are out of reach: partial protection mainly used in electrical service rooms.

2.3.3. Additional protection

Some installations may however have special risks, in spite of the use of the previous systems: insulation which may be defective (worksites, conductive enclosures), protective conductor absent or which may be cut, etc.

In this case the NF C 15-100 standard defines an additional protection: the use of highly sensitive residual current devices (RCD) ($I\Delta n \leq 30$ mA). These RCDs provide protection for persons by detecting and cutting the fault current as soon as it appears.

2.4. INDIRECT CONTACT PROTECTION

2.4.1. Energised equipment grounds

These equipment grounds can be the external housing of a motor, of a switchboard or of domestic electrical equipment. They are metallic or conductive and contain energised active parts. They must not be confused with the electronic grounds specific to the operation of electronic assemblies and are connected to the earth via a protective conductor (**PE**). When no insulation faults are present, these electrical grounds must be at a zero potential with respect to earth since they are normally accessible to unauthorised persons. When an insulation fault is present, this equipment ground is in contact with an active part and the current flowing through the fault and through the equipment ground returns to earth either via the protective conductor or via a person in contact with the equipment.

The characteristic of an indirect contact is that the fault current never totally flows through the human body.

2.4.2. Indirect contact protection measures

They are of two types according to NF C 15-100:

Protection without power supply disconnection: use of very low voltage (VLSV, VLPV), electrical separation of the circuits, use of class II equipment, installation with additional insulation, separation distance or interposition of obstacles, local electrical bonding not connected to earth. (See course SE180.)

Protection by automatic power supply disconnection: it is necessary because the previous protection measures are, in fact, only local measures.

This protection against automatic disconnection is only effective when the following two conditions are met:

- ***1st condition***: all the accessible equipment grounds and conductive elements must be interconnected and earthed. Two simultaneously accessible mechanical grounds must be connected to the same earth connection.

- ***2nd condition*** (when the 1st is met): the disconnection must be achieved by automatically switching off the part of the installation where the insulation fault is located, to prevent a person being subjected to a contact voltage Uc for a time which renders this hazardous.

Figure 3: Switch-off when Uc appears

The higher this voltage, the faster this faulty part of the installation must be switched off.

This switch-off of the installation will be different according to the different arrangements (neutral arrangements): see following chapter: the TT, TN and IT arrangements.

The NF C 15-100 standard defines the maximum disconnection time for the protection device in normal conditions.

(UL = 50 V) is the highest contact voltage which can be maintained indefinitely without danger to persons).

Presumed contact voltage (V)	50	75	90	120	150	220	280	350	500
Maximum disconnection time for the device and protection(s) U_L = 50 V	5	0.60	0.45	0.34	0.27	0.17	0.12	0.08	0.04

Table 2: Maximum authorised disconnection time according to the contact voltage

3. EARTHING AND GROUND NETWORK

3.1. EARTH AND EXPOSED CONDUCTIVE PARTS

3.1.1. Earth electrode (earth connection)

3.1.1.1. Prime function of an earth electrode

The prime function of an earth electrode is the protection of persons.

It is a fact that we live on Earth! And it is vital to earth exposed metal parts of electrical equipment to avoid electrocution by indirect contact should an insulation fault occur. This measure has been stipulated in the standards since 1923 (IEC 364; NF C 15-100).

The fault current varies in strength according to the earthing system used, and measures are taken to ensure that contact voltage does not exceed conventional safety voltage for a stipulated time: UL (50 V in a.c.); *(See course eon Electrical Safety SE180).*

The exposed metal parts of electrical equipment are connected to the protective conductors (PE) in turn connected to the earth, thus forming the earthing arrangement.

3.1.1.2. Second function of an earth electrode

The second function of an earth electrode is to minimise common mode disturbances external to the LV installation.

An example is 50/60 Hz overvoltage in the event of MV/LV transformer breakdown (see figure left side) or overvoltage due to lightning (see figure right side).

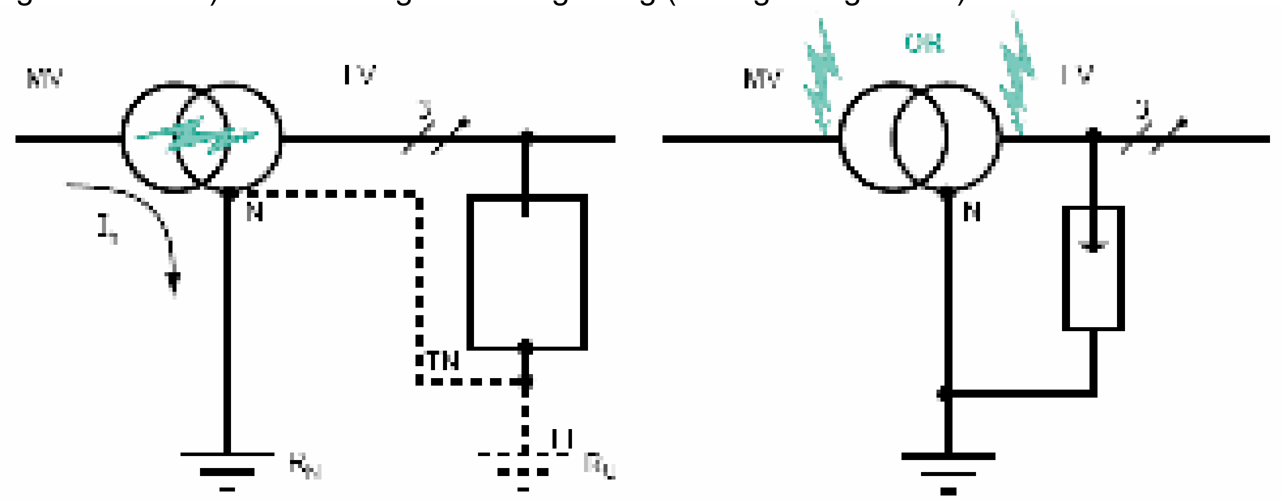
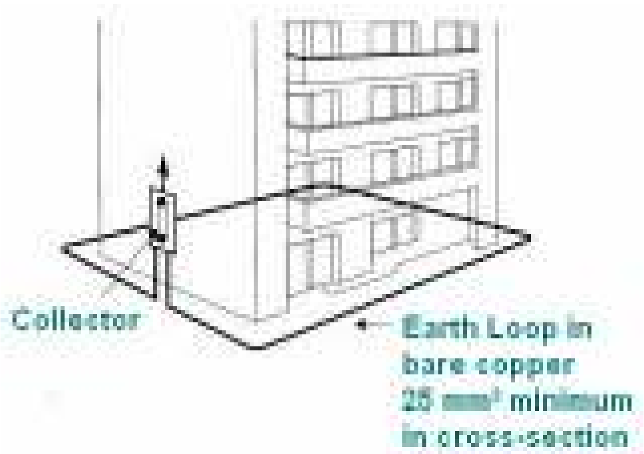


Figure 4: Overvoltage due to transformer breakdown and due to lightning

With reference to the above, NF C 13-100 has laid down limit earth electrode values in France.

Lightning, MV/LV faults and safety of persons call for use of low impedance earth electrodes (Ih_{MV} can reach 1000 A and the insulating voltage of sensitive devices is 1500 V!). This problem particularly needs to be managed in TT earthing systems.



Naturally multiple earth electrodes should be avoided unless they are interconnected.

Figure 5: Earth Electrode, foundation Loop type

The earth electrode may be one or more spikes* pressed into the ground or a foundation ditch loop, or a combination of both.

*Saying spike is a "general" word as any electrician thinks immediately of the "traditional" copper bar, but an earth electrode can be of "anything": rods or tubes - flat steel wire or cable - plate - framework in foundations concrete - metallic water pipes – etc, as long as it is metallic, conducts electricity and has the adapted dissipation surface in the soil with a low resistance/resistivity.

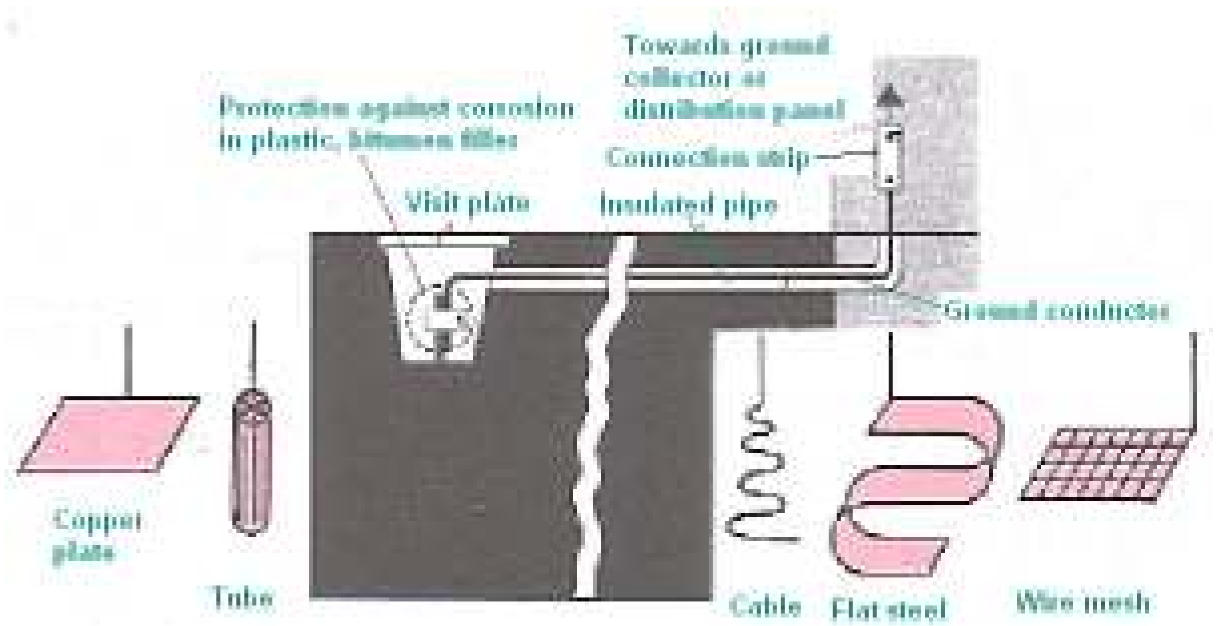


Figure 6: Earth Electrode, "spike" type

3.1.1.3. Execution of earth electrodes

a) For a spike: **R =** ρ / L with L: length of the spike

b) Earth digging loop / foundation ditch loop:

Considered as the best system
Resistance in ohm : $R = 2 \rho / L$
With ρ: resistivity of soil in ohm-m and ***L:*** length of the loop

c) Rods (tubes):

- Solution for existing building
- In round plain Cu, diameter /15 mm
- In galvanised steel:
  - Plain, round diameter / 15 mm
  - Tube diameter/ 25 mm
  - Shaped plate: 60 mm sided minimum
- Length / 2 m

$R = 1 / n \times \rho / L$ n: number of rods

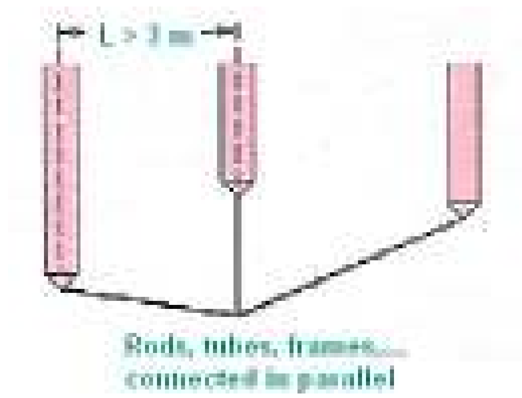
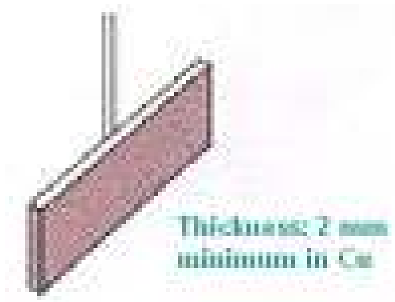


Figure 7: Earth Electrode in tubes

d) Vertical plates



- Plate rectangular or squared (L /0.5m)
- Depth in soil: centre of plate /1m deep
- Copper of 2 mm thickness (minimum)
- Galvanise steel of 3 mm thickness (minimum)

$R = 0.8 \rho / L$

Figure 8: Earth Electrode in vertical plate

3.1.2. Equipotential bonding system

3.1.2.1. Types of conductive parts

A building contains a variety of metal conductive parts, for example:

- the metal casings of electrical loads and electronic equipment,
- the metal structures of buildings,
- the water or gas pipes and facilities,
- the functional bonding conductors of the signal transmission electronic equipment (0 volt),
- the shield and Faraday cage type exposed conductive parts whose function is to block electromagnetic fields.

Like for the earth electrode, the EBS *(Equipotential Bonding System)* has two functions:

3.1.2.2. First function: protection of persons

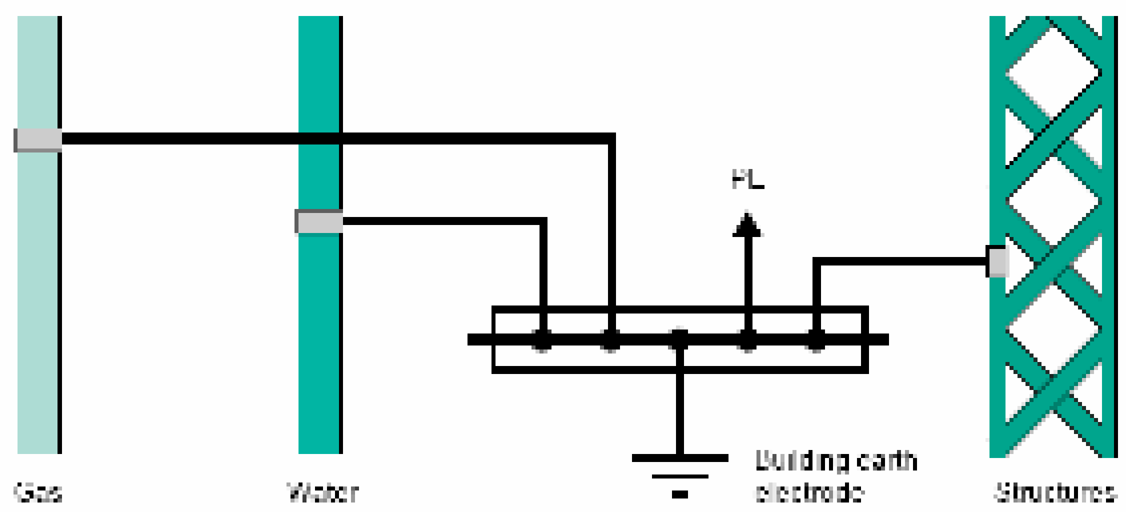


Figure 9: Connection of all exposed conductive parts to the main equipotential bonding.

Dangerous potentials may be present between metal casings, gas or water pipes and the metal structures of buildings. To ensure protection of persons, all simultaneously accessible exposed conductive parts must therefore be interconnected and the building must be made equipotential.

It is with this in mind that installation standards stipulate that all the above mentioned exposed conductive parts ***must be connected to the main equipotential bonding regardless of the earthing (neutral) system*** (see figure).

The earthing of load exposed conductive parts forms a star-shaped protection equipotential bonding system, with tree-structured distribution of the protective conductors (**PE**) as they are in the same cables as the live conductors.

(See following paragraph, "earthing on site" for details on the electrical ground different systems)

3.1.2.3. Second function: dependability of electronic systems

Electronic systems are more sensitive than people to differences in potential and electromagnetic radiation. In addition to conducted disturbance blocking devices, they require ground planes, shields and Faraday cages to block the electromagnetic fields, as well as equipotential bonding system, particularly in the case of devices communicating via data transmission bus.

In this case equipotential bonding must be optimum in the building since communicating devices, whether used for control/monitoring or computer purposes, may be located geographically at some distance from each other on the same floor of a building or even on different floors.

3.1.2.4. Solution

The solution is a meshed equipotential bonding system. A number of reasons justify this choice:

- The fight against lightning electromagnetic fields. Lightning may directly strike the building. If this happens, if only one lightning rod down-comer conductor is used, the lightning current will result in:

  - appearance of a very strong magnetic field in the building,

  - a pulsating electrical field due to the very high voltage developed in the down-coming conductor

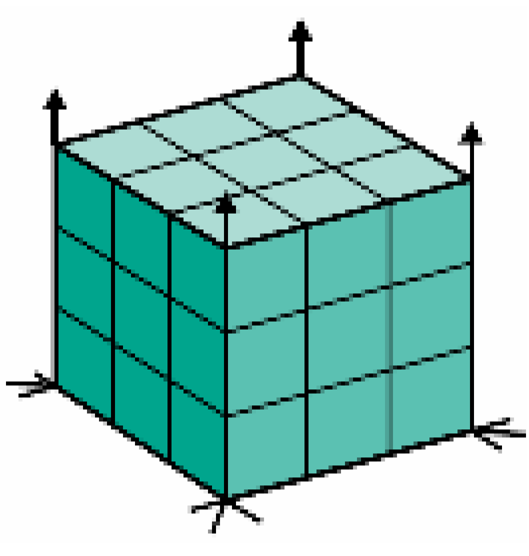


Figure 10: Horizontal and vertical mesh bonding of the building - a Faraday cage.

The solution is vertical mesh bonding with a down-coming conductor every 10 m for example. The advantage is the division of currents and hence of magnetic fields, and the self-attenuation of these fields inside the building due to their mutual opposition.

Lightning may fall near a building. If this occurs, protection of the installations inside this building requires creation of a Faraday cage and thus addition of a horizontal mesh bonding to the vertical mesh bonding (see figure).

- Locally, reduction of electromagnetic fields as a result of the ground plane effect.

If a sensitive device or communication bus is placed on a conductive surface, it is less exposed to electromagnetic fields as this surface develops a field which opposes the disturbing field.

This is why computer rooms have meshed floors and why low current cables are placed on metal trunkings.

- Minimisation of bonding impedances between any two points.

The impedance of a copper conductor rises with the frequency of the current that it conveys (inductance and skin effect). Thus at 1 MHz, Z is of the order of 10 W a metre.

Equipotential-bonding is considerably improved if the disturbing current is able to choose between a large number of routes.

3.1.3. Mesh bonding between protective EBS and other EBS

We have seen above *(and we see it again in the following chapter/paragraph)* that earthing arrangements dedicated to the protection of persons are star structured (tree-structured for the protective conductor) and that a single meshed EBS *(Equipotential Bonding System)* is required for dependability of electronic systems.

In theory these circuits can be separated in the building even if they are connected to the same earth connection.

Even if standards define several types of potential references (see table), in practice few electrical and electronic devices and systems make such distinctions. For example the notion of a noise-less exposed conductive part is questionable and rapidly going out of use in view of the development of communicating systems and the large number of interconnections.

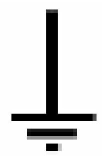
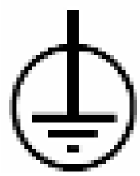
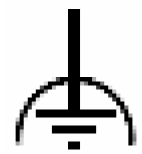
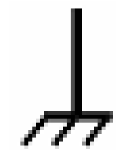
			
Earth	Protective conductor	Noiseless earth	Exposed conductive part
Terre	Conductor de protection	Terre sans bruit	Mechanical ground

Table 3: Examples of earth and exposed conductive part symbols as in NF C 03-202.

In high frequency, stray capacitances make these distinctions even more illusory. The equipotential protection system (electrical exposed conductive parts) and the equipotential functional system (other exposed conductive parts) thus need to be connected in the new buildings to form one single system of equipotential bondings.

This system must guarantee the integrity of the protective links (PE) to ensure protection of persons. There is no need to oppose high current star-shaped systems and the meshed systems required for low currents.

In existing buildings/sites it is advisable to ensure interconnection of exposed conductive parts between sensitive devices (if they communicate), to increase electrical continuity of trunkings and create meshed ground planes if required.

3.2. EQUIPOTENTIAL NETWORK

Extracted from Total Specifications GS ELE 031 chapter 4

3.2.1. Equipotential network for an onshore installation

3.2.1.1. Diagram

The equipotential earth bonding system shall comprise internal loops and a general earth grid, connected at least in two opposite points. These two links shall have the same cross-sectional area as that of the cable to which they are connected. The minimum equivalent cross-sectional area of these links shall be 70 mm² Cu.

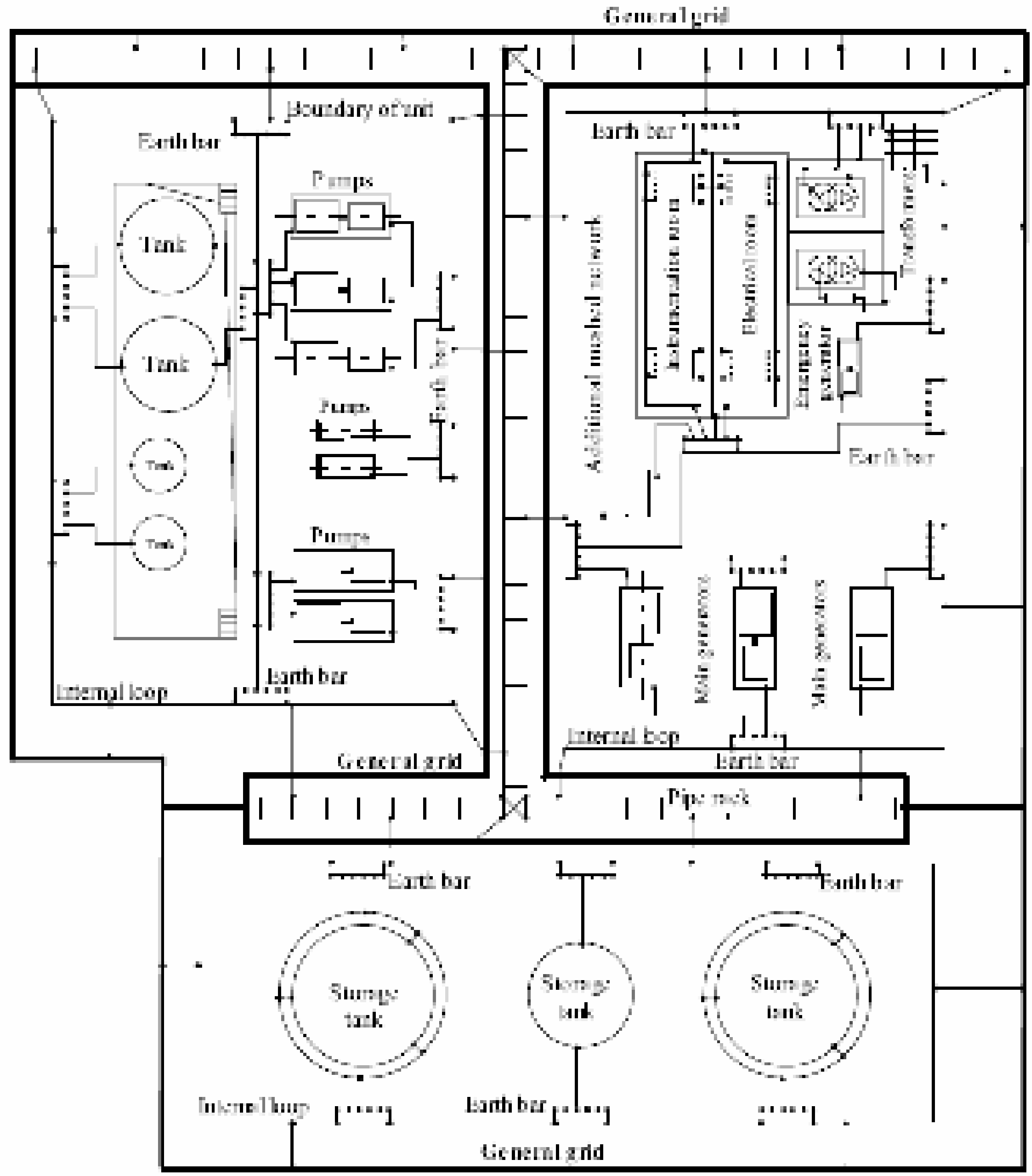


Figure 11: General plant earthing diagram

The general earth grid and internal loops shall comprise class 2 bar copper conductors with a cross-sectional area calculated in accordance with section 543.1.1 of IEC 60364.5.54. The internal loops shall be connected at both ends of each earth bar as shown in the figure.

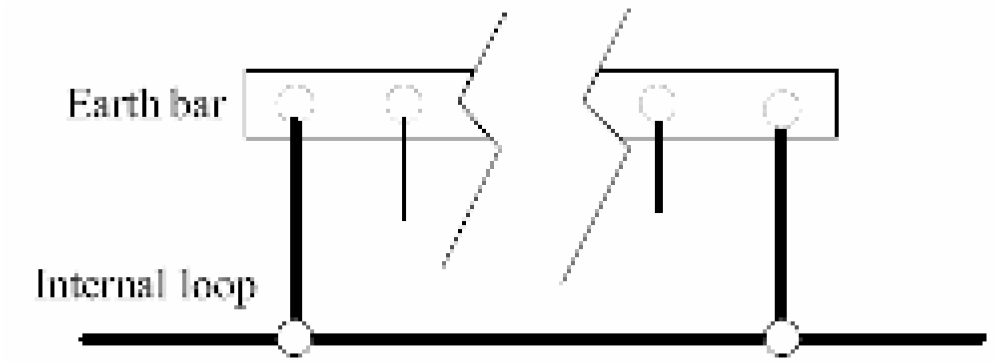


Figure 12: Interconnection internal Loops with earth bar

When the general grid is laid in trenches, it shall be at a depth of 0.8 m, following the route of other electrical cables, pipes, etc. When there is major risk of corrosion (soil or atmospheric), a special study shall be carried out.

3.2.1.2. Building reinforcements

For premises with a particular risk of electric shock (substations, power stations, pumping stations, etc.) having a reinforced concrete floor, the electrical continuity of the reinforcement shall be obtained by welds at the cross-points of the reinforcing rods (approximately one weld per square metre). The reinforcement shall be bonded electrically to the conductor running around the building at two opposite points if the length of the building does not exceed 10 m and at two additional points for every additional 10 m of length.

3.2.2. Equipotential bonding system for offshore platforms

The entire welded metal structure of a platform shall comprise the equipotential bonding system of general earth grid and internal loops.

Unwelded parts shall be interconnected at two points by tinned copper braids (stainless steel lugs shall be used if there is a risk of corrosion) with a cross-sectional area of 10 x 3 mm and stainless steel terminals welded to the structure.

3.2.3. Protective conductors

Any electrical equipment that is not class II rated or is connected to a system operating at a voltage other than the safety extra low voltage shall be connected to the equipotential bonding system by its own earthing conductor.

On skid, electrical equipment shall be connected to the skid structure via a welded stainless steel boss.

In TNS systems, the protective conductor shall be included in the multicore power supply cable and it may be separate from the power supply cable in other cases.

On electrical equipment, the protective conductor shall be connected using a dedicated earth terminal.

The cross-sectional area of this conductor shall be calculated in accordance with section 543.1.1 of IEC 60364.5.54.

Metal ducting (cable tray, conduit, etc.) shall be connected to the equipotential bonding system at both ends and every 25 m. Full continuity shall be ensured. In case of short length elements (less than 3 m) one end only may be connected to the equipotential bonding system.

Use of metal ducting as earthing conductor is strictly prohibited.

3.2.4. Instrument earthing

Instrument earthing shall be in accordance with GS EP INS 101 and GS EP INS 107.

3.2.5. Internal loops in structures

See figure

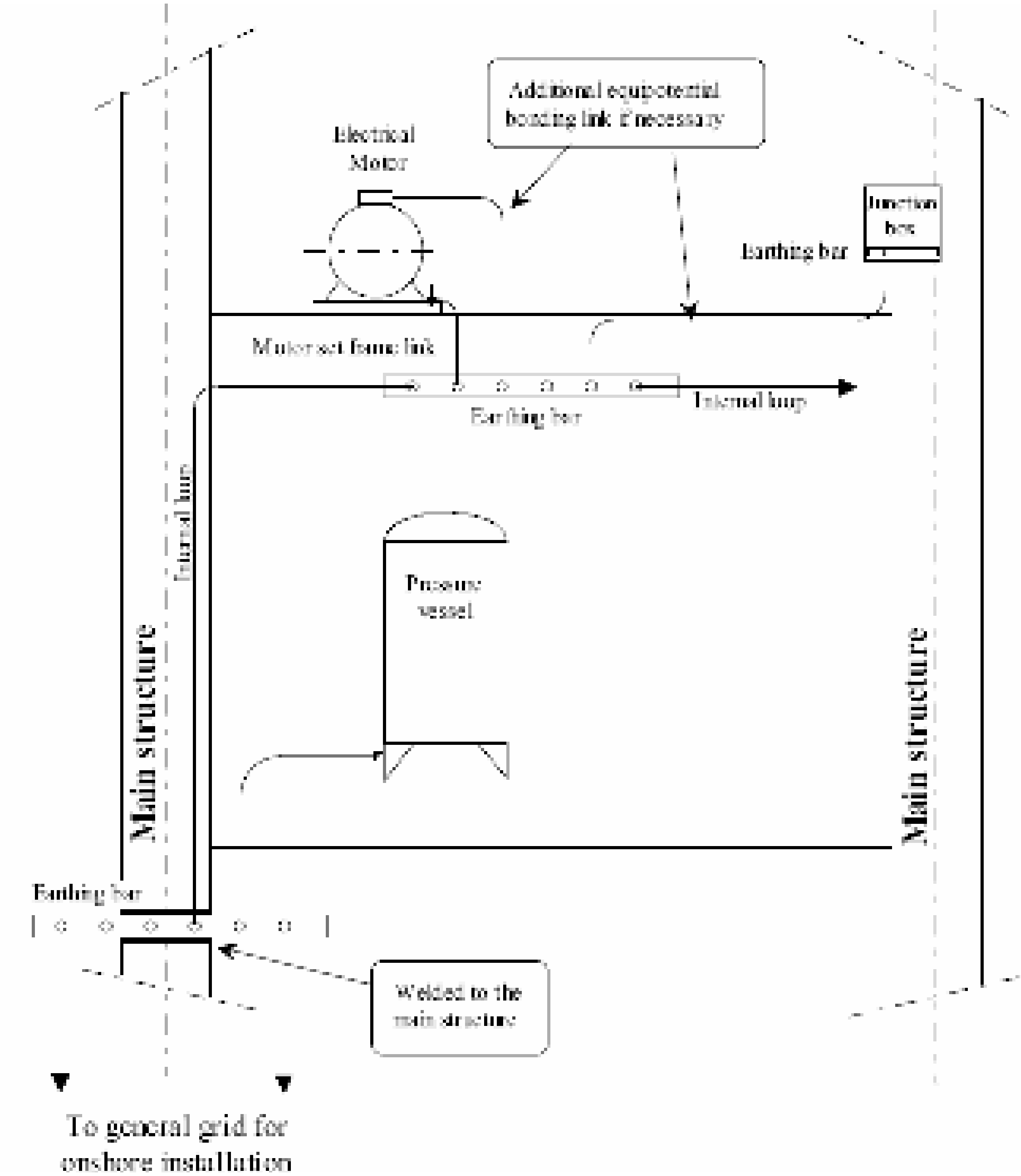


Figure 13: Internal Loops in Structures

3.2.6. Cable earthing

Cable armour and/or screen shall be earthed at both ends.

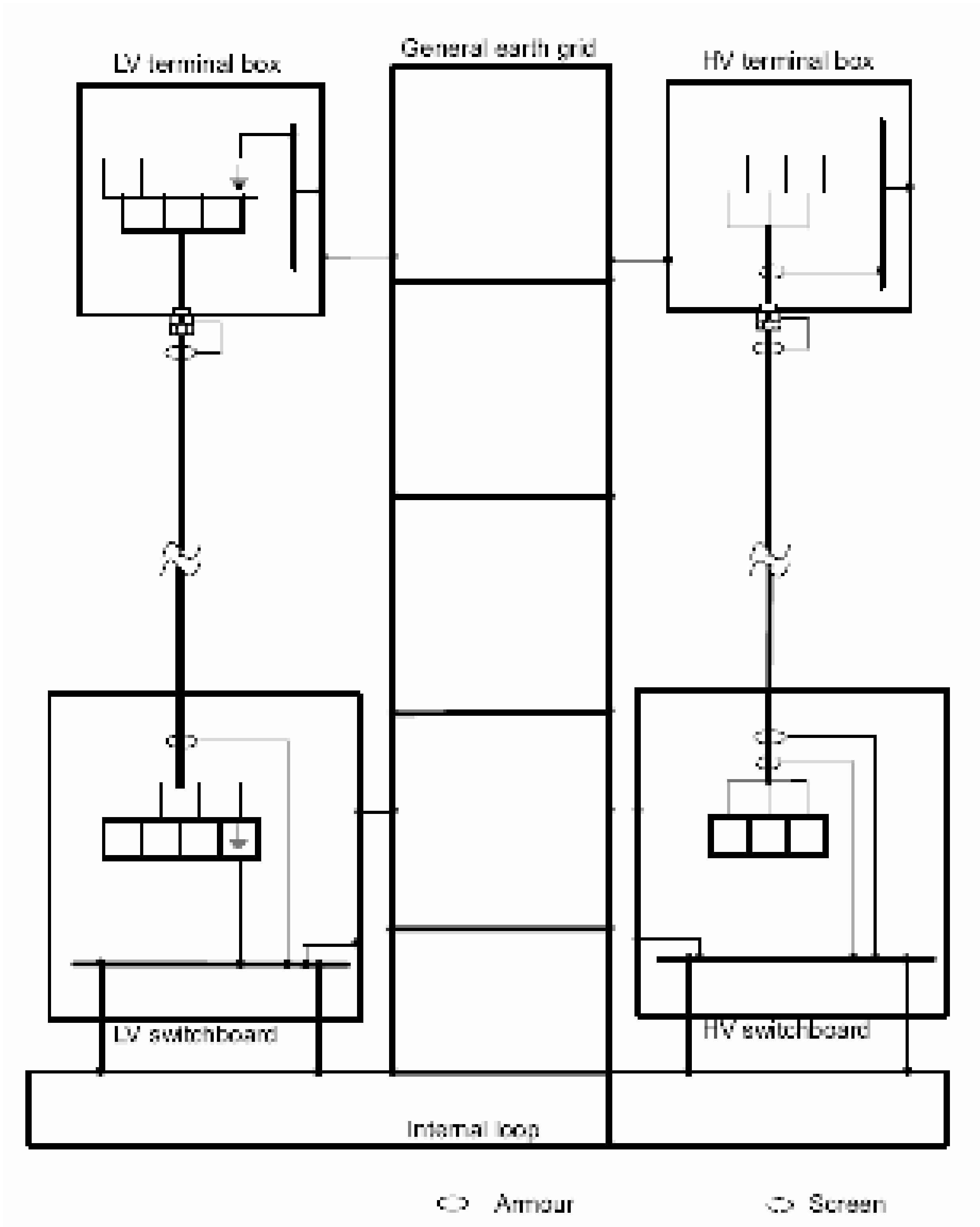


Figure 14: Cables earthing on site

3.2.7. Additional earthing considerations (GS ELE 031)

3.2.7.1. Additional meshed network

When the global earth grid impedance value exceeds 10 Ohms, an additional meshed network shall be provided.

3.2.7.2. Earth electrodes

When earth electrodes are required, their depth shall consider soil drying and freezing which could increase the earth resistance (Generally the burying depth of earth is approximately 2 m).

Earth electrodes shall be connected to a main earthing terminal.

The minimum cross-sectional area of these copper conductors shall be calculated as per IEC 60364 and not less than 35 mm2.

3.2.7.3. Protection against corrosion

All necessary precautions shall be taken to avoid electrolytic corrosion, especially for connections.

Mechanical clamps are prohibited for buried connections. Crimped, aluminothermic process joints and any other equivalent joints may be used.

3.2.7.4. Cathodic protection by imposed current

In all cases, technical and economical study shall be done in order to minimize disturbance of cathodic protection by imposed current.

For pipes installed with insulated joints between overhead and buried parts the insulated joints shall be protected by surge protective device if they are located in lightning protection zones.

For Tanks or equivalent buried large structures, the earthing network shall be done in galvanised steel and connected to the cathodic protection network. No isolating device shall be installed between buried large structures and earthing network.

Cathodic protection shall be laid-out taking into account losses caused by earthing.

3.2.7.5. Protection against static electricity

This protection concerns earthing of pipes, flares, tanks, columns and exchangers liable to generate static electricity.

These equipment shall be provided with welded lugs and connected to the nearest earth bar.

Storage tanks shall be fitted with at least two welded lugs, connected to the general earth grid or to an internal loop.

Particular attention shall be paid to the choice of materials for pipes conveying fluids or powder products. Metal pipes conveying products where friction generates static electricity shall be connected to the internal loop at least at each end.

3.2.7.6. Protection against stray currents

To channel stray currents to the equipotential bonding system, a copper conductor of 35 mm2 cross-sectional area shall be used to connect all metal components and, in particular:

- Structural steelwork (a few points)
- Ladders (one point at the bottom)
- Rack supports (one point in every four supports)
- Piping shall be electrically bonded as follows:

  1. For piping which is in direct contact with structural steelwork no bonding connections are required between the pipe and the metallic structure. Nevertheless the electrical resistance between flanges and between pipes and earthing network shall be measured and found less than 0,5 ohms.

  2. GNL and gas piping shall be bonded to the earth at least at one end.

3.2.7.7. Loading - Offloading station

The structural steelwork of the station shall be connected to the equipotential bonding system at several points.

Pipes, loading arms, down-tubes, weighing systems, rails, shall be at all times electrically cross-bonded and connected to the equipotential bonding system by a copper conductor with a minimum cross-sectional area of 35 mm2.

A removable device connected to the equipotential bonding system subject to the same conditions shall be used to connect tankers, road or rail tanks, during filling, emptying or refuelling (helicopters).

The loading/offloading station shall be equipped with an interlocking device to allow operation only when continuity of equipotential bonding is achieved.

3.2.7.8. EMC (Electromagnetic Compatibility)

In case of electromagnetic disturbances, at least provisions shall be taken in accordance with IEC 61000-5-2 as regards the earthing systems.

3.3. EARTHING ON SITE

Let's try, in this paragraph, to be a bit "more practical". We are going to see (nearly) the same things that in the previous paragraphs, but more "physically" being closer to the site effectiveness trying to interpret the "wordings" of Standards.

3.3.1. Earth electrode resistance

- **Onshore** :

  < 10 ohm in the non-hazardous areas

  < 1 ohm in the hazardous areas

  Regarding the nature of the soil and depending on the season, these figures could be not easily obtained. Generally, the total resistance of the interconnected earthing network will be acceptable, but a particular attention shall be drawn to the bonding and the equipotential links to avoid any dangerous difference of potential between two points at close interval.

- **Offshore** :

  A measurement performed between any two frames or between one metal frame and any point of the structures or any two points of the structure shall **not give a reading above 0,5 ohm.**

3.3.2. Earth electrode onshore installations (obviously)

The earth systems are completed with **inspection chambers** and **earth rods**.

The number of earth rods and their lengths (or depth in the ground) are calculated at the time of the project to have an earth system with as low a resistance as possible.

The ground resistivity (for the current return via the soil) is also taken into account for this calculation.

Why do we need inspection chambers?

On industrial sites the integrity of the earth system is checked at least once a year by an approved independent organisation.

During his visit, the inspector must disconnect each earth rod and measure the "earth resistance" specific to each rod.

On site, please leave these earth inspection covers free and accessible, it could be you who will sign the next inspection report and have to take measures for the "retest" to complete the parts left blank in the report.

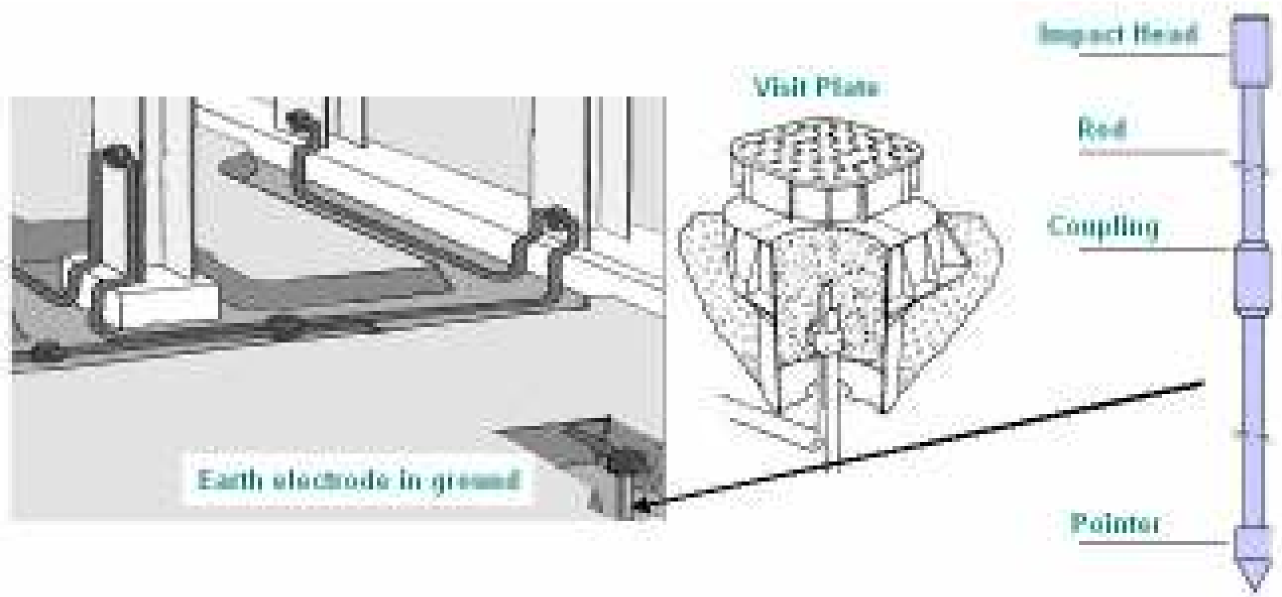


Figure 15: Earth electrode and its visit plate

3.3.3. The two (main) earthing connections/distribution

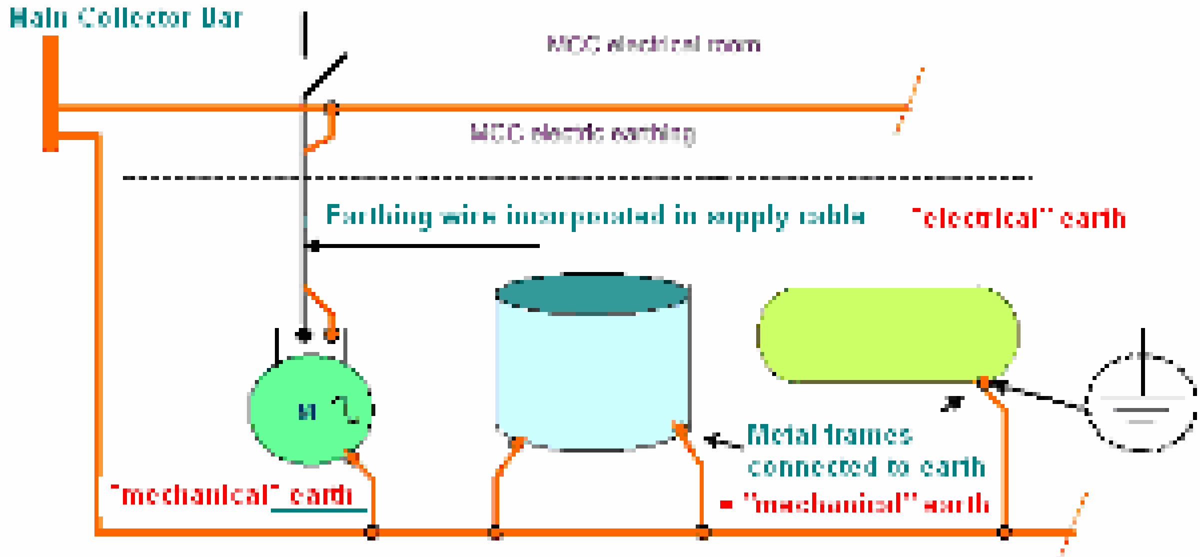


Figure 16: Tthe two earthing wires: “electrical” and “mechanical”

There are no specific names to differentiate the two “complementary” earthing connections. The terms ***"electrical" and "mechanical"*** have been invented here for easier understanding. However, on an industrial site, it is essential you know that:

- An **electrical device** (motor, lamp, heating, etc.) ***is connected to earth at least twice***: to the "mechanical" ground (equipment grounds, on-site loop), and to the "electrical" ground by its power cable which must have a "**PE**" conductor, the green-yellow wire.

- A **metal frame** even without electrical equipment (tank, separator, skid, etc.) ***is connected to the "mechanical" ground at least once***. There may be several "mechanical" connections, this depends on the electrical ground quality and volume of metal to be grounded. The regulations / standards must be consulted to know these details.

The "electrical" grounds and "mechanical" grounds are connected to the main earth collector bar, but they run separately on the plant. And it is the same in electrical room (see figure)

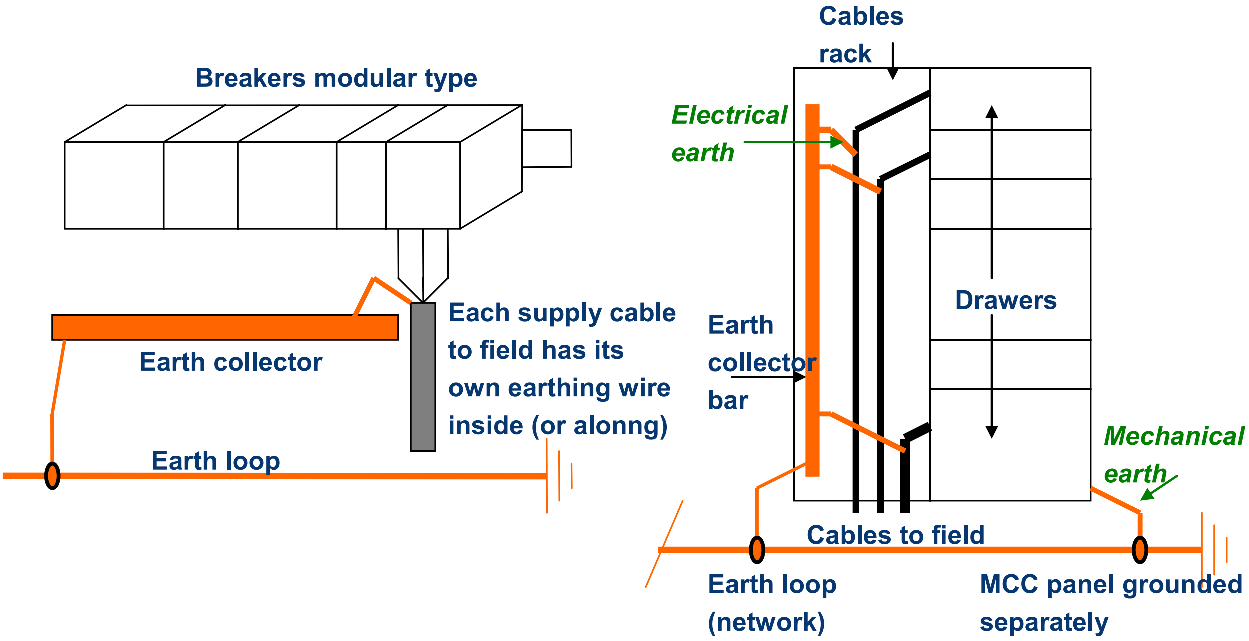


Figure 17: Connections of earth wires on electrical panels side

And (more advice…), on "your site", when you see "mechanical" grounds which are not connected or even incorrectly connected, even though they do not concern you, you should know that you are actively contributing to the equipment's corrosion and that you may be partly responsible for a future accident due to an electrical fault if you do nothing.

3.3.4. Sections of earth conductors

3.3.4.1. Earthing conductors (mechanical) connected on earth loop

***Minimum** cross section (as per Total Standards)*

16 mm² copper with mechanical and corrosion protection

25 mm² copper without corrosion protection. (bare copper)

Practically, having seen last projects/ constructions, the "installed" section for the earthing conductors and the main protective conductors (main loops of the earthing network) is **95 mm²**. In hazardous areas the supplementary equipotential bonding shall be always made with 95 mm² section.

Construction drawings provide necessary indications about the **size** and **number** of earthing conductors, this for each type of equipment. Hereafter, table showing the minimum cross-sections to use.

Equipment for bonding	As per original Total standards	New "effective" trend
Main earth loop	70 mm²	95 mm²
Motor > 30HP	25 mm²	35 mm²
Motor < 30HP	10 mm²	16 mm²
Tanks, vessels & structures	25 mm²	35 mm²
Bonds between earth loop & Platform legs / structures of steel modules	70 mm²	95 mm²

Table 4: Minimum cross section (Cu) of earthing conductor

These minimum sizes given here do not mean you do have to connect with these sections of cables. *(I have seen this reaction).* The bigger is your ground connection cable, the better is the protection; you can as well lay several cables in parallel.

Also to know/remember: cross-section and number of earthing connectors of a piece of equipment is function of its metal volume. A big loading tank can have 10 to 20 connecting wires of 240 mm² cross-section each. (*and we can still have the lightning protection + specific mesh in the ground + ….)*

All pipes to be earth bonded to each other using flange earth lugs.

All cable ladder to be bonded to the earth loop at each end.

Structures of steel modules to be bonded to main earth system in 2 positions (minimum)

3.3.4.2. Protective Earth Conductors - PE (electrical ground)

It concerns the wire incorporated in the supply cable, the one being insulated green-yellow

Cross - sectional area of phase conductors of the installation	**Cross - sectional area of the corresponding protective conductor**
S in mm²	in mm² or function of S
S < 16	= S
16 < S < 35	16
S > 35	0,5 S

Table 5: Cross section of the PE conductor incorporated in the supply cable

Examples: I calculated a motor to be supplied by 3 phases in 6 mm², the cross section of the cable is 4G6 mm² (*4 wires of 6 mm², one being the ground wire insulated green-yellow*) – *and I still need a "mechanical" connection in 16 mm²*

For a motor to be supplied in 3 phases 25 mm², the cable is either 4G25 (*no arm having a bigger section)* or 3x25 +1x16 – *and still a "mechanical" connection in 35 mm²….*

For a motor to be supplied in 3 phase 120 mm², the cable is 3x120 + 1x70 *(+ ……?)*

The PE conductor could be run apart the supply cable

The cross - sectional area of every protective conductor which does not form part of the supply cable or cable enclosure shall be, in any case, not less than
:

- 2,5 mm² if mechanical protection is provided
- 4 mm² if mechanical protection is not provided

It shall be installed jointly (and attached all along with tie-raps) with the supply cable and shall follow the same route

3.3.5. Earthing and bonding for package units

The description in the following is from Total SPEC ELC-180 (03/1995). It gives a general reference for how to connect / interconnect the earthing system and if it applies for packages, it applies as well for the rest of the installation

All non-current carrying metallic parts directly exposed to electrical potential from cabling, wiring, relays, metering etc. shall be earthed by a separate insulated earth conductor of suitable cross section.

The SUPPLIER shall ensure that all metallic vessels, tanks, skids, forming part of the package which are not welded to the structure shall have earth bosses welded at diagonally opposed points. Welding shall comply with the appropriate NDT specification.

Frames of motors, generators, metallic housings, control cabinets, panels, control stations etc. shall be separately earthed through a proper earth terminal.

In electrical rooms the earthing bar of each switchboard shall be connected to the main earthing grid using a green-yellow sheathed copper cable sized for the maximum fault current.

Each earthing bar shall be linked to the general earthing system of the plant/platform at two points in diametrically opposite positions; the SUPPLIER shall make provision for these connection points and fit them with appropriate terminals welded to the package structure.

The type of connection shall be agreed with the COMPANY.

Where a motor is located in ductwork i.e. a fan or otherwise enclosed, the SUPPLIER shall ensure that the motor frame earth conductor is brought outside for the purpose of earthing.

All metallic cable trays shall be electrically continuous and earthed by a separate conductor.

The SUPPLIER shall provide a separate earth bar on the package for the termination of skid/package earthing.

Earth cables shall be PVC insulated copper, 500 V, coloured green/yellow and suitably sized.

A separate earth conductor shall maintain Earth continuity across bolted gasketted joints. There is no requirement for this across machined face flanges, i.e. Exd surfaces.

All cable armour (power and control cables) shall be earthed at both ends by means of earthing tag washers.

Luminaries, socket outlets and control stations shall be individually earthed by means of a conductor included in the multicore cable linking them to the package edge junction box

Pipework flanged joints shall be electrically bonded as follows:

a) For steel piping which is in direct contact with structural steelwork no bonding connection are required between the pipe and the metallic structure. Nevertheless the electrical resistance between flanges and between pipes and ground shall be measured and found less than 10 ohms.

When piping incorporated electrical apparatus (heat tracing tape, instruments, etc...) and for personal security, bonding of flanges can be omitted provided the electrical resistance between pipes and any close metallic part does not exceed 0.5 ohm.

b) For cupro-nickel piping, which is electrically insulated from the structural steelwork to prevent galvanic corrosion, all pipe flanges shall be provided with a bonding connection. Each pipe run within a module shall be earthed at two positions to the metallic structure. The two earthing positions should be at opposite ends of the pipe run unless otherwise agreed by COMPANY.

c) Piping interfaces between pipes manufactured from dissimilar metals require an insulated flange to prevent galvanic corrosion. Each pipe shall be bonded to the metallic structure at either the first flange back from the insulated flange, or at an earthing lug as appropriate.

d) GNL and gas pipes shall be bonded to the earth at least at one end.

3.3.6. Quality of connections

A « good earth » is the one with the lowest resistance. This is achieved with a meshed network of adequate sections of ground conductors but it depends also of the connections done between these same conductors / ground networks.

Anyone “wandering” on a site has in mind a picture of a bare copper/steel cable or a sheathed (green-yellow) cable disconnected, pointing miserably towards nothing or seeming to wait for your leg…. This cable was either not reconnected after a repair/maintenance intervention (*still the main cause nowadays)* or it broke at the connection point due to galvanic corrosion (*less and less now as connections are of better qualities)*, and for this (wrong) type of connection you are directly responsible.

You must not join “directly” a copper wire with a steel frame; you must not assemble copper and aluminium cables; in fact you “can” but creating a natural galvanic couple which will destroy the continuity of contact between the two materials.

When having to join two different metals , to assure the contact continuity (in quality and duration), you have two solutions

- Use a bimetal interface (like a washer
- Perform aluminothermic welding

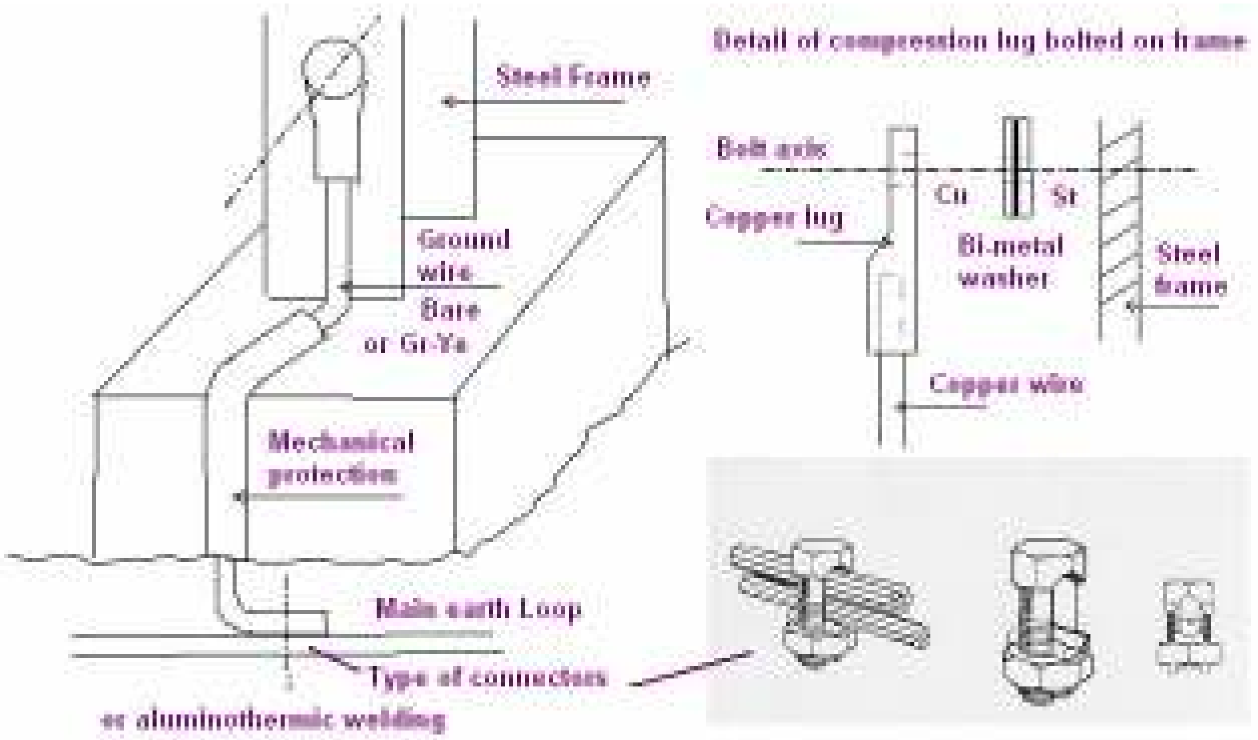


Figure 18: Ground cable connection using bi-metal washer

Note: the earth loop connections (copper cable on copper cable) are generally made using the thermowelding principle; the "Cadwel" system (or aluminothermic welding). This system is also used for the copper cable connections on the metal structure, to prevent galvanic corrosion.

Figure 19: Examples of good weld joints with aluminothermic method

Aluminothermic welding principle

The principle is to use the reduction of copper oxide by aluminium. The “cadwel” system uses a type of gun powder which when ignited reaches sufficient temperature to melt the two materials to be assembled. This causes an exothermic reaction and forms a bath of melted copper (or melted copper/steel or melted Cu/alu). This melted bath then flows onto the conductors.

4. SPECIFIC GROUND FOR LIGHTNING PROTECTION

4.1. DIRECT PROTECTION

4.1.1. General

A system protection against the lightning strikes comprises different ‘element’ systems, which are complementary:

1) Protection system against directs effects (of lightning strikes).

It has as function to collect the lightning strikes, which in its absence would have struck the building or the structure to be protected. Then to run out the currents of the lightning towards the ground, avoiding the (current) ingress inside the volume to be protected.

This system is sometimes called “**external protection**” generally, this protection is ensured by the ***Air terminal associated with lightning conductors.***

The theory and technologies of the systems and materials uses are presented in this paragraph

2) The grounding system (which cannot be seen alone in this course)

It is probably the most important part of the protection. A good grounding system is absolutely necessary. The two other parts of the protections (*air terminals* and *surge protectors)* would have no effect without the possibility of "evacuation" for the unwelcome extra voltages and extra currents.

Interconnection of all grounding loops - or not interconnecting - is subject of a debate enlightened in the following paragraph, as well as specific materials and theory.

3) Protection system against indirect effects:

it has as function to protect the interior installations and equipment electric/electronic as well as the people against the induced voltage and the rises in potential.

This system is sometimes called “**internal electrical protection**”. Generally, this protection is ensured by the ***Lightning Surge Protectors.*** See course EXP-MN-SE110

Direct Protection is only one third of the necessary Lightning Protection.
***Grounding* and *Electrical (Surge) Protection* are the Mandatory Complementary Two Other Elements of a Lightning Protection Installation.**

General trend is to install air terminal captors, descent cables, and a 'quick' local grounding, then to believe: "Protection is done". This is a thoughtless and even dangerous behaviour, as it becomes a provocation for lightning to strike and damage the installations.

4.1.1.1. Protection against direct effects theory

The techniques of protection against the lightning strikes can be classified, according to their philosophy of action in 2 types:

- Protections known as "passive"
- Protections known as "active"

The electrical field breaks between a thundery cloud and any rough bit on the ground level causing the strike.

We can protect an installation theoretically in 2 manners:

- By eliminating the rough bits that are at the origin of the strike and by maintaining the elements to be protected on the same potential (potential of the ground), it is the **passive protection**.
- By creating voluntarily some rough bits, to attract the strikes and channel the energy towards the ground, it is the **active protection**

The active protection is carried out by ***air terminal & lightning conductor.***

The passive protection is carried out by ***grid cages (cages of Faraday).***

4.1.1.2. The complete Air terminal / conductor installation

They include:

1) Devices of capture

2) The conductors of descent

3) The earth electrodes

In practice, there are two types of air terminal installations:

- Air terminations in metallic rods. It consists in laying out, above the structures to be protected, conducting rods of adapted length, rods which are connected by descent conductors to earth electrodes.

The rod, also called pointer, can be topped with an additional capping device according to some vendor specific technologies.

- The grid cage lightning protection. It consists in laying, around the building to be protected, a Faraday screen cage whose meshes are connected to earth electrodes at the foot of the building.

Note:

It is important to keep in mind that the trajectory of the lightning channel is not directly affected by the height of the objects located on the ground. It is only at the very last stage of its descent that the strike decides of its point of impact. **A lightning Air Termination does not attract the lightning** at the time of its formation; it collects the electric discharge only if it is already ***spontaneously very near****.*

The lightning direct protection system shall be of the enhancing type designed to attract lightning from a predetermined volume and to safely convey the lightning current to earth through a known and preferred route.

The lightning direct protection system shall include components as follows: air termination(s), mechanical support(s), down conductor(s), performance recording equipment, and an **earthing system**.

4.1.2. The air termination - Capture Devices

They are metallic rods, capped with pointer or "early streamer emission system" or metallic taut cables.

4.1.2.1. Franklin rod

Or: "*Metallic rod with a pointer*"

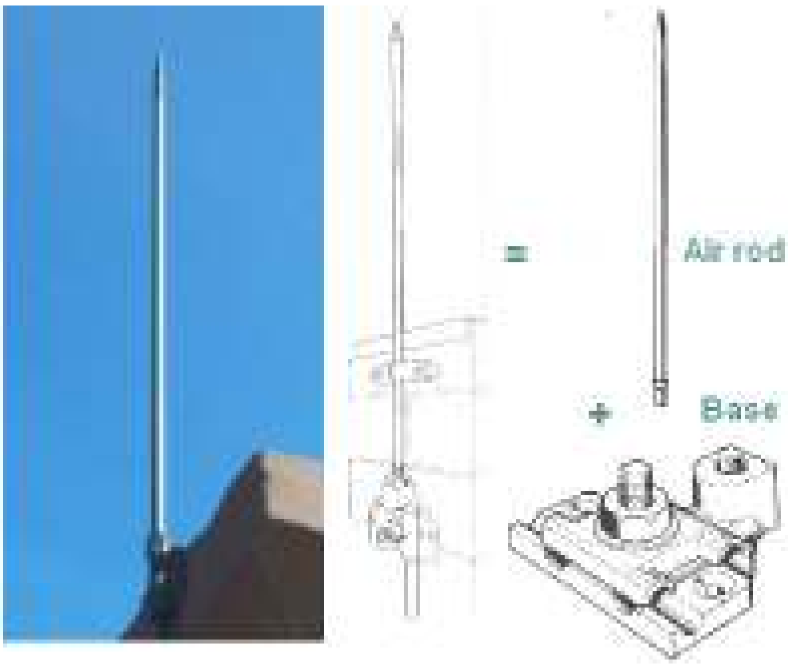


Figure 20: The Franklin rod

Franklin lightning conductors, which are tapered, have a perfectly slender and attractive point.

They exist in nickel/chromium-plated copper and stainless steel versions.

They have a standard length of 2.4 m and can be extended by the addition of treated steel or stainless steel elevation rods.

These systems do not require guying and can be up to 7 or 8 m long. The tip of 2F Franklin lightning conductors features a solid point of marine bronze or stainless steel

Installation of rods on a structure:

To study the best lay-out, the 'Rolling Sphere Method is the widest used principle. (see course SE110 and Total course on Lightning)

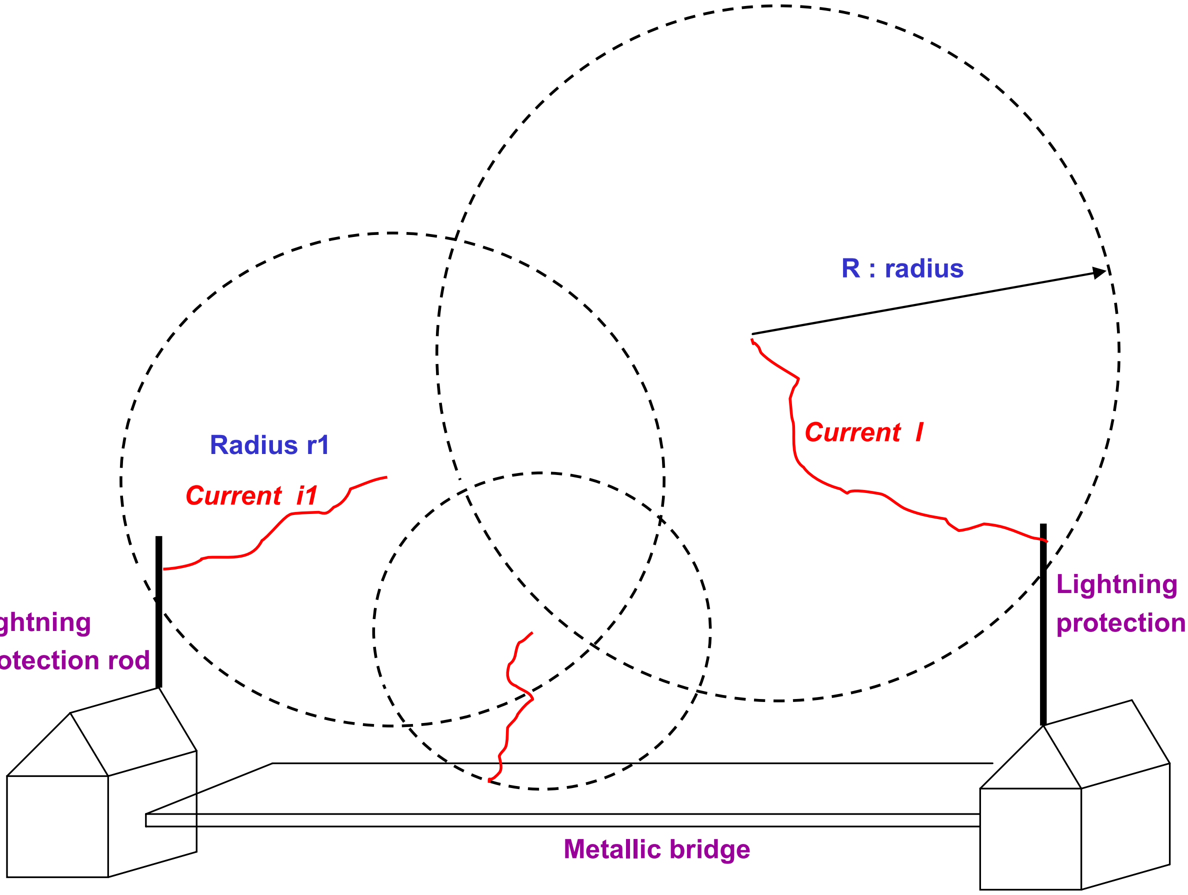


Figure 21: The electro-geometrical model (sphere) of a lightning strike

The main problem becomes the choice of radius R for the sphere. If a radius r1 is chosen, it corresponds to a protective current *i1* as per the Electro-geometrical model. When striking current is smaller than i1, it can go across the protection.

The only 'safe' protection is to consider the smaller striking current possible, being 2 kA, R is then equal to 15 meters. *(In this theory, lightning strike intensity – 1 to 400 kA – is function of the sphere radius).*

The risk according to the chosen protection

The 100% protection does not exit in lightning protection and this regardless any type of system (including other than Franklin rods).

Example with an "accepted risk" of 7 kA as current protection, the statistics show that only 5% of strikes are under these 7 kA. The associated radius of 36 meters (Rolling Sphere) is the base for the protection calculation wit a theoretical "risk of failure" of 5%.

If the building to protect is an isolated one (a country farm in Europe for example), the chance of strike happening is one over 140 years; with the 5% considered 7 kA protection, it becomes a risk of one strike per 2800 years……..

International standards (C.E.I.) has 'normalised those risks, introducing several levels of protections, each one corresponding to a Rolling Sphere radius, a protective angle for the Franklin rod, a distance between linking protective conductors.

PL	RoF (%)	R (m)	Angle α(°) for a given h(m)					WoM (m)
			10 (m)	20	30	45	60	
I	0.5	20	45 (°)	25	-	-	-	5
II	5	30	55	35	25	-	-	10
III	15	45	60	45	35	25	-	15
IV	30	60	65	55	45	35	25	20

Table 6: Parameters giving the capture devices choices inducing a protection level

PL: protection level
RoF: risk of failure
R: radius of the fictive Rolling Sphere
h: height of the Franklin rod above the surface to protect
WoM: width of the meshed network (distance between conductors)

Angles of protection are different according to protection level. These angles cannot be defined in 'h' (height of rod + pointer). When height of the building is bigger than the radius of the Rolling Sphere, there is a risk of 'side impact'.

It is why, you can see on sky scrappers, striking rods installed on the vertical surfaces (at regular intervals).

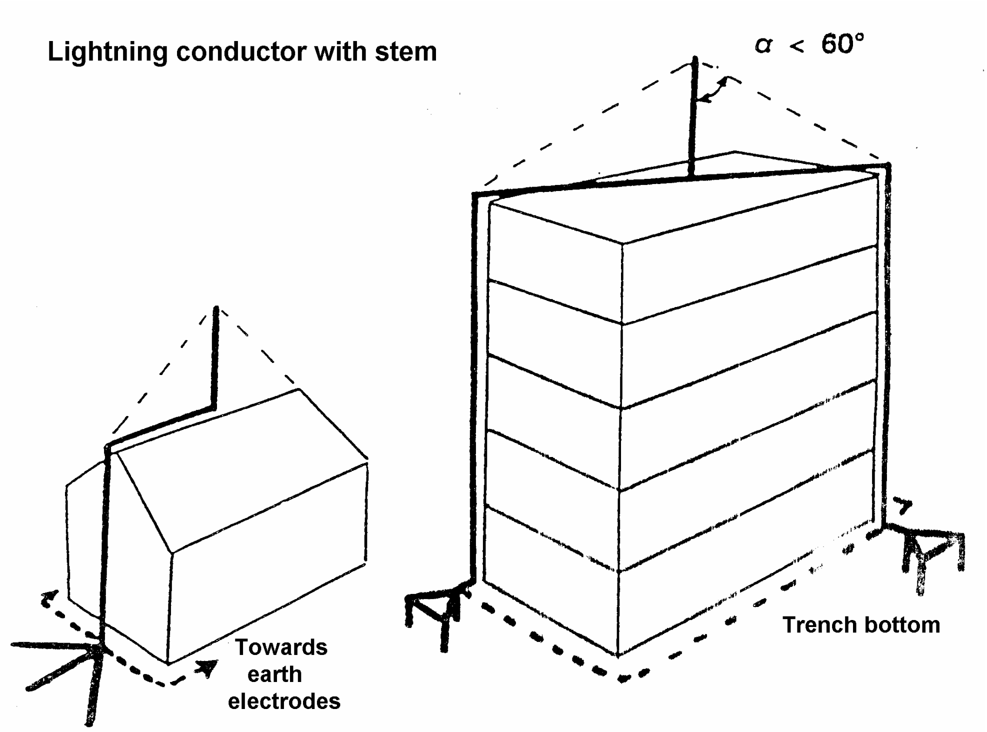


Figure 22: Installation of striking rods according to protection level

4.1.2.2. Early Streamer Emission (ESE) or "ionisers"

Relatively new technology, mainly developed by Australia (Dynasphere product) and France (Saint-Elmo rod)

The 'idea' is by creating a surrounding 'ionised area', to provoke a preferable channel for the descending leader as a "strike-exciter". Their descent conductor is a high voltage type cable.

Tests have been done comparing ESE air terminal with 'classic' Franklin rod; it results a difference in 'reaction time' called Δt which is the time *in advance* for which an ESE reacts, it conducts to an increase of protection distance

$\Rightarrow$ $\Delta L = V \times \Delta t$ with V = lightning speed estimates at 10^6 m / s

Figure and table gives the **Rp (Radius of protection)** for a "normal" type with a simple striking rod and in comparison the **Rp** for an ESE system depending the speed of the lightning.

See as well the explanation figure

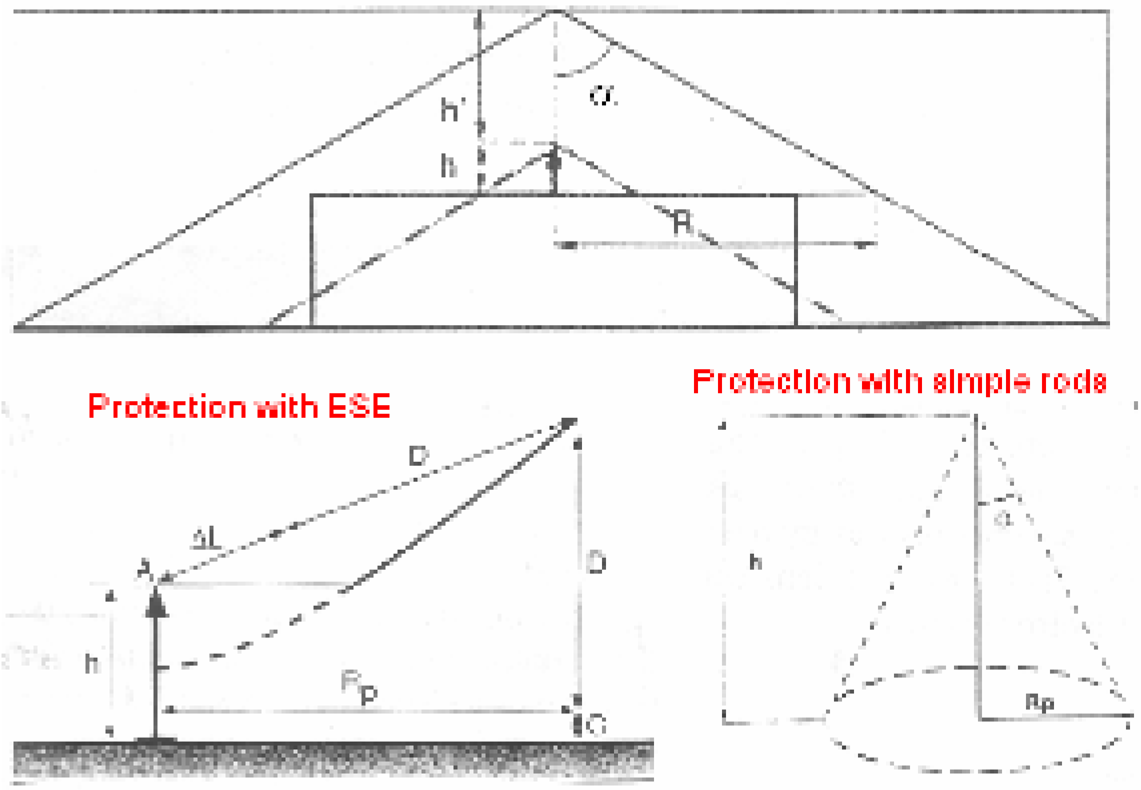


Figure 23: The ESE extended range of protection

Height of rod in meters	Rp for Franklin type in meters	Rp for air termination type ESE in meters					
		"Lead" for striking in microsecond (Δt)					
		5	15	25	35	45	50
2 m	5.50m	8.00m	12.2m	17.0m	21.6m	25.6m	27.6m
5 m	8.50m	20.0m	31.7m	42.5m	52.5m	63.5m	68.5m
10 m	10.0m	22.9m	33.5m	43.9m	54.1m	64.2m	69.3m

Table 7: Comparison of Rp between one ESE and Franklin rod

R: *radius of protection in a horizontal plan placed at a vertical distance* ***h*** *of the tip of the ESE*
h: *height of the ESE device, distance between tip of this ESE and the surface to protect*
h': *extra virtual height above h. (according to the type of ESE)*
R = (h + h') tg α *where $\alpha = 60°$*
D*: distance for arc striking (radius of the sphere*
ΔL*: gain in length for ascending leader*

These values of radius are according to French standards. France was the only country to establish standards for ESE (standard NF C 17-102.) and the first with Australia to put on the market a product (now Australia has also a Standard).
The ESE is subject to strong critics such as: "they are not better than Franklin rods". To these critics, we can remind the words of Albert Einstein: *"Great spirits have always encountered violent opposition from Mediocre Minds"*

Hereafter are the descriptions of some of the available products.

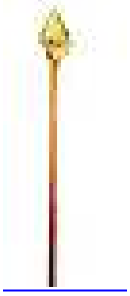
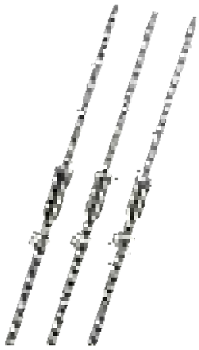
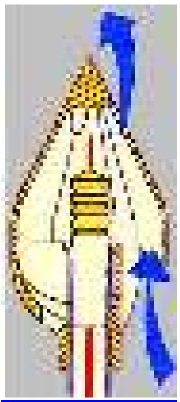
Saint-Elme - Franklin France	**Pulsar - Helita (France)**	**Dynasphere - Erico (Australia)**
 Capture rod tipped with the Saint-Elme		 The Dynasphere
 **Piezo electric stimulator** at end of the rod	*The metal cylinder contains the electric device of the Pulsar system that generates the brush discharges.*	
Principles – as per vendor documentation		
The basic principle of the Saint-Elme lightning conductor is to increase the number of free charges (ionized particles and electrons) in the air surrounding the lightning rod and to create, within a cloud–ground electric field, a channel of high relative conductivity constituting a preferential path for lightning.	When the lightning approaches the ground, a luminous ascending brush discharge is initiated at the lightning conductor. In the case of a Franklin rod, this ascending brush discharge propagates in the direction of the descending leader after a long transition phase. The Pulsar initiation advance permits to reduce the required time for the formation and continuous propagation of the ascending discharge and brings thus a higher efficiency for the lightning capture than a Franklin rod tip.	The terminal consists of a central hub deflection unit (stainless steel) and an exciter unit (epoxy resin). Its upper part has one or more stainless steel ion emitter points. It establishes a potential difference between the exciter set, which has the same charge as the surrounding air, and the point and deflection unit, which are at earth potential.

Table 8: Examples of ESE systems on the market

4.1.2.3. The Faraday cage

It could look like a 'complement' to Franklin rods, as a mesh of protecting conductors is necessary for the Franklin rods protection. For Faraday cage the protection is completed by 'strike points' rods (look alike the Franklin rod)

In fact a Faraday cage is the best-adapted protection against lightning strikes. All buildings, pipe racks, storage tanks, towers…, having a metallic frame have already a Faraday cage design.

With non-metallic buildings, an "artificial cage" can be installed, doing it with 'lightning conductors'.

In all cases the elements of Faraday cages must be connected to a (or the) earth termination network.

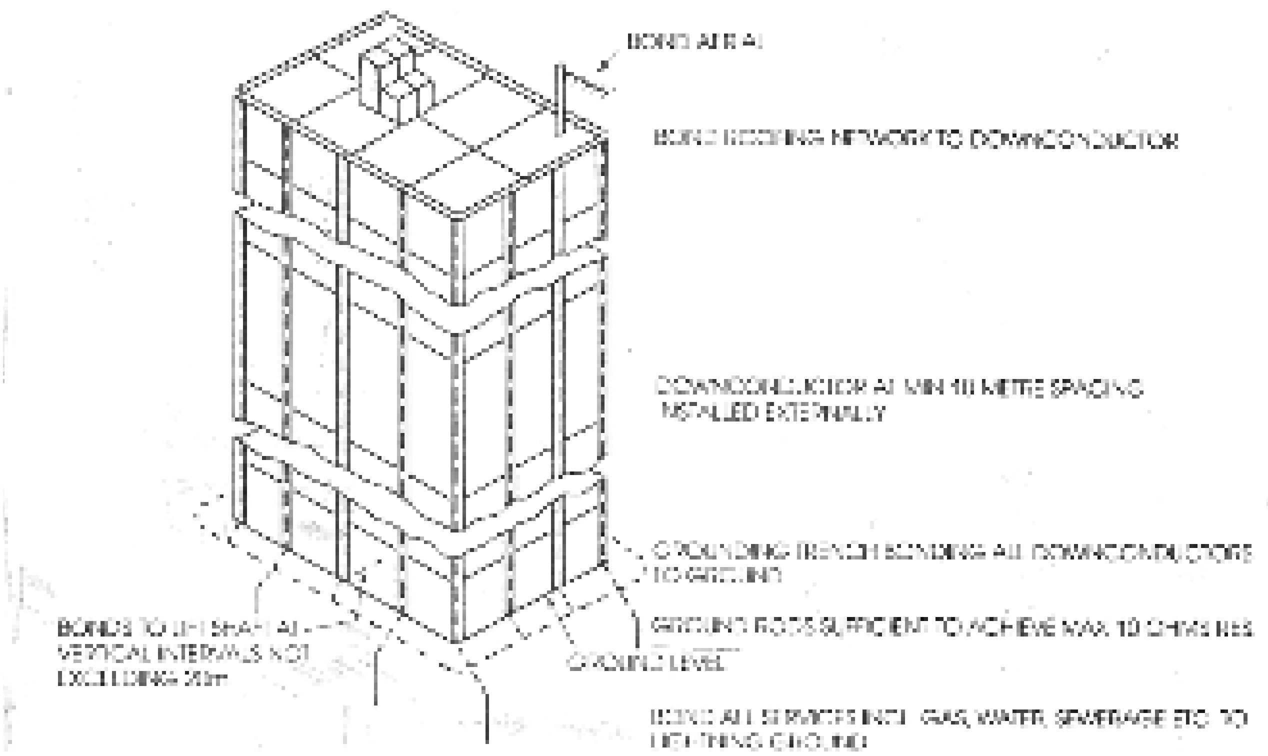


Figure 24: Faraday cage method of protection

Protection by a meshed cage is done on top and around the building with wide-meshed 'net' of lightning conductors.

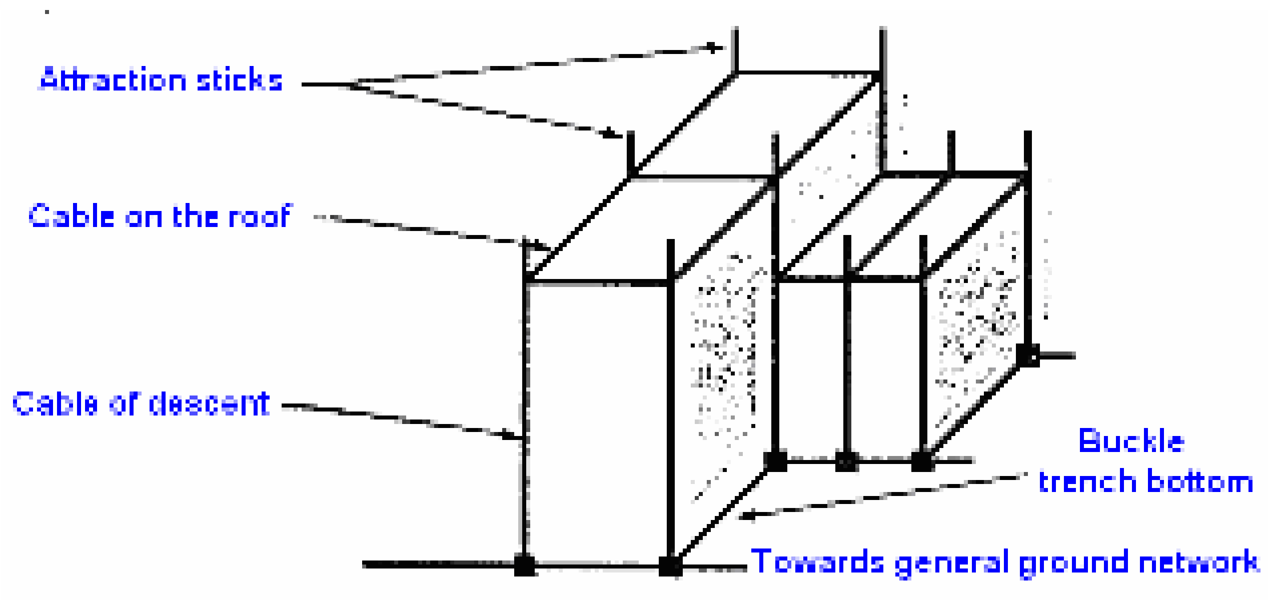


Figure 25: Main frame of a Faraday cage

Strike point rods (small length) are installed at cross-point of conductors in angles and any "pointing" part. Descents are outside building, mainly in angles. They are connected to the earth termination network, itself around the building. Distance between lightning conductors (width of meshes) is function of the required level of protection (Rolling Sphere Radius). It is a **passive protection** conducting directly the lightning strikes currants towards the ground.

Division of the current within the "mesh network" lightning conductors limits (generally) the radiant effects inside the building.

Figure 26: Faraday cage in construction (ammunition depot…)

All the lightning conductors of the mesh are subject to direct lightning strikes and capable to direct the current towards the ground.

On high risk structures such as explosives factories, no part of the roof should be more than **2.5m** from an air termination conductor. This is generally achieved by applying a 5m x 10m mesh to the roof.

However, for most structures, a mesh of 10m x 20m is considered sufficient, giving a maximum distance from any part of the roof to the nearest conductor of 5m.

Other examples of protection by Faraday cage:

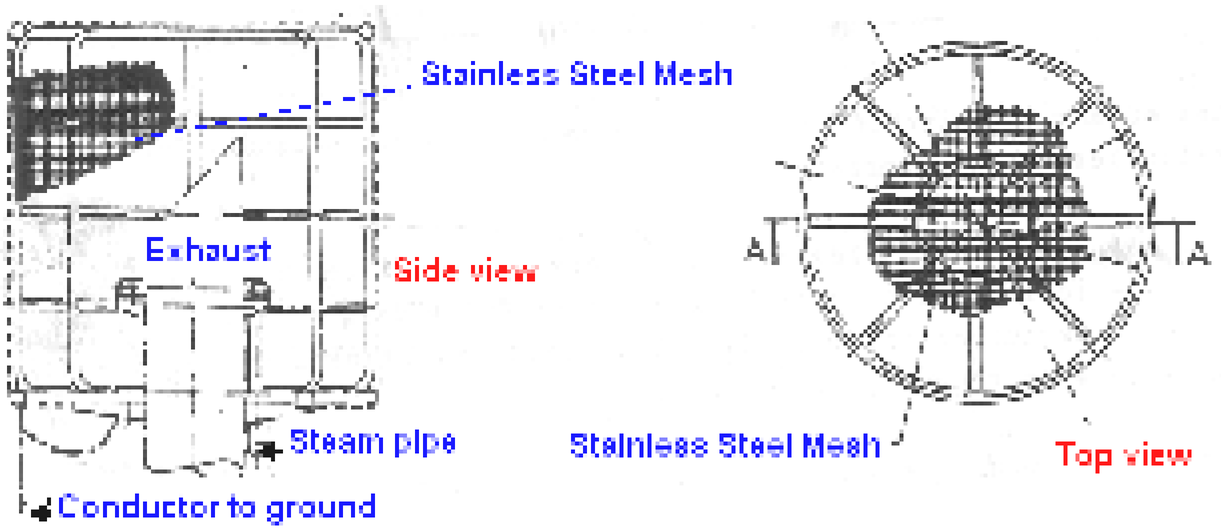


Figure 27: Faraday or mesh cage installed on top of an exhaust pipe (chimney)

4.1.2.4. .Other protections

Taut cable

Metallic cables installed above the structures to protect, tightened on supports if metallic themselves, are part of the protection.

Used to protect overhead lines (high voltage), High voltage substation, storage tanks (floating roof).

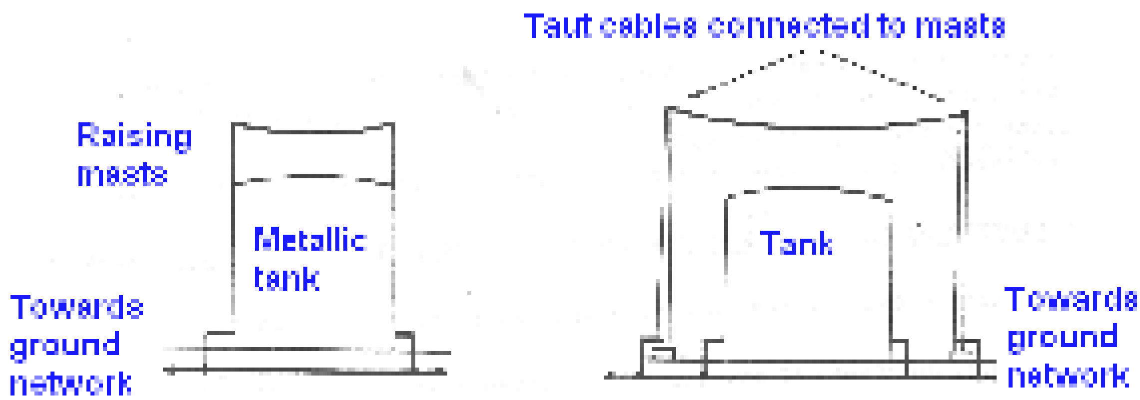


Figure 28: Storage tank protection with taut cables

The umbrella

Used mainly in south-east Asia, mainly to protect communication towers or masts, but also tanks.

Their efficiency cannot be denied, *I still have in mind the picture of strikes on communication towers making like fireworks*

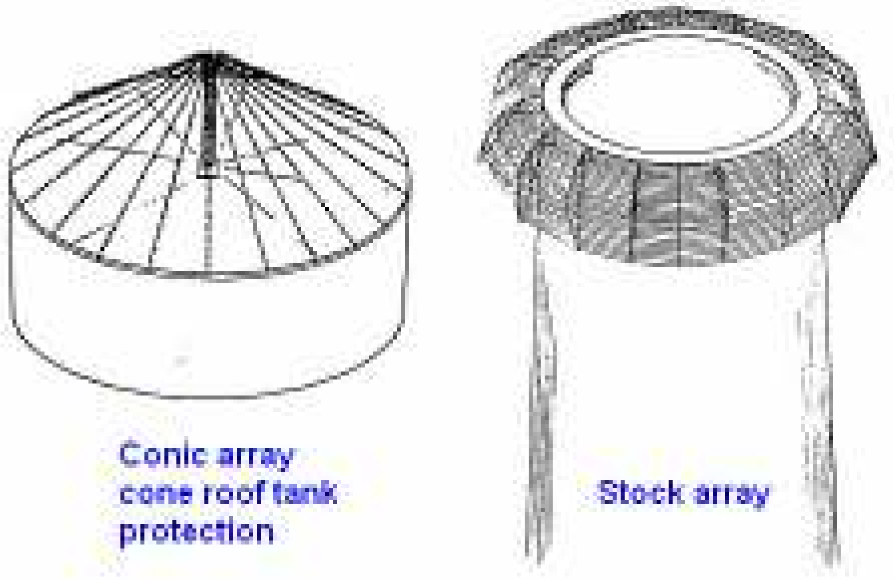


Figure 29: The umbrella style lightning protection

4.1.3. The down conductor (descent-meshing-bonding)

This can be parented with a ground-interconnection wire

The function of a down conductor is to provide a low impedance path from the air termination network to the earth termination network, to allow the lightning current to be safely conducted to earth.

Standards advocate the use of various types of down conductors. A combination of strip and rod conductors, reinforcing bars, structural steel stanchions, etc. can be used as all or part of the down conductor system - providing they are appropriately connected to the air and earth termination networks, and are known to offer good electrical conductivity.

Standards suggest there is no advantage in using 'shielded' coaxial cables as down conductors. In fact there is thought to be the disadvantage that potentials up to hundreds of kilo-volts can occur between the inner and outer conductor (shield) at the top of the down conductor so triggering a *side flash*.

Down conductor systems **should**, where possible, **take the most direct route** from the air termination network to the earth termination network. Ideally they should be symmetrically installed around the outside walls of the structure starting from the corners. Routing to avoid side flashing should always be given particular attention in designing any installation.

Down conductor sitting and distancing is often dictated by architectural circumstances. There should be positioned no more than 20m apart around the perimeter at roof or ground level, whichever is the greater. If the structure is over 20m in height, then the spacing is reduced to every 10m or part thereof

They are generally of a flat copper conductor 30 x 2 mm cross-section, or galvanised steel (33.5 x 3 mm), over-sized electrically but it must take into account the electrodynamic effects and the corrosion

For the ESE air termination, there could be (case of Dynasphere) a specific cable, described here in the following.

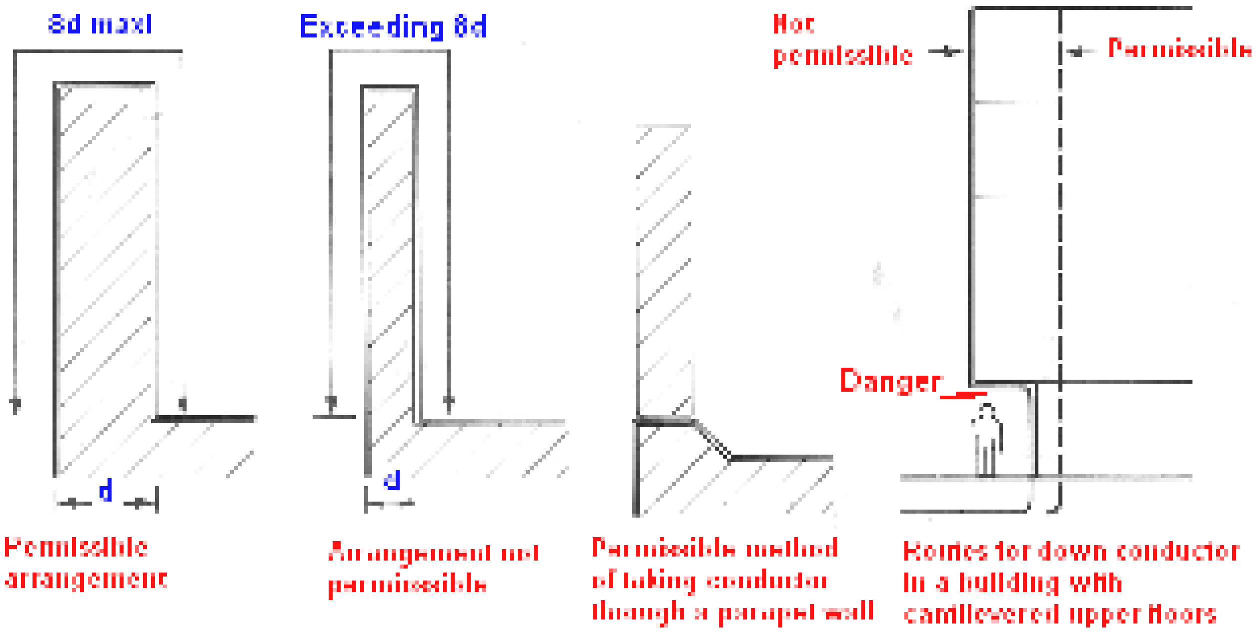


Figure 30: Routing of down conductor "permissibility"

One E.S.E. (*and in general one air terminal*) = one (minimum) dedicated descent conductor

4.1.3.1. Security proximity distance

A distance of at least one meter must be provides between descent lightning conductor and any electrical cable or any fluid canalisation running in parallel. This to avoid an induced dangerous potential in the neighbouring installations.

4.1.3.2. Side Flashing

The problems relating to side flashing have attracted a great deal of attention in recent years and are a very important consideration when designing a safe lightning protection system. Damage to life and property can occur if the danger of side flashing is not considered.

The principles of side flash can be explained by the following simple example (figure).

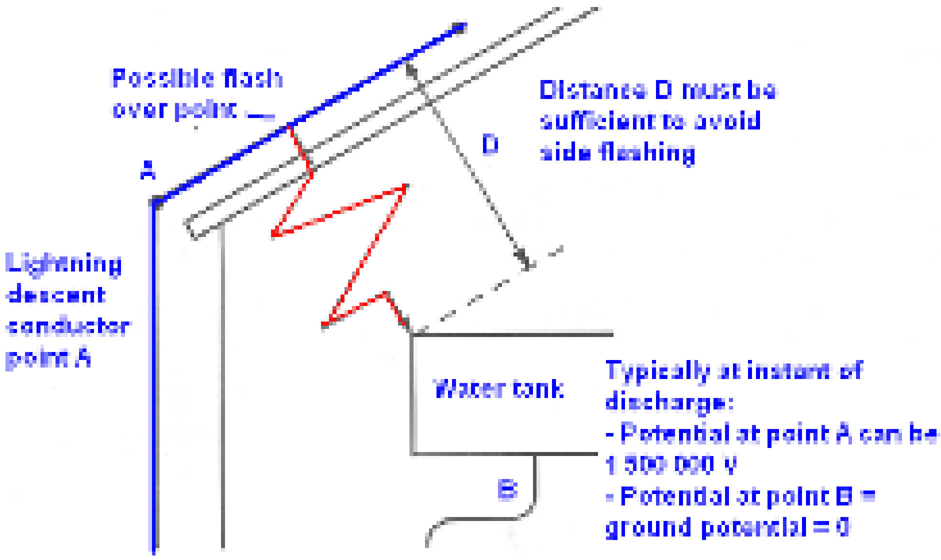


Figure 31: Phenomena of side flashing

4.1.3.3. The effect of Step and Touch Voltage on descent conductor(s)

Comments on the picture of this paragraph

1. Person ***X*** is in contact with the ground at ***a*** and ***b***; Person ***Y*** is in contact with the ground at ***c*** and the conductor at ***d***; Person ***Z*** is in contact with the conductor at ***e*** and a metallic hand rail ***f*** shown grounded at ***g***.

2. Person ***X*** is subject to step potential.

3. Person ***Y*** is subject to touch potential.

4. Person ***Z*** is subject to transferred potential.

5. The potential depends on the current magnitude and the impedance of the path of the lightning discharge.

6. Step potential increases with the size of the step ***a-b*** in the radial direction from the conductor and decreases with the increase in the distance between person ***X*** and the conductor.

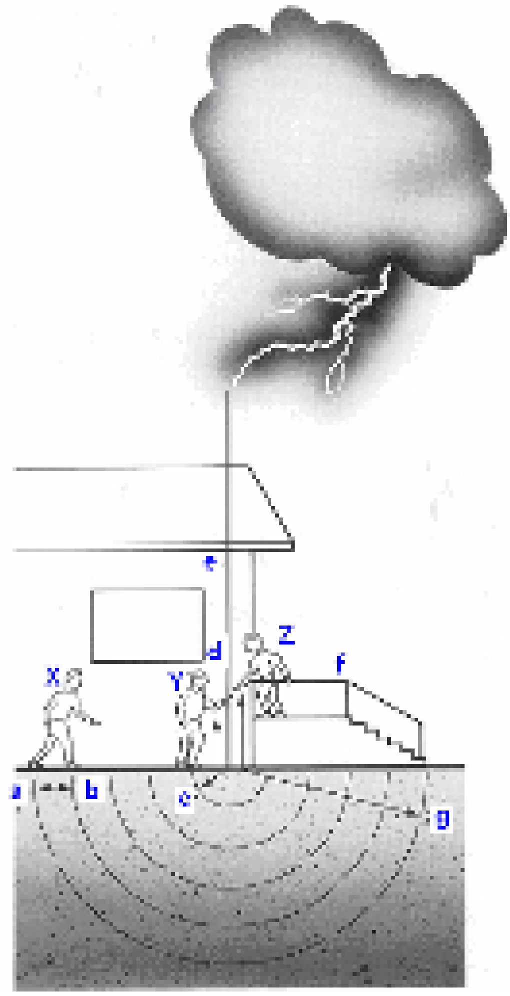


Figure 32: The effect of step voltage and touch voltage

7. The transferred potential increases with increase in the radial distance between the down conductor and the ground ***g***.

Extracts from the Australian Standard on Lightning Protection A.S. 1768-1983.

4.1.3.4. Specific E.S.E. descent conductor

Not all manufacturers are requesting specific descent conductors, but in case of Dynasphere (*Australian made, equipping some Total sites*) a high voltage type cable is required, it is the “TRIAX” down conductor

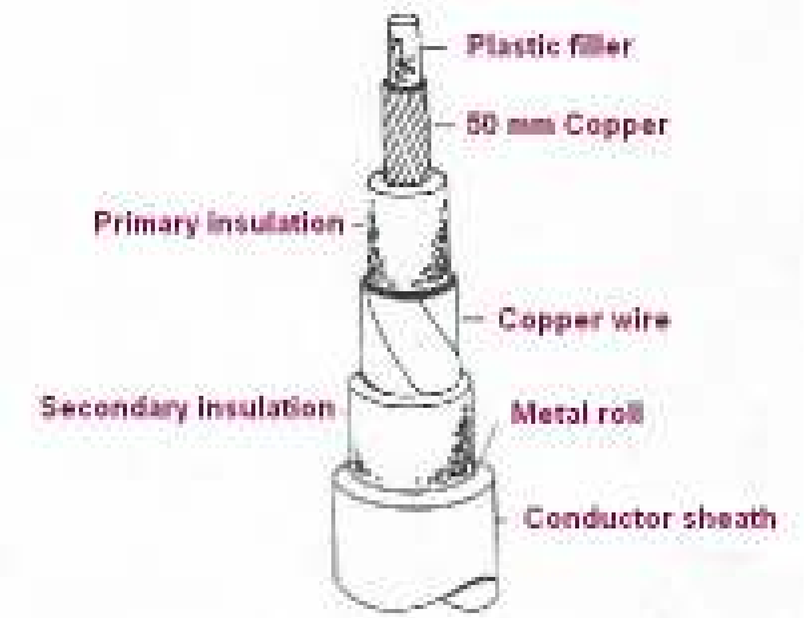


Figure 33: Triax construction format

The TRIAX down-conductor functions are to convey the lightning discharge current to ground virtually without danger of side flashing. A unique conductive outer sheath allows electrostatic bonding of the building through cable securing saddles…..etc, as per the vendor literature.

Anyway, follow “your” vendor recommendations; a high voltage cable is obligatory a complementary safety measure. *(But personally, knowing that the discharge can be in a range of millions -10^6 – volts, I am not going to touch the cable during a lightning storm…)*

4.1.3.5. Descent conductor – general recommendation

The following recommendations should be observed when installing the down conductor:

- use the shortest route down to the earthing point
- follow a straight line, avoiding sharp angles (radius of curvature > 20 cm)
- avoid upward turns (except when passing over obstacles lower than 40 cm where a 45° maximum incline is tolerated
- avoid passing close to any electric lines. If crossing cannot be avoided, the electric lines should be metal-shielded 1 m either side of where the down conductor passes and the cladding then connected to the down conductor

All descent conductors have to be tightly fastened, to resist to the pull out force electromagnetically induced. (fixing point at least each 50cm)

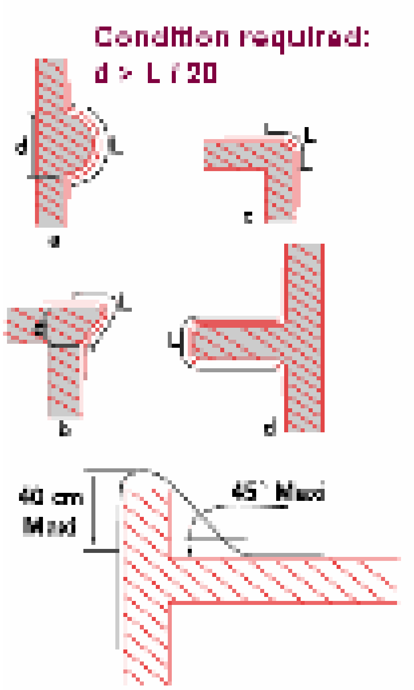


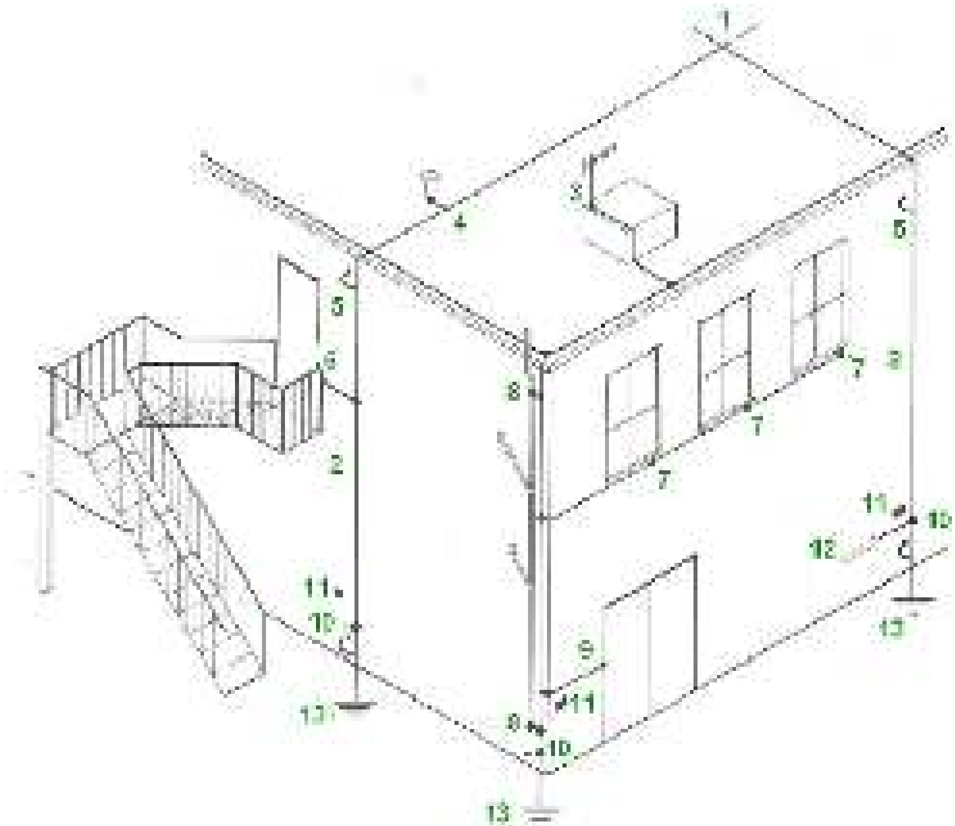
Figure 34: Down conductor recommendation

On a Total (remote and new) site, some operators had run a (temporary) extension cable (220V) to supply a TV set, a coffee pot, etc…, just to feel comfortable during night shift

They attached their cable alongside a descent conductor… I removed myself this cable, just in time, the same day, the lightning counter worked for the first time….

On an other site, in living quarters, one decided to erect a TV antenna mast during a lightning storm, he was badly burned…

4.1.4. Bonding



1: Air termination	*2: Down conductor*	*3: Bond to aerial*
4: Bond to vent	*5: Bond to re-bar*	*6: Bond to metal staircase*
7: Bond to metal windframe	*8: Bond to vent pipe*	*9: Bond to steel door frame*
10: Test clamp	*11: Indicating plate*	*12: Main earthing terminal*
13: Eart termination point		

Figure 35 Bonding on a structure

All metal work on or around a structure must be bonded to the lightning protection system if side flashing is to be avoided. When a lightning protection system is struck, its electrical potential with respect to earth is significantly raised and, unless suitable precautions are taken, the discharge may seek alternative paths to earth by side flashing to other metalwork in or on the structure.

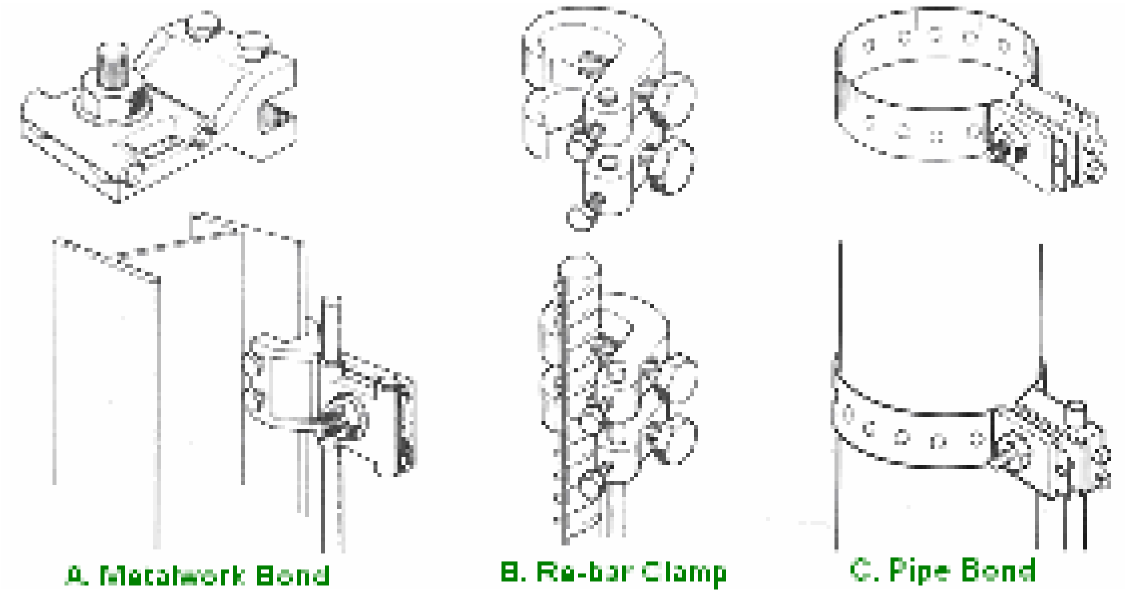


Figure 36: Illustrations of typical clamps used in metalwork bonding

Typically, water pipes, gas pipes, metal sheaths and electrical installations which are in contact with earth, remain at earth potential during a lightning discharge. Even metal parts that are not in contact with earth will see a potential difference between them and the lightning protection system during a discharge, even if this potential is smaller in magnitude to the metal parts in direct contact with earth.

It is vital that all exposed metalwork is bonded into the lightning protection installation (see figures)

4.1.5. Test Clamp - Lightning event counter

Figure 37: At bottom of descent: counter and test clamp

Air termination devices are normally equipped (on their direct descent conductor) with an event counter, totalling the number of strikes of at least a given value of the current.

A test clamp should be provided at the bottom of the descent in a P.V.C or concrete inspection pit so that the down conductor may be disconnected from the earth termination and regular checks of the earth termination resistance be carried out.

The test clamp (as on the figure) could be positioned at a height of two metres from the ground, the lightning flash counter (if required), should be placed just next to the test clamp.

The down conductor should be protected from the test clamp down to the ground by a stainless steel (or PVC) sheath.

4.2. GROUND IN LIGHTNING PROTECTION

4.2.1. Lightning Earthing Generalities

Earthing plays a vital role in all electrical systems. The main reasons for earthing are:

- To protect people and livestock
- To protect equipment
- To permit the equipment to function correctly
- To ensure the reliability of electrical services.

A good earth connection should possess the following characteristics:

- **Low electrical resistance** between the electrode and the earth. The lower the earth electrode resistance the more likely the lightning or fault current will choose to flow down that path in preference to any other, allowing the current to be conducted safely to and dissipated in the earth. A lightning ground resistance should have its value under 10 ohms.
- **Impedance value** (inductance) **the lowest possible** to minimise the electromotive force. For this effect it is strongly recommended to avoid grounding with only one underground horizontal wire or only one vertical electrode. Practice using deep well to catch moisture is not advisable as this system shows high impedance (above 10m deepness). Good advice is to multiply the horizontal wires and the vertical earth electrodes.
- **Good corrosion resistance**. The choice of material for the earth electrode and its connections is of vital importance. It will be buried in soil for many years so has to be totally dependable.
- Ability to **carry high currents** repeatedly.
- Ability to perform the above functions for a **minimum of 30 years**.

4.2.2. Soil Conditions

Achieving a good earth will depend on local soil conditions. A low soil resistivity is the main aim and factors that affect this are:

- Moisture content of the soil.
- Chemical composition of the soil, e.g. salt content.

- Temperature of the soil.

The following tables illustrate the effect these factors have on the soil resistivity.

Effect of Moisture on Resistivity		
Moisture content % by weight	Resistivity ohm - cm	
	Top Soil	Sandy loam
0	1000 x 10^6	1000 x 10^6
2.5	250 000	150 000
5	165 000	43 000
10	53 000	18 500
15	31 000	10 500
20	12 000	6 300
50	6 400	4 200

Effect of Salt on Resistivity	
Added Salt (% per weight of Moisture)	Resistivity ohm - cm
0	10 700
0.1	1 5020
1.0	450
5	190
10	130
20	100

Effect of Temperature on Resistivity *For sandy loam 15.2% moisture*		
Temperature		Resistivity ohm - cm
C	F	
20	68	7 200
10	50	9 900
0	32 (water)	13 800
0	32 (ice)	30 000
- 5	23	79 000
- 15	14	330 000
Note: if your soil temperature decreases from + 20°C to – 5°C, the resistivity increases more than ten times		

Table 9: Factors affecting soil resistivity

Note: Although *"effect of Salt""* quotes figures for salt laden soil, it is now deemed bad practice to use salt as a chemical means of reducing soil resistivity, because of its very corrosive nature. Salt along with other chemicals, has the disadvantage of leaching out of the surrounding soil after a period of time, thus returning the soil to its original resistivity.

Once the soil resistivity has been calculated from the local soil measurements, the appropriate earth electrode system can be chosen by using typical formulae listed below:

Horizontal strips (Rectangular Section)

$$R = \frac{\rho}{275L} Log10 \frac{200L^2}{wD}$$

Horizontal strips (Circular Section)

$$R = \frac{\rho}{275L} Log10 \frac{200L^2}{dD}$$

Vertical strips (Rectangular Section)

$$R = \frac{\rho}{275L} Log10 \frac{800L}{w}$$

Vertical strips (Circular Section)

$$R = \frac{\rho}{275L} Log10 \frac{400L}{d}$$

Where:

R = Apparent earth electrode resistance in ohms
ρ = Soil resistivity in ohm-cm
D = Depth of electrode in metres
D = diameter of electrode in centimetres
L = Length of electrode in metres
W = Width of electrode in centimetres

For Example

If we require an earth electrode resistance of 20 ohms and we have established by a soil resistivity survey that ρ = 10,000 ohm-cm. (several electrodes in parallel will reduce the general earth resistance)

If for this example we assume that the soil is suitable for deep driven rod electrodes then we can calculate the depth of rod required to obtain the desired 20 ohms resistance.

From above, for vertical strips (circular section): $R = \frac{\rho}{275L} Log10 \frac{400L}{d}$, thus, R = 20 ohms and ρ = 10 000 ohm-cm

Assume we use a standard 5/8" diameter rod (nominal diameter 14 mm)

Actual shank diameter 14.2 mm, thus, d = 1.42cm L =?

If we let L = 6 mm and substitute to see what of R is obtained: $R = \frac{10000}{275x6} Log10 \frac{400x6}{1.42}$

R = 6.0606 x 3.228 = 19.56 ohms

Thus 6 m of extensible rods (5x1.2m) can be used to obtain the desired resistance value of 20 ohms.

The above example illustrates the importance of the accuracy of the soil resistivity figure. If the survey is inaccurate, then the calculated apparent earth electrode resistance R will be Inaccurate and misleading

4.2.3. Principle of Earthing according to Lightning air termination

4.2.3.1. Grounding for Franklin rod

Position of the Lighting ground specific system is always directed towards the outside of the building / structure to protect.

The conductors, parts of **crows foots** or interconnecting electrodes must be distant of at least 3 m from any metallic pipe / rack not entering the building / structure being protected (different installations). If this constraint cannot be respected, a good and permanent ground interconnection has to be established between these different installations.

For each individual descent conductor, from each Franklin rod, earthing should be done by

- Ground conductor of same component, same section than the descent conductor, laid in **crows foot** method such as (for example) 3 conductors up to 10 metres length, horizontal at a depth of at least 60 cm.

- A set of 3 vertical electrodes, of at least 2m depth, laid in equilateral triangle of minimum 2 m side dimensions. Electrodes being interconnected at their tip by a conductor of at least the same size of the descent conductor.

- Interconnection with the main earth loop network with a conductor of at least the section of the descent conductor. (See following paragraph "Interconnections debate…").

4.2.3.2. Grounding for Faraday cage

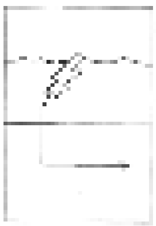
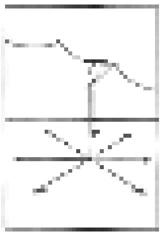
For each individual descent conductor, earthing should be done by

- Ground conductor of same component, same section than the descent conductor, laid in crow foot method, but with small dimensions; for example 3 conductors of 2 or 3 metres length at a depth of at least 60cm.
- A set of 2 vertical electrodes of at least 2m., distant of at least 2 m and interconnected with a conductor of at least the section of the descent conductor.
- Interconnection with the main earth loop network with a conductor of at least the section of the descent conductor..

4.2.3.3. Grounding for Taut cables

Same as per Franklin rod method

4.2.4. General Methods of Earthing

Method	Schematics	Comments
Single Strip End Connected		Poor results as lightning has only one path. High ground voltages will be experienced at injection points.
Radial Earthing, Single Radial		Ideal for medium resistivity areas and radials up to 30 metre length. Lightning current split 6 ways.

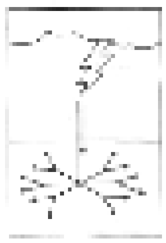
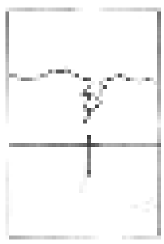
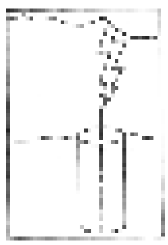
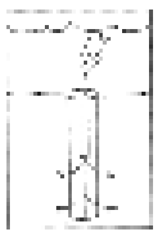
Method	Schematics	Comments
Radial Earthing, Crows Foot Radial		Ideal in areas of higher soil resistivity. Creates multiple paths for lightning current and high capacitive coupling to ground. Note: Earth Gel is generally very effective with Radial Earthing
Copper Clad Steel Rod earthing		Effective with only one rod when high ground water level exists.
Multiple Rod Earthing		Place rods according to best depth driven with first rod. Spacing of each rod should be 2 x depth
Deep Drill Earthing		Required in dry areas and where ground water level is very low. Essential to make continuous contact between wall of hole and rod. Drilling mud and gel is very effective. **Cautious about high impedance
Earthing with Limited Area and Pedestrian Traffic		Use deep drill hole and place one or two concentric plastic cylinders over top 3-4 metres. This reduces ground voltage rise at the surface.

Table 10: Different principles / methods of earthing in lightning protection

4.2.5. Specific Materials for earth termination network

4.2.5.1. Deep Driven Earth Electrodes

A soil resistivity survey indicating lower resistivity at greater depths will make the deep driven earth electrode a logical choice. Deep driven earth electrodes are more likely to reach permanent moisture unaffected by seasonal changes.

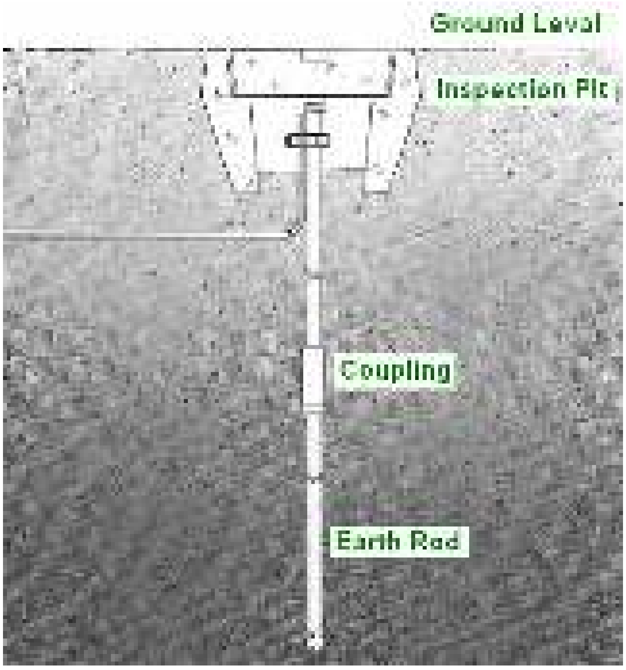


Figure 38: Deep driven Earth Electrode

A common misconception is that increasing the diameter/width of the rod/strip electrode will give a significant reduction of earth resistance. Tests have shown that increasing the diameter of a rod electrode from 12.5 to 25 mm has increased the weight by 400%, increased the cost by 400%, but only reduced the earth resistance by 9.5%.

To obtain a low overall resistance, current density should be as low as practicable in the soil which is in contact with the electrode. This can best be achieved economically by having one electrode dimension very large in comparison with the other dimensions. This is best achieved by a rod or strip electrode.

4.2.5.2. Parallel Earth Rod Electrodes

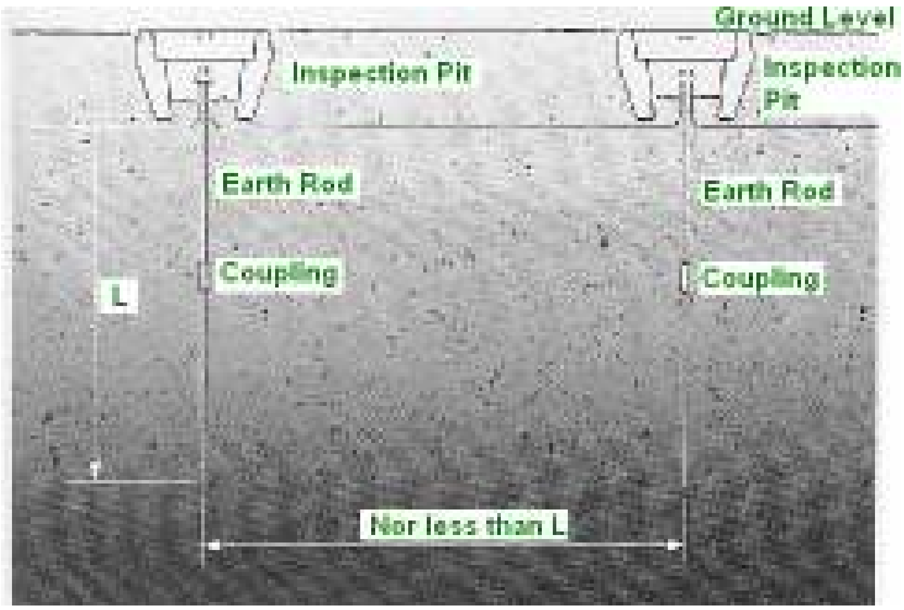


Figure 39: Spacing or Paralleling Earth Rod Electrodes

Where ground conditions make deep driving of earth rods impossible, a matrix arrangement of rods coupled to one another by conductors can be used.

If possible, the earth rods must be spaced at least equal to their driven depth. No significant decrease in resistance will be obtained by spacing greater than twice their driven depth.

If earth rods cannot be driven in a parallel line, a 'Crows Foot' configuration can be used, ensuring that the spacing depth ratio is still maintained

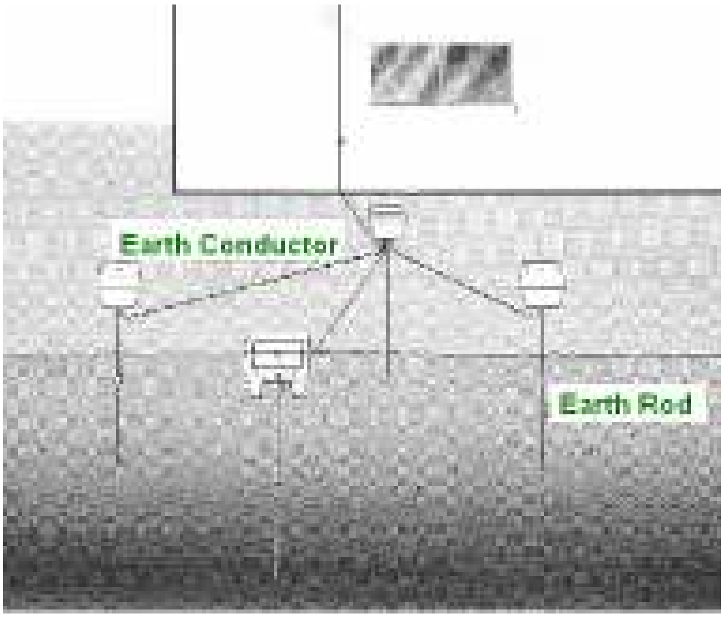


Figure 40: Crows Foot Earth Configuration

4.2.5.3. Radial Strip Electrodes

Ground that has one metre depth of soil before encountering bedrock will best be suited to a buried radial electrode, provided the system is installed below the frost line and below the area that is subject to seasonal weather changes.

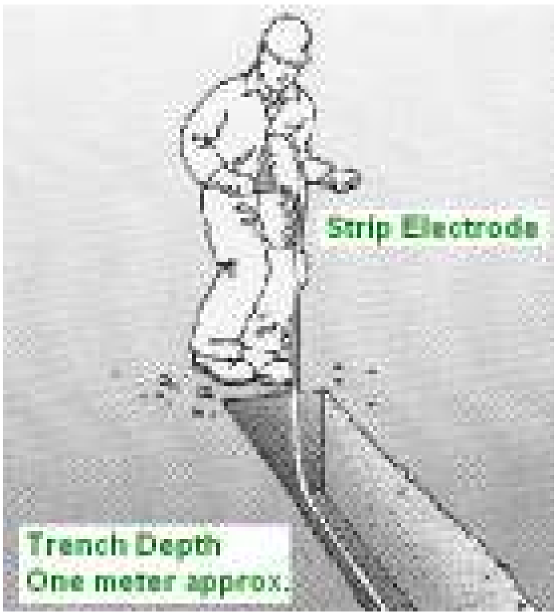


Figure 41: Buried Strip Earth Electrode

4.2.5.4. Solid Plates or Mats

Earth plates or mats can be buried instead of driving rod electrodes but installation is expensive and time consuming

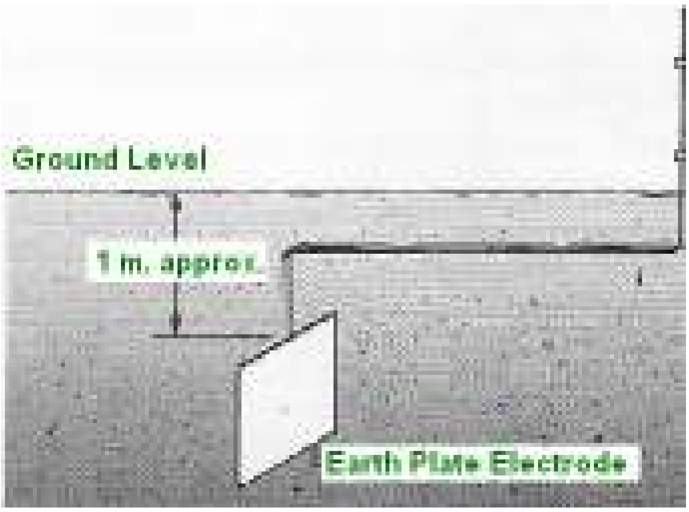


Figure 42: Buried Earth Plate Electrode

4.2.5.5. Reinforcing bars in foundations as natural earths

This is an economical method of using the mass of metal already underground in the form of the reinforcing bars, within the structure's foundations. Precautions should be taken to ensure there is electrical continuity between these reinforcing bars and the earth/lightning protection connections above ground.

4.2.5.6. Underground Pipe Work System

Buried water pipes were previously considered to be a reliable method of earthing but the increasing use of plastic pipes or replacing metal joints with plastic ones now makes this method unreliable.

Other forms of earth electrode can be used, including ring conductors or radial strips emanating from a particular point, or a combination of conductors with earth rods.

4.2.5.7. Voltage Gradient

A further factor affecting the choice of an electrode system is the electrical considerations.

Step and touch voltages on the surface of the ground in the vicinity of earth electrodes must be restricted to safe values.

This can be achieved by using electrodes to form a ring around the area to be protected. The electrodes must be buried sufficiently deep to reduce surface potential.

An effective method of reducing the voltage gradient of rod electrodes is to install them with the top of the electrode some distance beneath the surface of the soil. The connection between the electrode and down conductor being made with insulated conductor.

4.2.5.8. Corrosion

The correct choice of materials for a lightning protection system is vital. Metal fittings must be compatible with the metal or metals used externally on the structure over which the system passes or with which it may be in contact.

Aluminium and copper, the two metals most commonly used in lightning protection systems, **are not compatible,** so great care must be taken when both are used in a system particularly where they come into contact with each other.

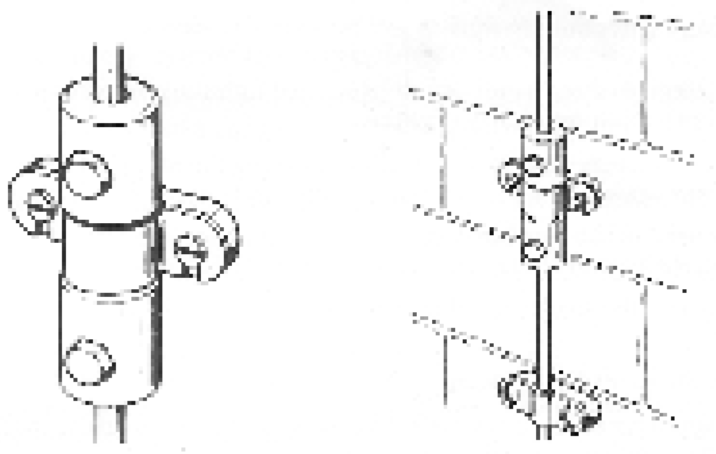


Figure 43: Example of Bi-Metallic Connector

If aluminium is selected as the material for air termination networks and down conductors, it has to be connected to copper at or around the test clamp. This connection should be positioned at the beginning of the earth termination network. This is because the Earthing Code do not permit aluminium to be buried underground.

The contact surfaces of dissimilar metals should be kept completely dry and protected against the ingress of moisture, otherwise corrosion will occur. A particularly effective means of excluding moisture is to use inhibitor pastes, bitumastic paint, or approved protective wrappings.

As aluminium is prone to corrosion when in contact with cement and mortar mixes, aluminium conductors need to be fixed away from the offending surface with an appropriate fixing.

4.2.6. Improvement in soil continuity

Improvement of earth distribution by

- Adding earth electrodes to the already existing ones
- Multiplying the earthing solutions and interconnect all systems together
- Apply a treatment to reduce impedance of the soil.

Improvement with soil conditioning agents

Introducing a soil-conditioning agent into the ground can reduce the soil resistivity and hence reduce the earth resistance.

There are various agents available, the choice of any particular one will depend on the type of earth required - temporary or permanent; the locality; the condition of the soil, etc.

Moisture forms an important part in obtaining a low soil resistivity value and it is the impurities in the water that produce this. One way of reducing the soil resistivity is to pour chemical solutions i.e.: copper sulphate; sodium carbonate; calcium sulphate, over the local area and allow it to migrate through the soil. The disadvantage of this is the large volume of solutions required, which makes it a cumbersome and time consuming exercise. Also chemicals will eventually leach out of the local soil, returning it to its original high resistivity. Dissolving chemicals into the soil is also likely to encourage corrosion of the earth electrode. Hence the reason for not recommending the use of salt as a means of reducing the soil resistivity.

Other soil-conditioning agents are available including “*Bentonite”* and “*Marconite”.*

Bentonite is used as an earth-electrode back-fill to reduce soil resistivity by retaining moisture. The clay consists largely of sodium “montmorillonite”, which when mixed with water swells to many times its dry volume. It has the ability to hold its moisture content for a considerable period of time and to absorb moisture from the surrounding soil (e.g. from rainfall).

Marconite is a conductive carbonaceous aggregate which when mixed with conventional cement, effectively increases the surface area of the earth-electrode, thus lowering its earth resistance. Ideal for use on sub-stations and transmission/distribution networks or in hot, dry climates, and also has electromagnetic screening and anti-static flooring applications.

Both products have applications with deep-driven electrodes. The ground/soil in question can be drilled using a portable drill rig, transported to the site. Significant depths can be reached depending on the type of ground.

The electrode assembly can then be inserted into the predrilled hole and back-filled with Bentonite or Marconite, or any other appropriate conditioning agent.

It is vital with any earthing system that regular inspection is carried out for possible damage. Regular checks on earth electrode resistance to ensure optimum protection are advised.

An other simple method to improve soil quality is to "import" massive quantities of topsoil having good resistivity.

4.2.7. Grounds interconnections debate

Do we need to interconnect the specific Lightning Ground network with the other earthing networks?

4.2.7.1. Total Specification GS EP ELE 031

Hereafter, extracted from this specification, the paragraph 3.7

The purpose of the earthing system is to dissipate as much as possible the lightning current into the soil (50%) without producing dangerous potential differences in the earthing system.

Earthing system shall be meshed like the following figure:

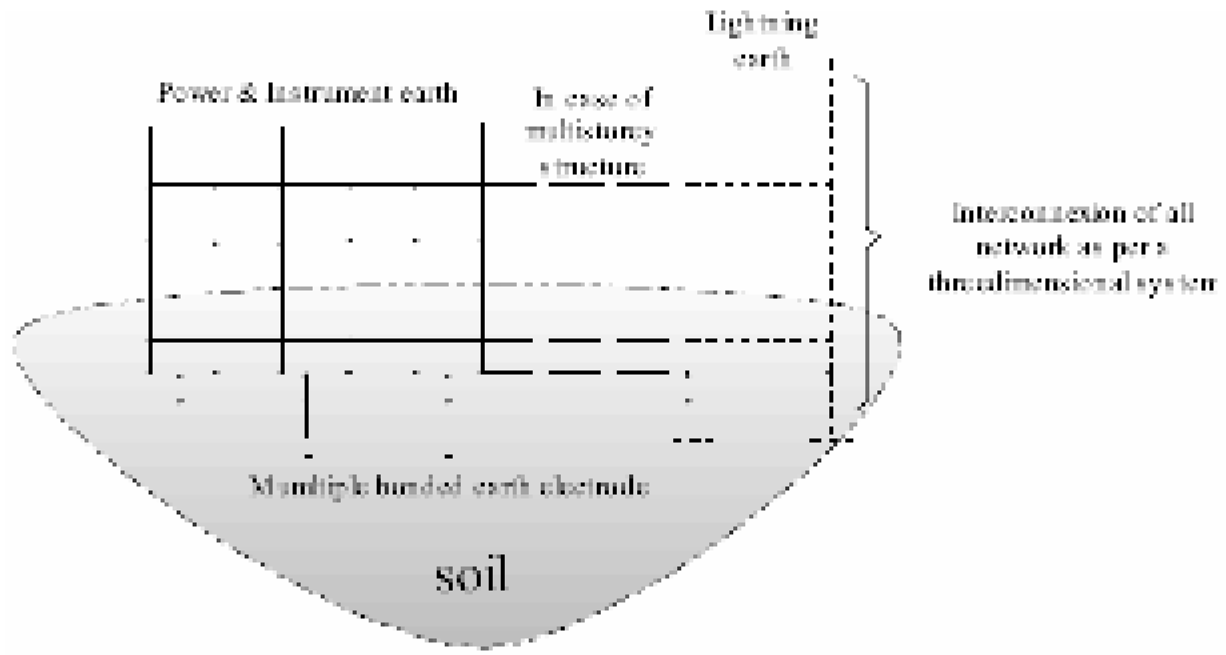


Figure 44: Site Earthing / Meshing as per paragraph 3.7 of GS EP ELE 031

This does not mean that the different ground networks (electrical, lightning, instrumentation, telesystem,…) are interconnected on Total sites. Strong habits, personal well convinced minds are ferociously against the interconnections and do defend vigorously their “independence”, with sometimes, poor arguments to defend their position…

Hereafter is a personal analysis (and judgment) about the “interconnection “problem”.

4.2.7.2. Case of separate Grounds between Network and Lightning Protections

When a "normal" strike occurs, on the air termination (specially installed for that purpose) the overvoltage and high currents are driven away the ground installation network. Everything is, at it "should be"; no interference between the different earthing systems (as long as they are clearly distant from each other)

All the manufacturers, all the engineering and standardisation offices do not guaranty a 100% protection. Air terminations are there to support the strikes but nevertheless, within the protected area, an "unexpected" event could direct a strike a “wrong way” towards a building or a structure.

Everyone, with field experience have seen or heard about lightning causing big damages inside installation believed to be "well" protected.

Probabilities are low for such happening in descending strikes, but are more present for ascending ones. A small not directly protected building could have more 'capacitance' ready to strike than an air termination nearby.

In that case ("unexpected" strike), interconnection with the lightning ground is welcome as well as the 'electrical' surge protectors devices.

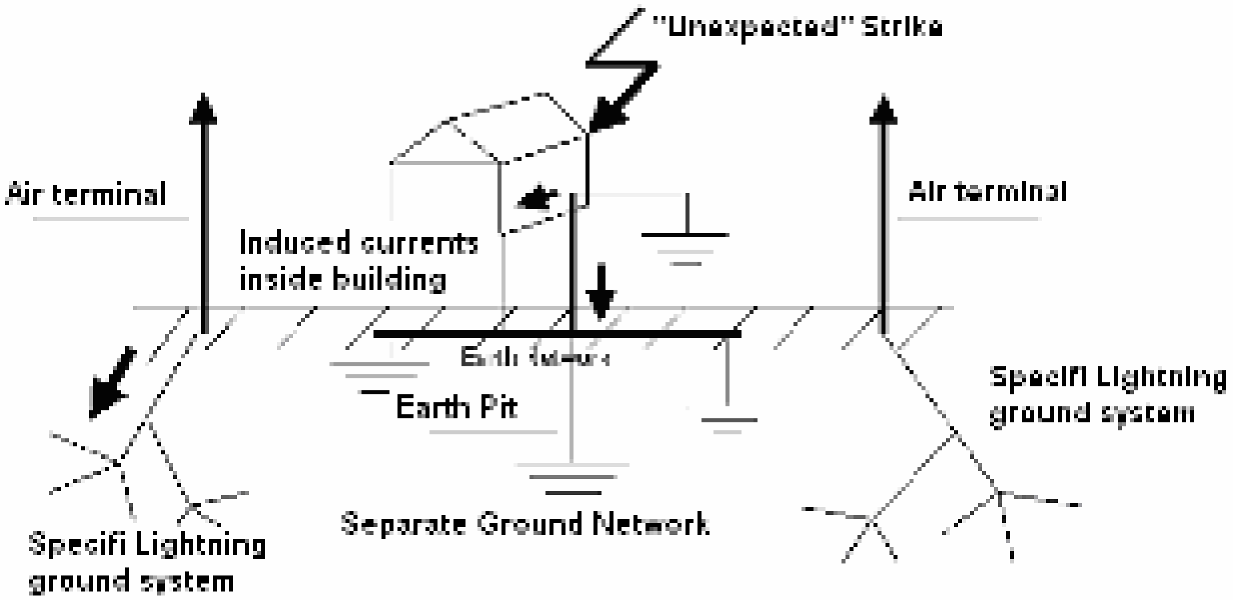


Figure 45: Lightning and other ground networks are separated

4.2.7.3. Case of Interconnected Grounds between Network and Lightning Protections

When strike occurs on the air terminal, the overvoltage can spread on the entire network, bringing “parasite” currents and voltages in "feed-back". Preferable paths could be taken according to resistance value of the different branches of the network.
This is the main concern for those against interconnection

This can happen with insufficient direct ground termination for the capturing device and / or bad connections. The ground network could be as well with insufficient meshing and/or too small copper wires cross sections.
It enlightens as well the necessity to have good engineering, proper measurement of soil resistivity and earthing value as well as a permanent survey and maintenance of the earthing network

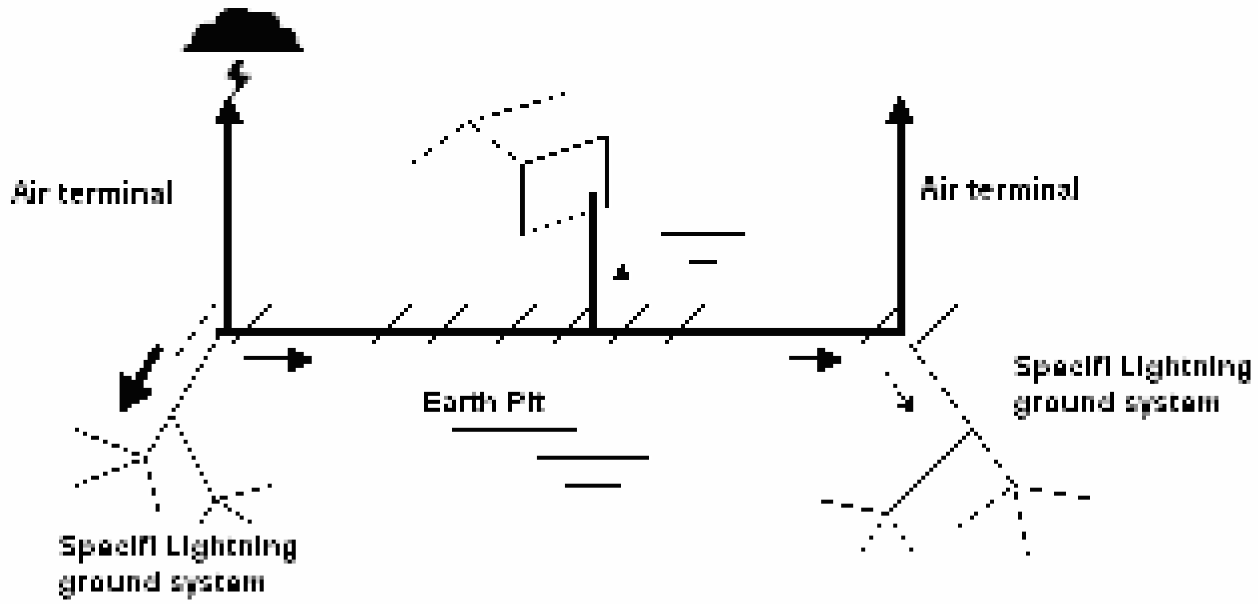


Figure 46: Lightning and other ground networks are interconnected

4.2.7.4. Conclusion

For those in favour in Separate grounding::

Argumentation such as: “*Air Terminal is for receiving strikes whose current must be routed directly to earth, without "feed-back" possible in the installation*”, leads to the following answer:

Inconvenient: is: *what about the "unexpected" strike creating induced current in cables on racks or even in ground;* And do not say, it does exist! It is impossible! I was on a new plant, under commissioning, lightning protection installed (ESE Dynasphere type), lightning ground network completed, but;;;; instrumentation ground kept independent (*even the electrical power supply -220 V - was "refused" to be interconnected*). First storm occurred,

I was on the plant and I saw the strike on an instrumentation power supply (220V) cable rack, in the middle of the onshore unit. The two Beckmann gas chromatograph / analyser concerned by the supply were dead…., power supply card burned.

As the "unexpected" always happens…., it is better to interconnect all the grounding networks, including Lightning, Telephone, Instruments, Radio, etc.

Of course this 'general' network should be of good quality, well engineered, well surveyed / maintained.

When in doubt, "excessive" grounding will be always better than "bad" and incomplete earthing.

5. INSULATION AND INSULATION MEASUREMENT

When we talk about earths or earthing arrangements, we wish to have the lowest possible resistance. With insulation, it the reverse, we must have the highest resistance and the highest possible dielectric strength.

Earth and insulation are directly linked since earthing fulfils its protection / surveillance function (with the residual current systems, permanent insulation monitors, etc.) if there is an insulation failure.

5.1. EARTH – CONTINUITY – IMPEDANCE

5.1.1. Measuring the earth connection

To measure the ohmic value of the earth connections we generally directly use a **earth resistance meter** with, as accessories, two 60 cm (diameter 1 cm) earth electrodes (the probes) made of good conductive material and three lengths of insulated electric wire (cross-sectional area 1.5 or 2.5 mm²) of at least 25 m each. *(The dimensions and methods given here and blow must be considered to be "standard" methods, each earth resistance meter manufacturer has his own specific technique which, in any case, will be very similar to this one. Follow the instructions in the user guide supplied with the measurement instrument).*

To take the measurement we plant the two probes into the ground in the shape of a triangle (at least 20 cm into the ground) with the points of the triangle at least 20 m apart and the two probes connected to S and HE and we connect the output E to the earth connection (decoupled). The probes can also be aligned with 40 m between the HE probe and the earth connection, and with probe S in the middle.

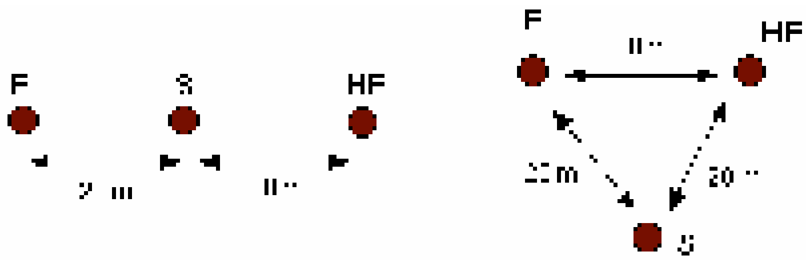


Figure 47: 3-point earth connection measurement

If the distance of 20 m between each probe cannot be respected, several measurements must be taken and then we take an average of the different measurements. The measurement is directly read on the earth resistance meter.

This resistance can also be determined using an ordinary ohmmeter, by taking three measurements.

- from E to S (R_{E-S})
- from S to HE (R_{S-HE})
- from E to HE (R_{E-HE}) then by performing the following calculation: **$R_E = (R_{E-S} + R_{S-HS} - R_{E-HE}) / 2$**

The following measurement configuration (see figure) uses the same principle, only the letters have changed. Follow the instructions in the instrument's user guide for the connections.

On the instrument, the earth to be measurement is the connection marked ''T' and the probe inputs are marked A and B
In the drawing, the earth to be measured is marked 'Z' and the probes are marked X and Y.

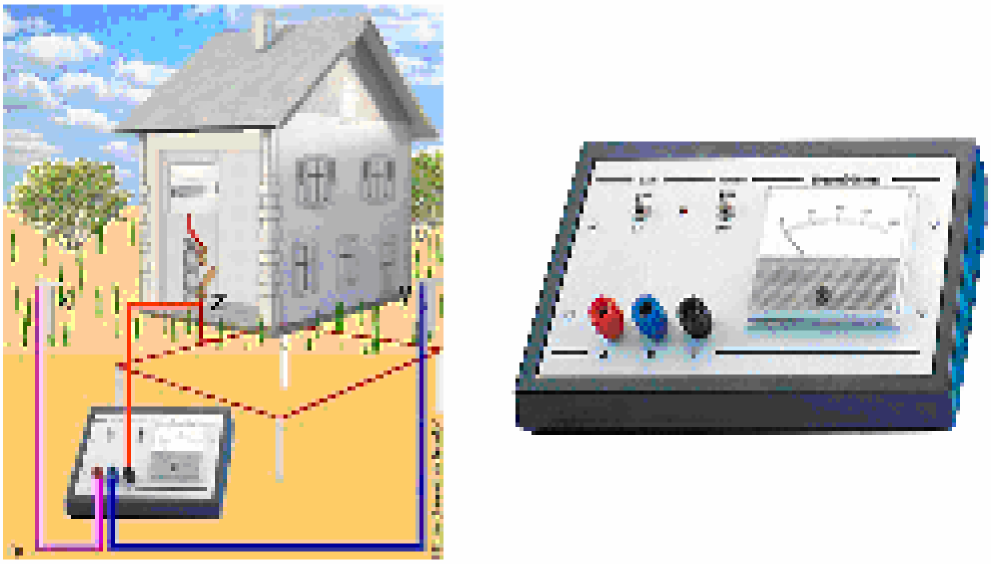
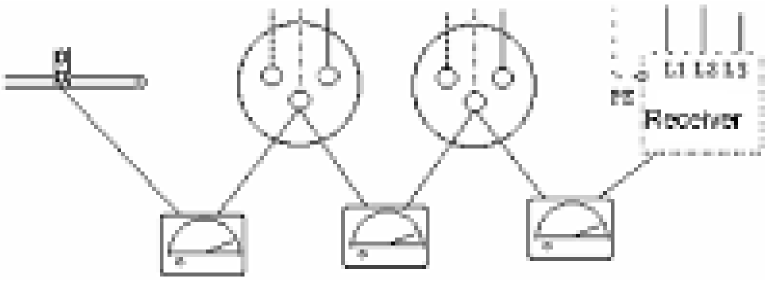


Figure 48: Measuring an earth

5.1.2. Protective conductor continuity

To take this measurement we must measure a very small resistance between the earth electrode, and the conductors and conductive objects/receivers connected to the PE (do not forget the protective cells in the network connections).

Figure 49: Measuring the protective conductor (PE) continuity



An ohmmeter (analogue or digital) can be used to check the value of this resistance.

If it is just a question of testing a continuity (e.g. to find out if it is the correct wire) we can use a buzzer, a torch or quite simply the "beep" function of your multimeter (used as an ohmmeter).

Figure 50: Continuity check with contact stick

The continuity tests can be used for all types of electrical equipment. A simple light fitting must be earthed and the earth continuity test is part of the ***annual*** tests and measurements. In industry and in buildings receiving the public, this test must be carried out annually by an independent organisation. In the photo, the contact stick is connected to an ohmmeter which has a second conductor connected to a reference earth connection.

5.1.3. Measuring the loop impedances

Extract from Total precommissioning specifications

The IEC364-3 standard for the protection of personnel states that the contact voltage (touch voltage) must not exceed 50 Vac rms. Therefore, the loop impedances must be less than the values indicated in the following table:

Distribution system	Id (mA)	UL (V)	RA (ohms)
240 V 3 ph 60 Hz	300	50	167
440 V 3 ph 60 Hz	300	50	167
6.6 kV 3 ph 60 Hz	30,000	50	1.67

Table 11: Loop impedance values according to the distribution systems

Definitions

RA = The ohmic value of the earth resistance of all the conductive parts interconnected to an earth connection.
Id = First fault current between a phase and a equipment ground
UL = Conventional contact voltage

All the tests must be carried out in compliance with the details and diagrams (given below) by using an AC test generator. The current injected must be equal to 1.5 times the nominal current of the circuit being tested but must not exceed 25 A. All the current sources of the circuit being tested must be isolated before the test is carried out.

The ohmic value measured will be equal to:

X = U / I = Test generator voltage / test generator current

Example 1: motor supplied at low voltage from a switchboard

a) Connect the test generator between point ‘R’ on the switchboard busbars and point ‘E’ on the earth bar (in the same switchboard).

Close circuit breaker ‘B’ and determine the impedance value of loop E1 by short-circuiting phase ‘R’ (at the motor) with the equipment ground.

b) Short-circuit the impedance ‘F’, close circuit breaker ‘E’ to determine the impedance value of loop E2

c) The total impedance of the loop = E1 + E2

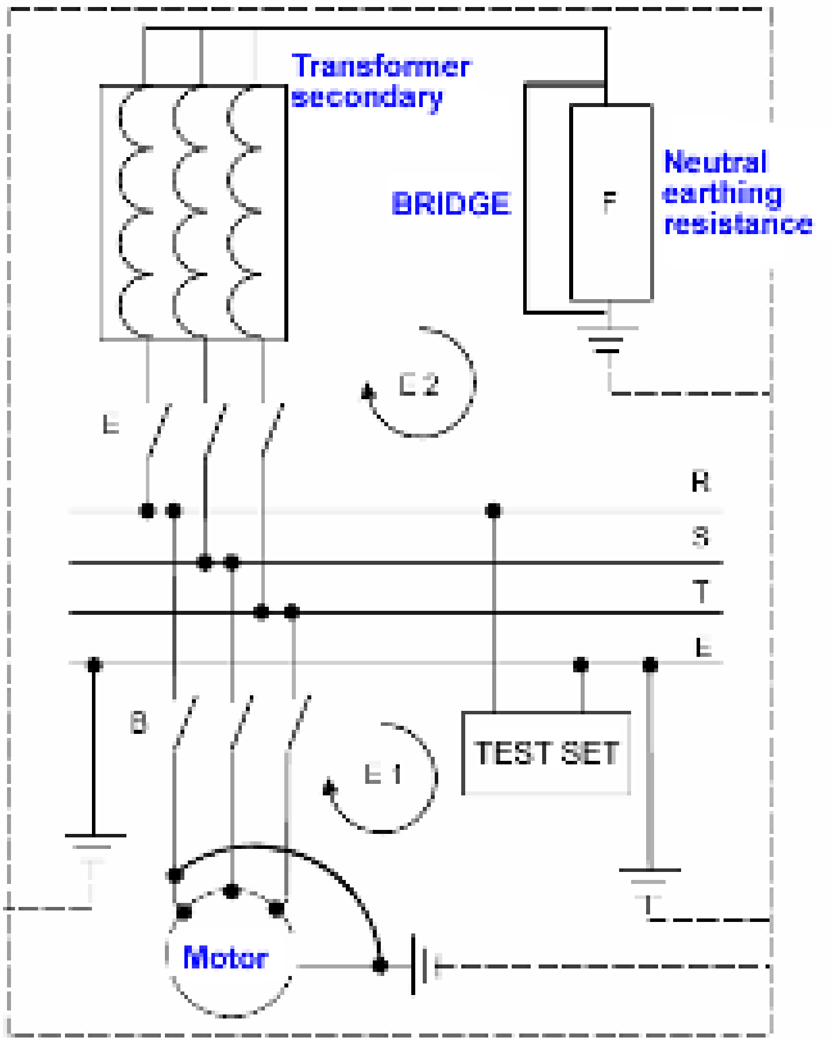


Figure 51: Loop impedance test - example 1

Example 2: lighting circuit supplied from a switchboard

a) Connect the test generator between point ‘T’ on the switchboard busbars and point ‘E’ on the earth bar (in the same switchboard). Close circuit breaker ‘A’ and determine the impedance value of loop E3 by short-circuiting the phase and equipment ground at the light fitting

b) Short-circuit impedance ‘F’, close circuit breaker ‘E’ and determine the impedance value of loop E4

c) The total impedance of the loop = E3 + E4

Note (for commissioning): the loop impedance test for the low power circuits (such as the lighting circuits) is left to the discretion of the commissioning supervisor.

Depending on the site's protection level, only one single test (on a single circuit) may be necessary per switchboard, on condition that this single test is satisfactory.

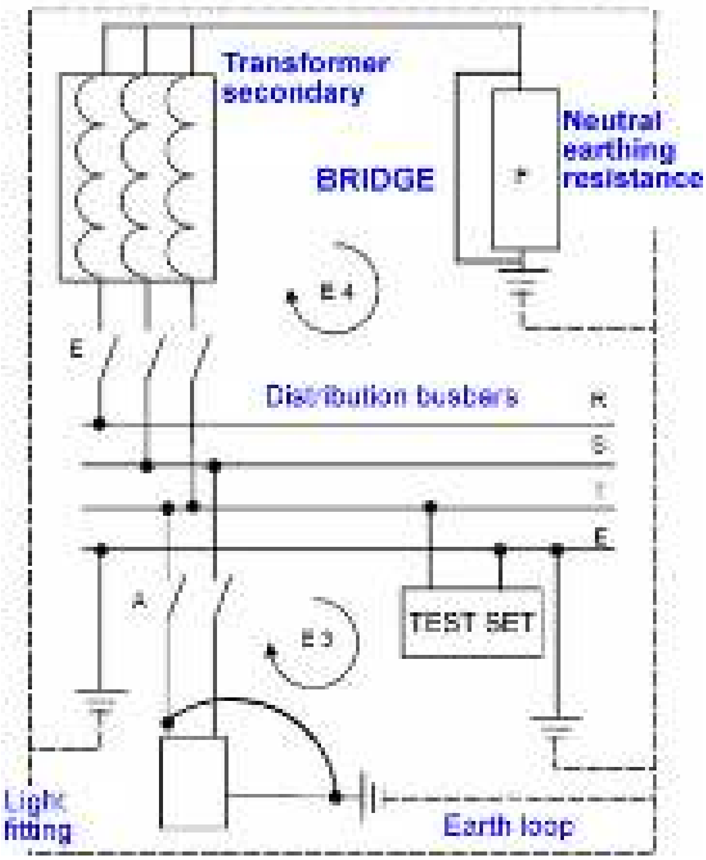


Figure 52: Loop impedance test - example 2

Example 3: HV motor supplied from its protection cubicle

a) Connect the test generator between point 'R' on the switchboard busbars and point 'E' on the earth bar (in the same switchboard).

Close circuit-breaker 'A' and determine the impedance value of loop E6 by short-circuiting phase 'R' (at the motor) with the equipment ground.

b) Connect the test generator between point 'R' on the switchboard busbars and point 'E' on the earth bar (in the same switchboard).

Close circuit breaker 'B' and determine the impedance value of loop E5 by short-circuiting phase 'R' (at the earthing transformer) with the equipment ground

c) The total impedance of the loop = E5 + E6

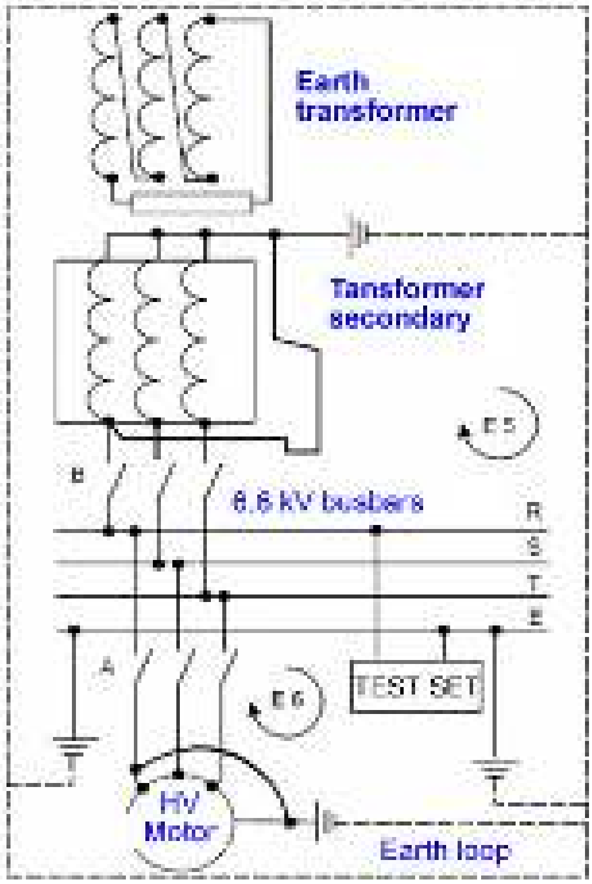


Figure 53: Loop impedance test - example 3

5.2. INSULATION

5.2.1. Insulation resistance measurement and dielectric test

These two concepts which characterise the quality of an insulating material are too often confused and merit being explained again.

5.2.1.1. Dielectric strength test

This test is more commonly known as a "***breakdown test***" and expresses an insulating material's capacity to withstand a medium-duration overvoltage without arcing (sparking).

In reality, this overvoltage can be due to lightning or to the induction resulting from a fault on a power transmission line, for example. The main purpose of the dielectric test is thus to ensure that the construction rules relating to the creepage distance (also known as "leakage path") and the isolating distances in air, as specified in the standards, are respected.

The test is often carried out by applying an AC voltage, but it can also be performed with a DC voltage. The instrument used for these measurements is an insulation tester.

Figure 54: Example of an insulation tester

The result obtained is a voltage value, very often expressed in kilovolts (kV).

The dielectric test is more or less destructive in the case of a fault, depending on the power of the test instrument used.

It is therefore reserved for new or renovated equipment: only equipment which successfully passes the test will be put back into service.

Regular dielectric strength tests (HV) under the maintenance programme:

In 1996, the cable manufacturing industry decided that regularly carrying out dielectric strength tests using DC generators on low voltage cables with PVC (XLPE) insulations inevitably leads to a deterioration of the insulation. Since then, the tests at the highest dielectric strength voltage for LV cables have been "deferred", at the request of the manufacturers.

High voltage insulated polythene (EP) cables are not subject to the same deterioration during tests using DC injection and following ageing. They can be tested, at least when they are first installed, using the following test values.

A commissioning recommendation for HV cables with the DC voltages to be applied according to the cable service voltage.

The tests are carried out using an insulation tester or hi-pot tester. The tester voltage depends on the thickness of the insulation (wall mils) with approximately 300 V per mil (1 mil = 1 milli-inch = 25.4 microns = 25.4 x 10^{-3} millimetres).

Important: To repeat what we have just said, these tests must only be carried out once (at the maximum test voltage) before commissioning, and it is always better to obtain the manufacturer's approval first.

Acceptance test (commissioning) for HV cables				
Before commissioning				
Operating voltage between phases	DC Hi-Pot Test		DC Hi-Pot Test	
	(15 Minutes)			
	Wall - mils	Kv	Wall - mils	kV
5,000	90	25	115	35
8,000	115	35	140	45
15,000	175	55	220	65
25,000	260	80	320	95
28,000	280	85	345	100
35,000	345	100	420	125
46,000	445	130	580	170
69,000	650	195	650	195
Note: if the leakage current stabilises, the test time can be reduced to 10 minutes				

Table 12: HV cable test voltages for commissioning

Concerning the hi-pot tests, later, during maintenance operations, it is not easy to give test voltage values. Each manufacturer and each company (Total and others) may have its own standards, the dielectric strength test voltage then depends on the age of the cable and its visual state of deterioration. An old cable will not "appreciate" its service voltage being exceeded, a cable head will not like to be disconnected, handled and reconnected too often.

That is why only one cable test frequency is given below, so ask your superiors for the voltage value to be applied, it is their responsibility. It is too easy to hold the person carrying out the test responsible when the cable has broken down during the test.

"Hi-pot" test frequency			
After installation and after first test			
Type of service	**1st maintenance test**	**2nd maintenance test**	**Time between following tests**
Lighting – secondary circuits	No test	No test	No test
Motors – main circuits	3 years	8 – 9 years	5 – 6 years
Critical – emergency circuits	12 – 18 months	2 – 3 years	4 – 5 years

Table 13: HV cable test voltages - maintenance test frequency

5.2.1.2. Measuring the insulating resistance

The insulating resistance measurement is non-destructive in normal test conditions.

It is carried out by applying a DC voltage with amplitude less than that of the dielectric test, it is designed to give a result in kΩ, MΩ or GΩ. This resistance expresses the quality of the insulation between two conductive elements and provides valuable information on the risk of leakage currents. Since it is nondestructive it is particularly useful for monitoring the ageing of insulations during the equipment's operating life, or of an electrical installation. It can also be used as a basis for preventive maintenance.

This measurement is taken using an Insulation Tester which is also called a megohmeter or megger.

5.2.2. How to measure insulation levels

In practice, we initially check that the installation or equipment is de-energised, then we apply a continuous test voltage and we obtain the insulating resistance value. When measuring an insulation with respect to earth, we recommend that it is the positive pole of the test voltage which is earthed, to prevent earth polarisation problems when carrying out multiple tests.

All the standards concerning electrical installations and equipment specify the measurement conditions and the minimum thresholds to be respected for the insulation measurements.

5.2.2.1. Insulation measurements on electrical installations

The NF C 15-100 standard, which covers Low Voltage electrical installations, states that the insulating resistance must be measured on 100 m* sections with the installation de-energised:

- Before commissioning and ***with the receivers disconnected*** (circuits open) between each active conductor (phase and neutral conductors) to check that none of them has suffered mechanical damage during installation.

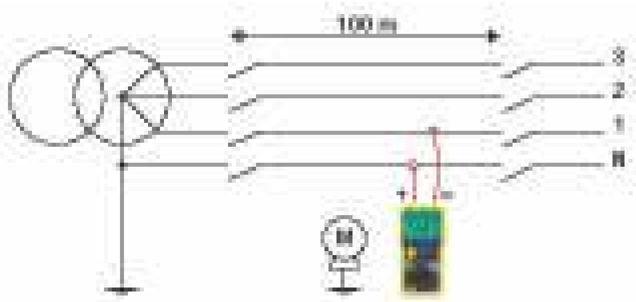


Figure 55: Insulation measurements on open circuits

- Before commissioning and ***with the active conductors connected together***, and with the receivers connected, to check the insulation of all the conductors with respect to earth.

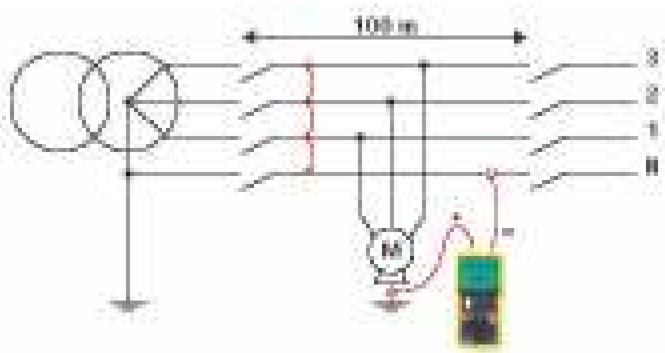


Figure 56: Connect the active conductors together

- If the installation has sensitive electronic devices, they must be disconnected or a check must be carried out during the measurements to ensure that the phase and neutral conductors are connected together. These measurements are also regularly carried out in tertiary and industrial installations.

The measurements can be carried out on shorter sections. In this case, the insulation value will be inversely proportional to the distance. For example, for a 50 metre section, $R_{insulation\ 50\ m} = 2 \times R_{insulation\ 100\ m}$

5.2.2.2. Insulation measurements on a rotating machine

We can test the quality of the winding insulation with respect to earth or the insulation between the windings.

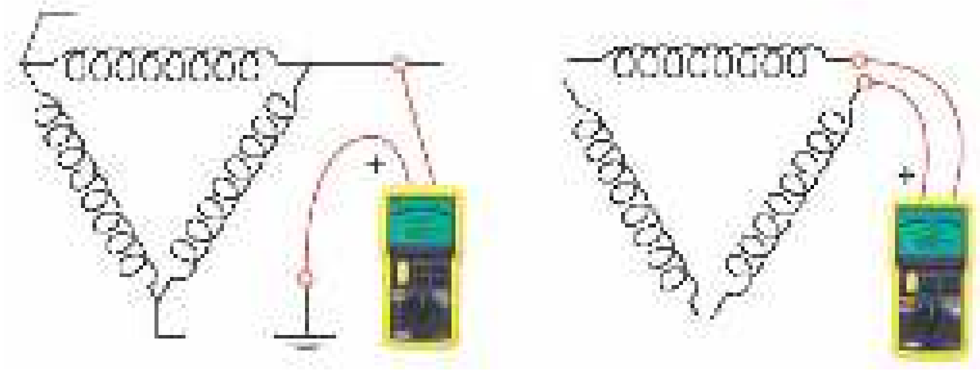


Figure 57: Insulation measurements on a rotating machine

We can also test the insulation of the motor connected to the installation, with respect to earth.

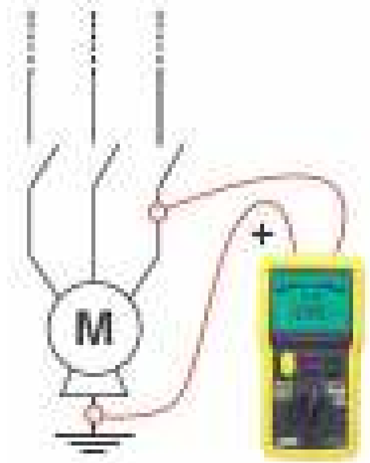


Figure 58: Phase/earth insulation measurement

The 500 V and 1000 V test voltages are, of course, the most commonly used during Low Voltage rotating machine tests (<1000 V).

On rotating machines operating above 1000 V (medium voltage), the insulation test voltages are normally 2500 V or 5000 VDC.

Figure 59: Insulation measurement on a motor

5.2.2.3. Insulation measurements on telephone cables

Insulation measurements are carried out on new cables at 250 V or 500 V, or on telephone lines in service at 50 V or 100 V to check whether the line is out of order.

The measurements can be taken between paired lines and the earthed screen, or between the metal screen and earth.

Figure 60: Insulation measurements on telephone cables

5.2.2.4. Measuring high insulations: advantage of a guard circuit

For high insulations (greater than 1 GΩ), the measurements can sometimes be disrupted by leakage currents which flow at the surface of the insulations, through surface dampness and dust.

The technician often only wishes to qualify the intrinsic quality of the insulations. For an exact measurement he must thus eliminate this surface leakage current which reduces the resistance displayed on the measuring instrument, to retain only the transversal current flowing in the insulation.

This operation is carried out simply by connecting the insulation tester's guard terminal to a point located between the " + " and " - " test points.

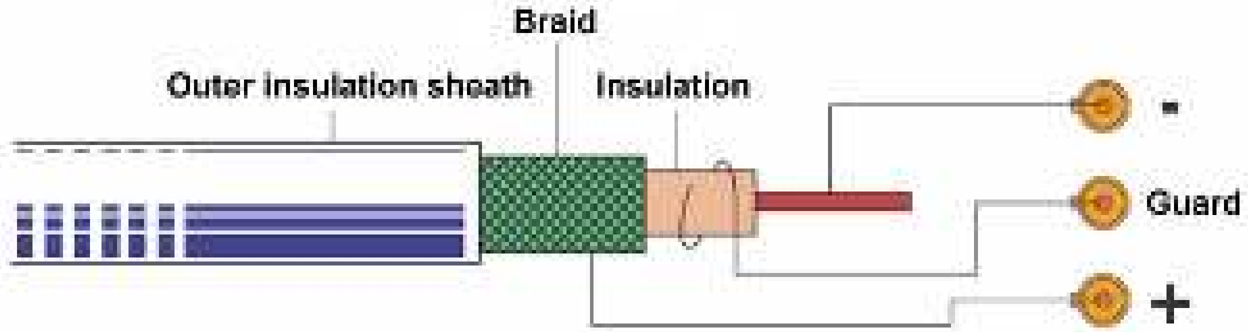


Figure 61: Measuring the guard circuit with high insulation measurements

This guard terminal shunts the measurement circuit, and thus reinjects the surface current at one of the test points without passing through the measurement circuit.

The guard will be connected to a surface likely to be the centre of flow of the surface currents, which are not characteristic of the insulations: insulating surface of a cable, of a transformer, etc. A good knowledge of the possible flow of the test current through the element tested is required to choose the best location for connecting the guard terminal.

5.2.3. Minimum insulating resistance values

The insulating resistance values are defined according to the nominal voltage of the circuit tested.

5.2.3.1. Electrical installations

The minimum values indicated in the following table correspond to those specified in the NF C 15-100 standard.

Nominal circuit voltage	Test voltage	Minimum insulating resistance*
Below 50V	250 VDC	0.25 MΩ
From 50 to 500V	500 VDC	0.5 MΩ
Above 500V	1000 VDC	1.0 MΩ

Table 14: Minimum LV insulating and test voltages

** Reminder: the insulating thresholds correspond to 1000 Ω per Volt of test voltage*

If the value measured with respect to earth is less than the required minimum resistance, we then disconnect the receivers from the installation and test the insulations of each conductor separately with respect to earth.

Pour specific applications, the thresholds can be different. Thus, for heating cables embedded in the walls of buildings, the minimum values according to NF C 15-100 are 250 kΩ for a nominal voltage of 230 V, and 400 kΩ for a nominal voltage of 400 V.

5.2.3.2. Electric equipment and motors

The number of standards covering electrical equipment is proportional to their diversity...

The test voltage of 500 VDC is the most commonly used and can be applied to tests for machines (EN 60204 standard), household electrical appliances (EN 60335), switchboards (EN 60439) and light fittings (EN 60598).

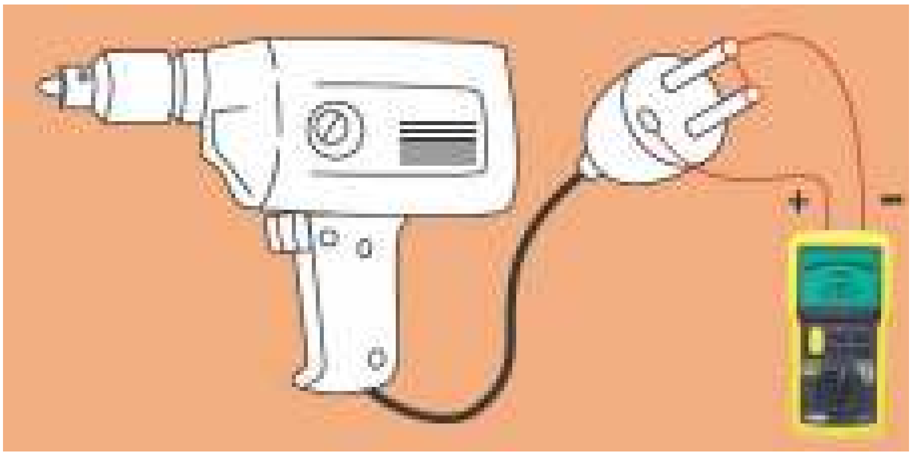


Figure 62: Insulation measurements on electrical equipment

The minimum thresholds can vary from one standard to another but, here too, 1000 Ω/V is often used as the reference value. Values below this must never be used.

5.2.3.3. Telephone installations

On new telephone lines, the insulation of non-filled cables, of length less than 2 km must be at least 1000 MΩ (and 2000 MΩ/km if the length exceeds 2 km). For filled cables, the values are respectively 750 MΩ and 1500 MΩ/km.

On lines in service, the tolerated insulation is less than that of new cables but it must never be less than half the values given for new cables.

5.2.4. Effect of climatic conditions

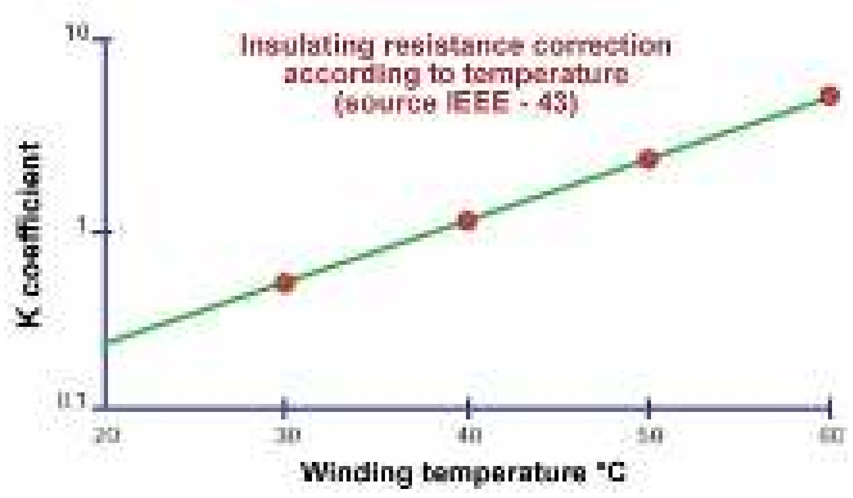
There are two environment parameters which considerably affect insulation:

5.2.4.1. Temperature

It varies the insulating resistance value according to an almost exponential law.

In the context of a maintenance programme for a company's motors, it is important to take regular measurements in similar temperature conditions .

Otherwise the results found must be corrected to make them correspond to a fixed reference temperature.



For example, the IEEE 43 standard for rotating machines states, as an approximation, that the insulation value must be halved for each 10°C temperature increase (and inversely). The curve (see figure) can also be used as a basis for the corrections.

Figure 63: Temperature correction

5.2.4.2. Humidity level

It affects the insulation according to the contamination level of the insulating surfaces. We must always ensure that the measurements are never taken if the temperature is less than the dew point.

Monitoring these two parameters (temperature and humidity) during insulation measurements will give reliable and comparable results, and thus good quality predictive maintenance, which guarantees a maximum operating lifetime for electrical equipment.

5.2.5. Interpreting insulation measurements

Interpretation is a fundamental aspect of all measurement. Individual insulation value measurements can produce random results if, for humidity conditions supposed to be fixed, the effect of temperature is not corrected.

The purpose of the two methods described below is to simplify the interpretation of the measurements and to detect and deterioration of an insulation by a series of observations over time.

5.2.5.1. Method based on the effect of test voltage application time (Polarisation index)

This method has the advantage that it is relatively little affected by temperature (thanks to its comparison principle) which makes it easily applicable without having to apply a correction to the results.

It is particularly well-adapted to the predictive maintenance of rotating machines and to the surveillance of the ageing of their insulation. Therefore, here is a reminder of the different currents flowing during an insulation resistance measurement (see graph).

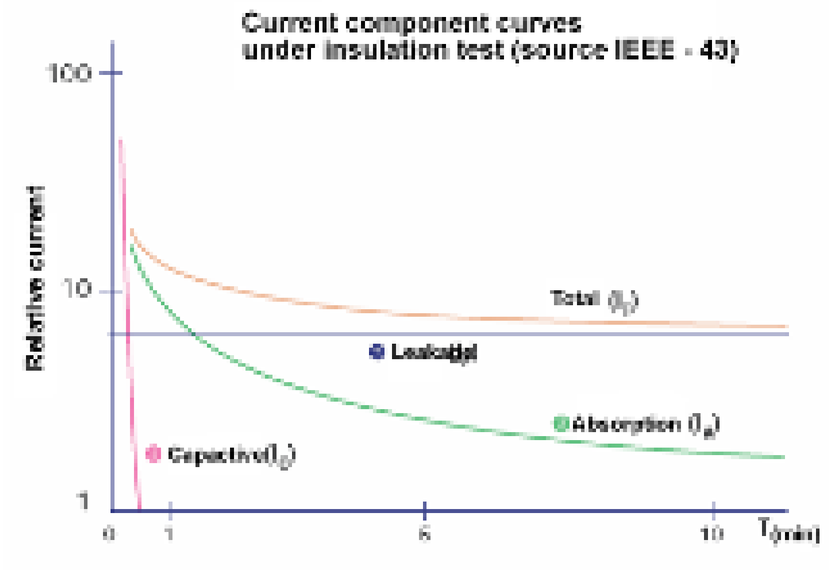


Figure 64: Curves of the current components during an insulation test

Capacitive curve (Ic): it corresponds to the load current of the capacitive component of the circuit tested. This transient current falls rapidly after a few seconds, or even a few tens of seconds, and becomes negligible with respect to the leakage current IF to be measured.

Absorption curve (I_A) : the dielectric's absorption current decreases much more slowly. In particular, it provides the energy necessary for the insulation material's molecules to become realigned according to the electric field applied.

Leakage curve (I_F**)**: this curve represents the leakage current characteristic of the insulating resistance.

Total curve (I_T**) =** (I_A) + (I_F) *(logarithmic scale, y-axis on the graph).*

There are two possible cases if the test voltage is applied for a long period.

a) The insulation is excellent (insulation material is in good condition, clean and dry).

In this case the leakage current is very low and the measurement is highly influenced by the capacitive load current and dielectric absorption current. The insulating resistance measurement will thus increase during the test voltage application time since these spurious currents are decreasing. The time necessary for the measurement of a good insulation to stabilise will depend on the type of insulation. With the old types of insulation, a stable value is generally reached in 10 or 15 minutes. With some recent types of insulation (e.g. epoxy-mica or polyester-mica), the measurement can stabilise after 2 to 3 minutes approx.

b) The insulation is bad (insulation material deteriorated, dirty or damp).

In this case, the leakage current is very high (and constant) and much greater than the capacitive load current and dielectric absorption current, and the insulating resistance measurement will rapidly reach a constant and stable level.

An examination of the curves for the insulation variation according to the test voltage application time (figure *"typical insulation resistance variations according to measurement time"*, the "absolute" insulation measurement can be completed by ratios reflecting the good or bad condition of the insulations.

For example, we calculate the ***quotient*** of the insulation resistance read after the test voltage has been applied for ***10 minutes***, over the value read after ***one minute*** of application.

We obtain a quotient called the ***"Polarisation Index (PI)".*** However, this index is not sufficient on its own. It only completes the absolute insulation values specified in the standards or defined by the rotating machine manufacturers.

PI = $R_{insulation}$ after 10 minutes / $R_{insulation\ after\ 1\ minute}$

- If PI < 1 the insulation is hazardous
- If PI < 2 the insulation is doubtful
- If PI < 4 the insulation is good
- If PI > 4 the insulation is excellent

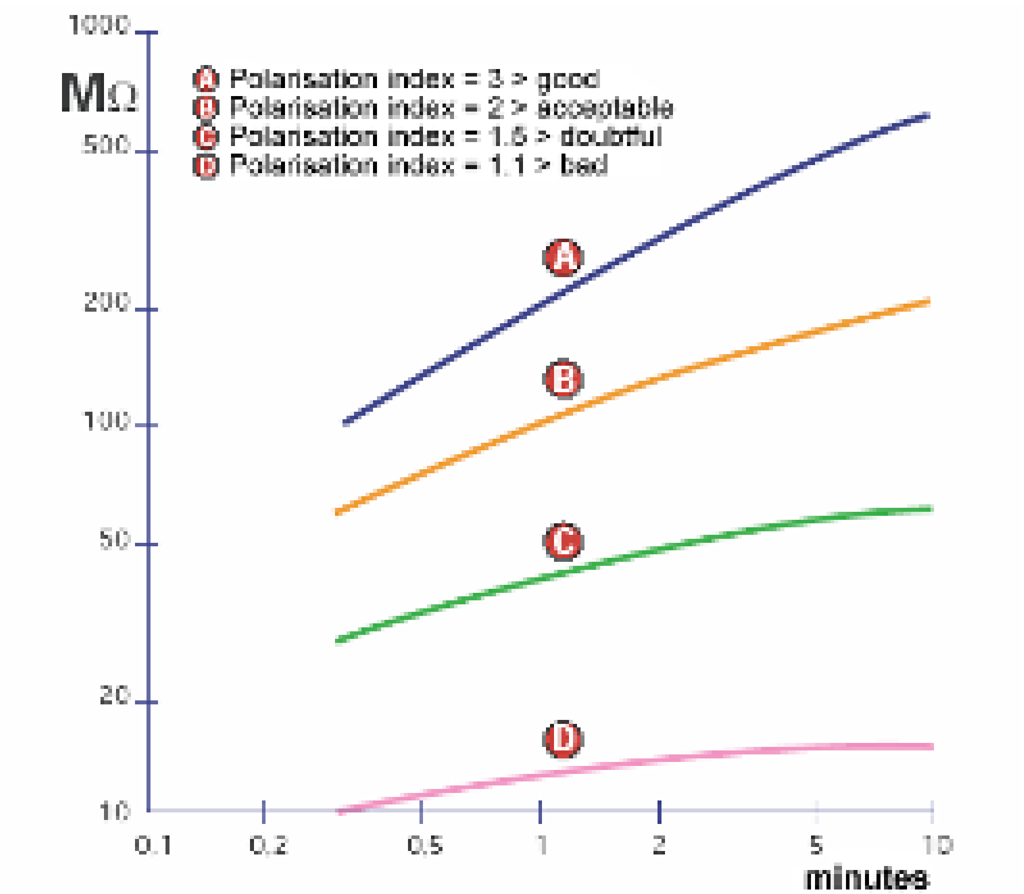


Figure 65: Typical insulation resistance variations according to measurement time

As described above, the most recent insulations have a dielectric absorption current which decreases more rapidly than with the older type of insulations. Therefore, the measurement sometimes stabilises after 2 to 3 minutes.

The ***"Dielectric Absorption Ratio (DAR)",*** which is the ***coefficient*** of the values after ***1 minute and 30 seconds***, can thus be sufficient to qualify the condition of some recent insulations as good.

DAR = $R_{\text{insulation after 1 minute}}$ / $R_{\text{insulation after 30 seconds}}$

- If DAR < 1.25 the insulation is insufficient
- If DAR < 1.6 the insulation is good
- If DAR > 1.6 the insulation is excellent

The change in the PI or DAR coefficients over time can thus greatly simplify the predictive maintenance of a company's machines, for example.

5.2.5.2. Method based on the effect of the test voltage variation (stepped measurement)

The presence of contaminants (dust, dirt, etc.) or dampness on the surface of the insulations is generally correctly indicated by the measurements based on the test voltage application time (DAR, PI, etc.). However, insulation ageing or certain types of mechanical damage can sometimes be missed by this type of test which is carried out at a low voltage with respect to the tested insulation's dielectric voltage.

However, a significant increase in the applied test voltage can break down these weak spots, which will result in a sharp reduction in the insulation value measured.

For this method to be effective we generally decide to apply a sufficient voltage step, with a ratio of 5 to 1, in one or several steps of equivalent durations (e.g. 1 minute), while remaining below the conventional dielectric test voltage (2 Un + 1000 V).

The results of this method are totally independent of the type of insulations and the temperature because they are not based on the intrinsic value of the insulations measured but on the effective reduction in the value read after an identical time, at two different test voltages. A reduction in the insulating resistance of 25% or more, between the first and second steps, indicates that the insulation is deteriorated.

5.2.6. Insulation values of the site equipment during commissioning

As per the precommissioning documents

Generator

The insulation test connections are identical for HV and LV.

A tester (megohmeter) with a 5000 V source must be used for the 5.5 / 6 kV windings and a 1000 V megohmeter for the 400/440 V inductance part; The preheating resistors and other accessories (at 220 V (in France)) must be tested at 500 V.

Minimum values for first test:
5.5 kV windings: 150 Megohms
400V windings: 100 Megohms
Field windings: 100 Megohms
Preheating resistors: 10 Megohms
Bearing insulation: 1 Megohm

When the minimum values are not reached, the measurement method using the polarising index must be used.

HV/LV transformer

The neutral earthing resistance must be disconnected (where applicable).

A 5000 V megohmeter must be used on the HV side (5.5 kV) and a 1000 V megohmeter must be used on the LV side (400 V).

Minimum values for first test:
HV windings: 150 Megohms
LV windings: 100 Megohms

HV cable

Dielectric strength test

As per the dielectric strength voltages defined above.
For example, for a 5.5 kV cable, an insulation tester (hi-pot) is connected and we slowly and progressively increase the voltage to 24/25 kV, the voltage is maintained for 15 minutes. The leakage current must not exceed 1 mA.

Insulation test to be carried out using a 5000 V megohmeter, the insulation must be at least equal to 150 Megohms

LV cable

A 1000 V megohmeter must be used for the 400 V cables and a 500 V megohmeter must be used for the 220 V cables.

Minimum values for first test:
400 V cables: 50 Megohms
220 V cables: 10 Megohms

HV motor

Each winding must be tested at 5000 V, between phases and between each phase and the equipment ground.
The accessories such as the preheating resistors must be tested at 500 V

Minimum values for first test:
Stator windings: 150 Megohms
Anticondensation resistors: 10 Megohms
Bearing insulation: 1 Megohm

LV AC or DC motor

Each winding must be tested at 1000 V, between phases and between each phase and the equipment ground.

The accessories such as the preheating resistors must be tested at 500 V

Minimum values for first test:
Stator windings, AC motor: 10 Megohms
Shunt windings, series windings, compound windings and armature for DC: 10 Megohms
Anticondensation resistors: 10 Megohms

6. LV NEUTRAL EARTHING ARRANGEMENTS

There are three types of earthing arrangements for LV networks *(in fact there are five with three variants of the TN configuration)* commonly called neutral arrangements:

- earthed neutral TT
- connection to neutral TN with 2 +1 variants:
  - TN-S separate neutral and PE
  - TN-C combined neutral and PE
  - TB C-S mixed distribution on the same network.
- isolated neutral or impedant neutral IT.

They differ by the fact that the voltage source neutral point is earthed or not and by the method of earthing the equipment grounds.

6.1. IEC 364 STANDARD CODING

- **1st letter: neutral point position**
  - T: directly earthed
  - I: isolated from earth or connected by an impedance
- **2nd letter: earthing method of the working electrical grounds**
  - T: directly earthed
  - N: connected to the neutral point of the source
- **3rd letter: respective situation of the neutral conductor and of the protective conductor**
  - combined neutral and PE
  - separate neutral and PE
  - Both together (3rd and 4th letter).

The rules for the protection of persons against direct contacts are independent of the earthing arrangements.

6.2. EARTHED NEUTRAL TT

- Neutral point of the transformer (or generator) directly connected to earth.
- Working equipment grounds connected to the installation's earth connection.
- Insulation fault current value limited by the earth connection resistances.

- Working equipment grounds earthed by PE conductor PE separate from the neutral conductor.

- Simplest solution to design and install.

- Mandatory trip on the first insulation fault, eliminated by a residual current device located at the head of the system (and/or on each outgoing line to improve selectivity, where necessary).

- No particular requirement with respect to the continuity of the neutral conductor.

- Can be extended without calculating the cable length.

- Does not require permanent monitoring during operation (only a periodic check on the residual current devices may sometimes be necessary).

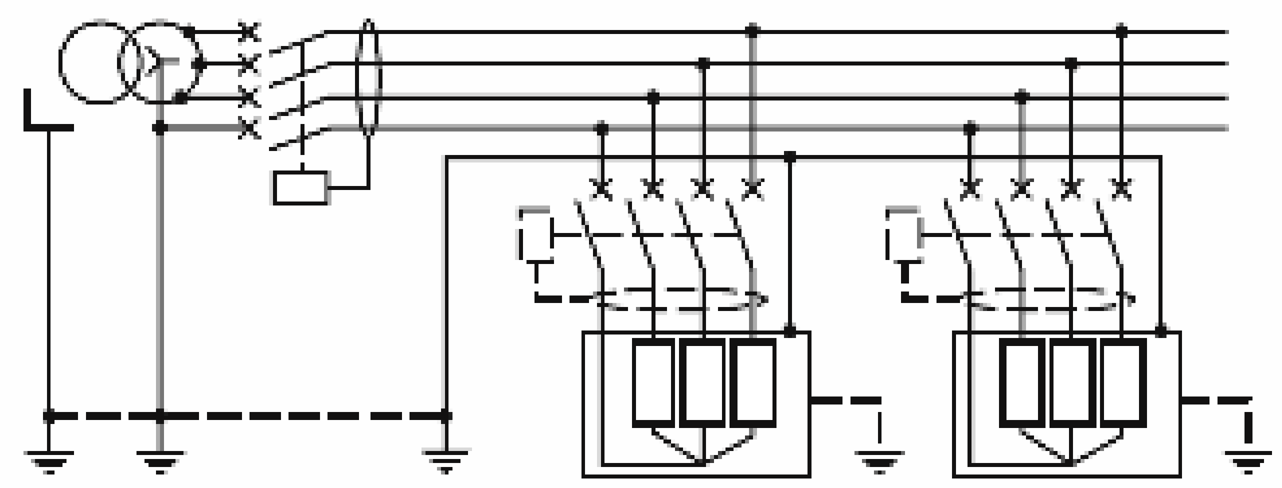


Figure 66: Earthed neutral arrangement TT

6.3. EARTHED NEUTRAL IT

- Neutral point of the transformer (or generator) isolated from earth or earthed via a high value impedance.

- The working equipment grounds are interconnected and connected to a same earth connection (if the earth connection of the station's equipment grounds is separate from the working equipment grounds or if there are several earth connections for the working equipment grounds, a residual current device must be installed at the head of the installation).

- The level of the first insulation fault current cannot create a hazardous situation.

- The current level of the double insulation fault is high.

- The working equipment grounds are earthed via the PE conductor which is separate from the neutral conductor.
- The first insulation fault is neither hazardous nor disruptive.
- There is no obligation to trip on the first fault, which provides a better service continuity.

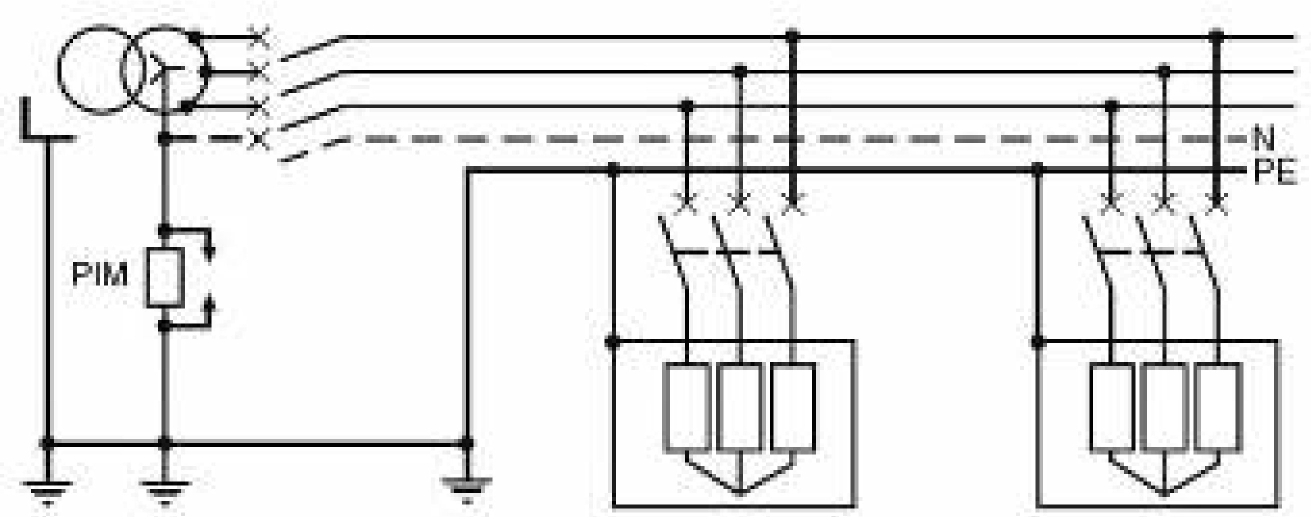


Figure 67: Earthed neutral arrangement IT

- There must be a mandatory indication of the first insulation fault, it must then be located by a Permanent Insulation Monitor (PIM) installed between neutral and earth.
- Mandatory trip on the second isolation fault by the overcurrent protection devices.
- The tests must be carried out to check that there is a trip on the second fault.
- Requires maintenance personnel available for locating and eliminating the first insulation fault.
- Solution providing the best service continuity during operation.
- Requires the installation of the receivers for a phase/equipment ground insulation voltage greater than composite voltage (first fault).
- The low insulation resistance receivers (induction furnaces) require the network to be divided.

6.4. CONNECTION TO NEUTRAL (TN)

6.4.1. TN-S arrangement (separate PE and N)

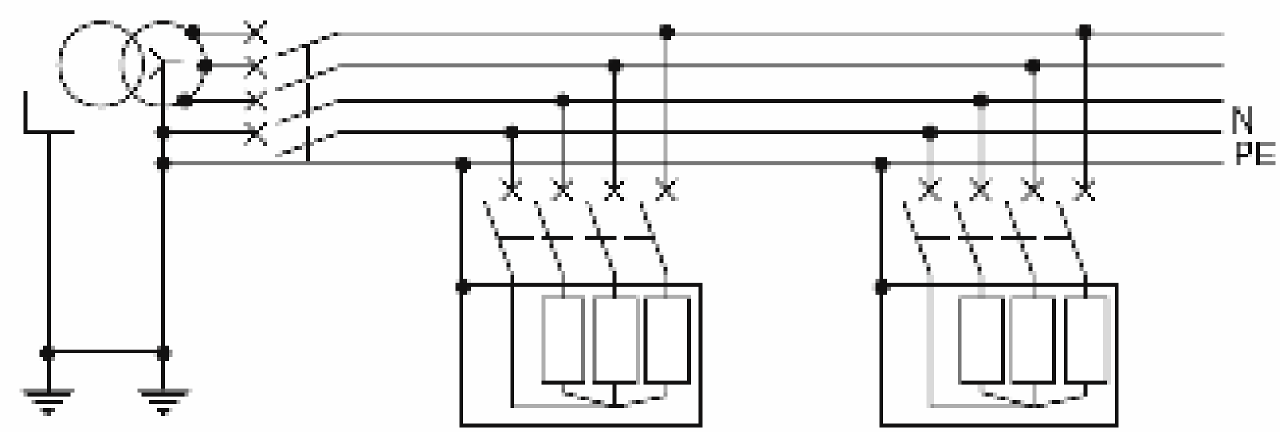


Figure 68: Earthed neutral arrangement TN-S

- Neutral point of the transformer and PE conductor directly earthed.
- Working equipment grounds connected to the PE conductor, itself earthed.
- High insulation fault currents (disturbances and increased fire risks).
- Separate neutral conductor and protective conductor.
- Mandatory trip on the first fault eliminated by the overvoltage protection devices.
- It is tricky to test whether the protections are operating correctly. The use of the RCDs eliminates this difficulty.
- The use of RCDs is always recommended to protect persons against indirect contacts, particularly at the terminal distribution end, where the loop impedance cannot be controlled.
- The trips must be tested:
  - during the design stage by calculation
  - mandatorily during commissioning
  - periodically (annually) by measurements.
- In the event of an extension or renovation, these trip tests must be repeated.

6.4.2. TN-C arrangement (PE and N combined to form PEN)

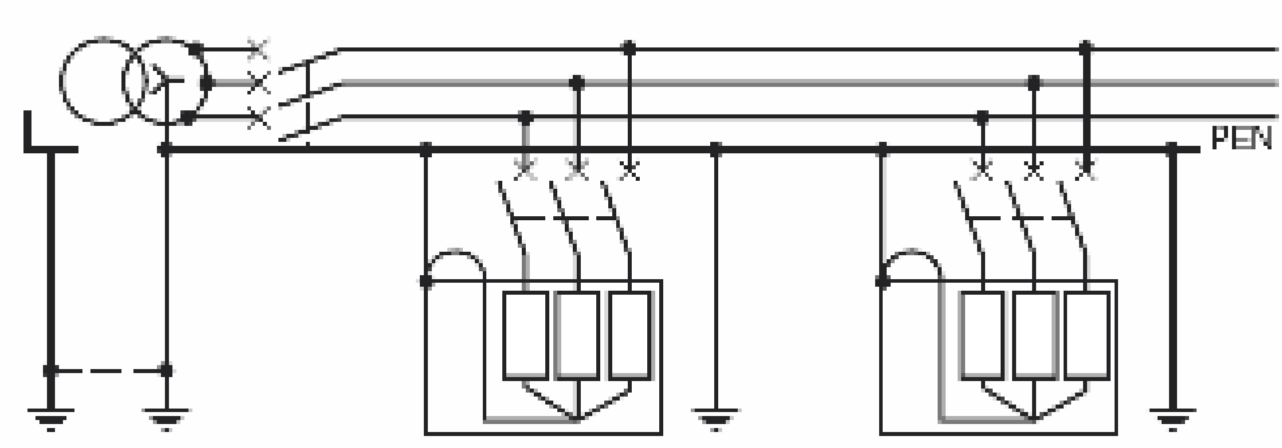


Figure 69: Earthed neutral arrangement TN-C

- Neutral point of the transformer and PEN conductor directly earthed.
- Working equipment grounds connected to the PEN, itself earthed.
- The insulation fault current values are high (disturbances and increased fire risks).
- Combined neutral conductor and protective conductor (PEN).
- The flow of the neutral currents through the conductive elements of the building and the equipment grounds is the source of fires and, for sensitive equipment (medical, computer systems, telecommunications), of disruptive voltage drops.
- Mandatory trip on the first insulation fault eliminated by the overvoltage protection devices.
- The trips must be checked:
  - during the design stage by calculation
  - mandatorily during commissioning
  - periodically (annually) by measurements.
- In the event of an extension or renovation, these trip tests must be repeated.
- The use of RCDs is always recommended to protect persons against indirect contacts, particularly at the terminal distribution end, where the loop impedance cannot be controlled (change to TN-S).
- It is tricky to test whether the protections are operating correctly (the use of the RCDs eliminates this difficulty but requires a TN-S arrangement).

6.4.3. Specific features of the TN arrangement (C, S and CS)

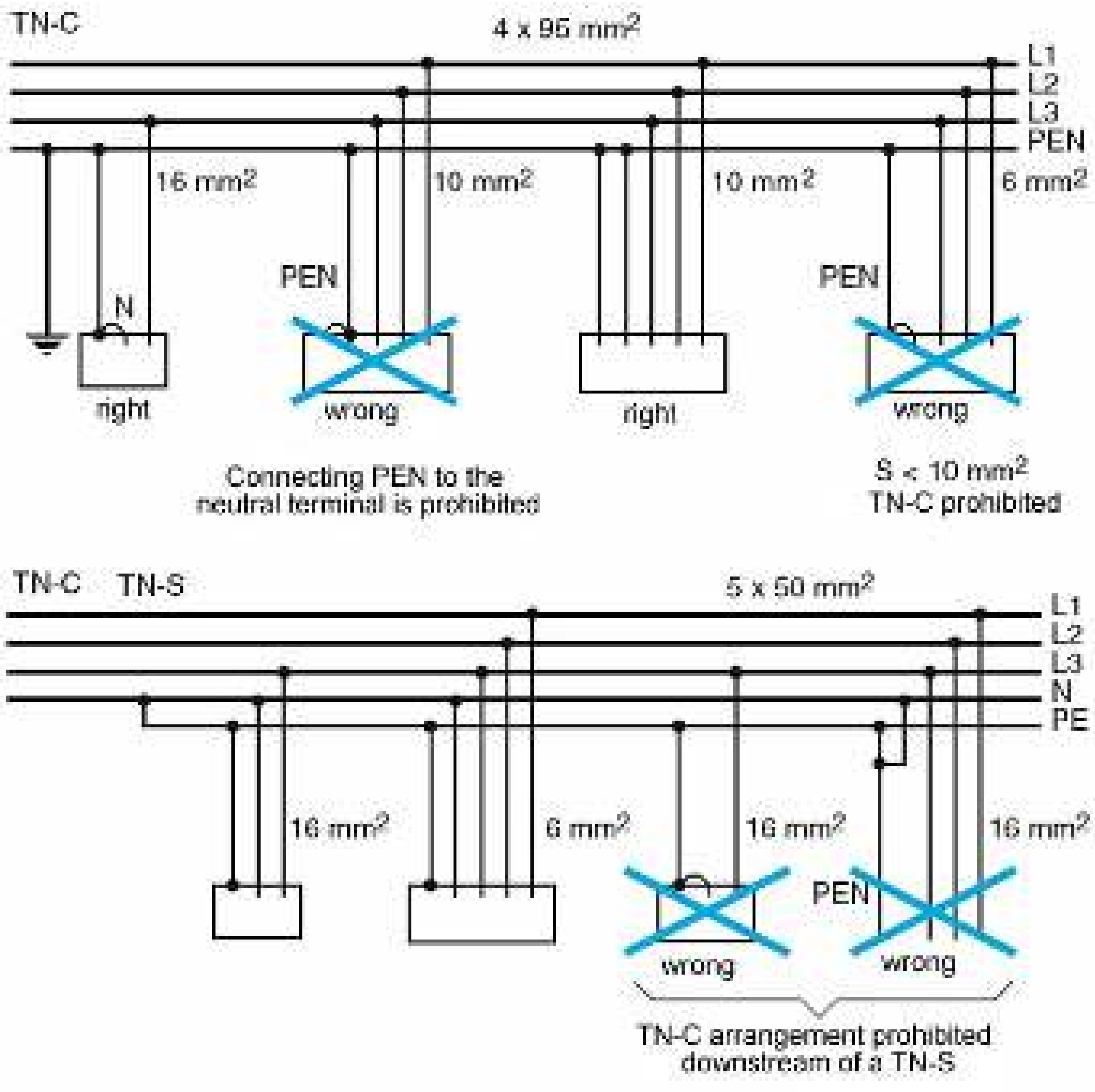


Figure 70: Specific features and constraints of the TN arrangement (C, S and CS)

- In a **TN-C** arrangement, the **combined PEN, Neutral and PE** conductor must **never be disconnected**.
- In a **TN-S** arrangement, as in the other arrangements, the **PE conductor must never be disconnected.**

- In a TN-C arrangement, the "protective conductor" function takes priority over the "neutral" function. In particular, a **PEN conductor must always be connected to the "earth" terminal** of a receiver and a bridge must be set up between this terminal and the neutral terminal.

- ***The TN-C and TN-S arrangements can be used in a same installation.***

- The **TN-C arrangement must be upstream of the TN-S arrangement**. The **TN-S arrangement is mandatory for cable cross-sections < 10 mm2 Cu or < 16 mm2 Al, or for flexible cables.**

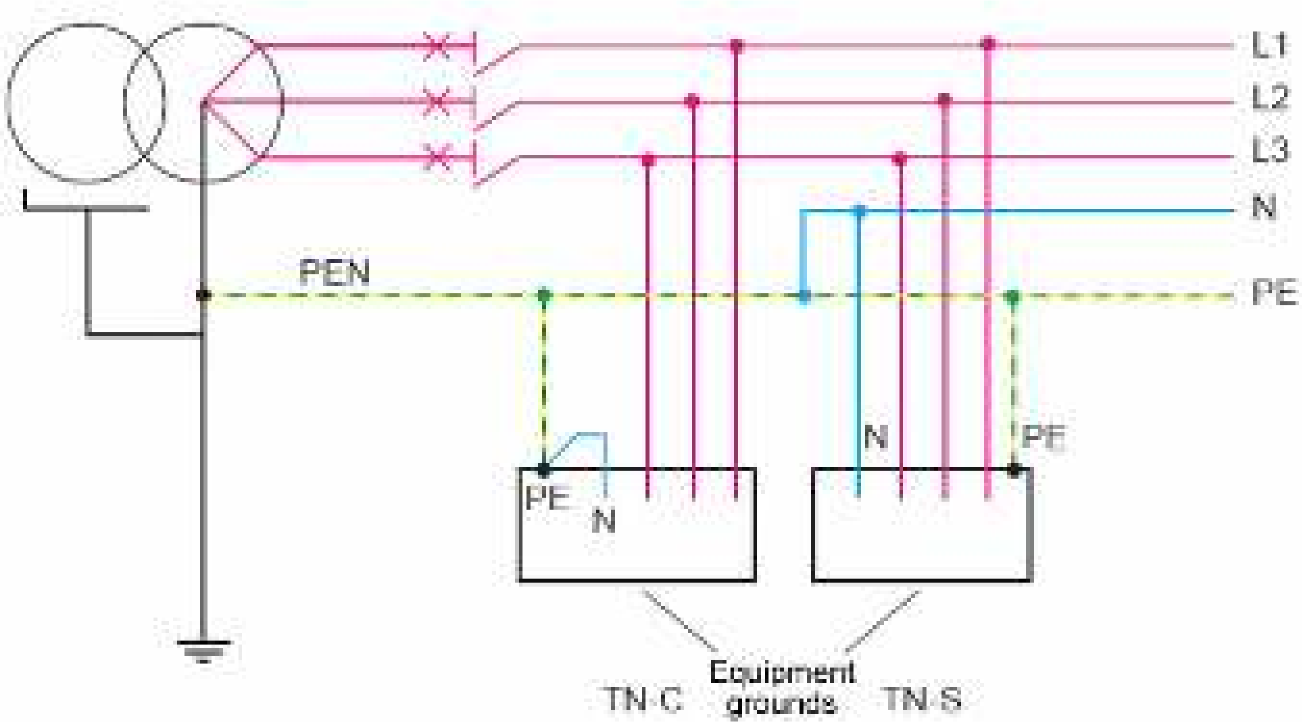


Figure 71: TN-C-S neutral arrangement

6.5. CHOICE OF AN EARTHING ARRANGEMENT

6.5.1. Selection criteria

For the protection of persons, the 3 earthing arrangements are equivalent if all the installation and operating rules are respected.

Given the characteristics specific to each arrangement, there can therefore be no question of making a choice based on a prioris.

This choice must result from discussions between the user and the network designer (project, installer, etc.) concerning:

1. the installation's characteristics,

2. the operating conditions and requirements.

It is illusory to wish to operate an isolated neutral system in a part of the installation which by nature has a low insulation level (a few thousand ohms): old installations, installations covering large areas, with exterior lines, etc.

Similarly, it would be contradictory in an industry where service continuity or productivity is imperative and the high fire risks of choosing an arrangement with connection to the neutral.

Note

When justified by the type of receivers used, it is often a good idea to have two different earthing arrangements in a same installation, the network must then be divided: each group of receivers must be supplied by an isolation transformer.

6.5.2. Method of choosing an earthing arrangement

1 Ensure that the installation is not in one of the cases where the earthing arrangement is imposed or recommended by the legislation (decrees, ministerial orders) (see table A below).

2 With the user (or his representative), work out the service continuity or productivity requirements according to the operation (maintenance service) (see table B).

3 With the user and with the design department, work out the synergies between the different earthing arrangements and the electromagnetic disturbances (see table C).

4 Check the compatibility between the chosen earthing arrangement and certain specific characteristics of the installation or of some receivers (see table D on the following pages, according to NF C15-100, section 707).

Table C summarises the specific cases of networks or receivers for which certain earthing arrangements are recommended or not.

6.5.3. Selection tables

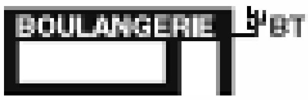
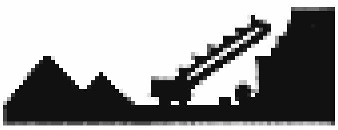
Frequent examples where the earthing arrangement is imposed (or strongly recommended) by official texts		
Building supplied by a public distribution network (domestic, small tertiary, small workshop)		**Earthed neutral (TT)** French interministerial Order of 13.2.70
Establishments receiving the public		**Isolated neutral (IT)** Safety regulation concerning the risks of panic and fire in premises receiving the public.
Safety circuits (lighting) subject to the worker protection decree		**Isolated neutral (IT)** French ministerial Order of 10 November 1976 relating to safety circuits and installations (published in the French Official Journal No. 102 NC of 1st December 1976).
Mines and quarries		**Isolated neutral (IT)** **Earthed neutral (TT)** French Decree No. 76-48 of 9.1.76 Circular of 9.1.76 and regulation concerning the protection of personnel in mines and quarries, appended to Decree 76-48.

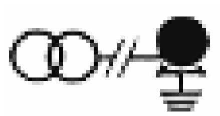
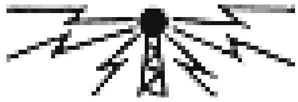
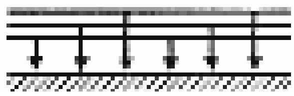
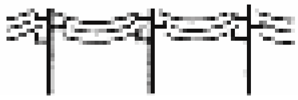
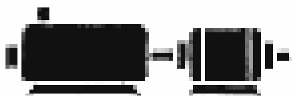
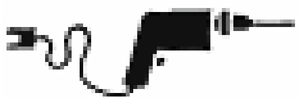
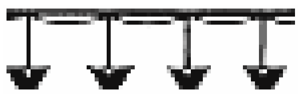
Table 15: Neutral arrangement selection – Table A

Maintenance performed by a qualified electrician	***Essential service continuity***	
	YES	***NO***
YES	**Isolated neutral *(IT)***	**Isolated neutral *(IT)*** ***Earthed neutral (TT)*** ***Connection to neutral (TN)***
	Combined with other measures, where they exist (normal -standby, protection selectivity, automatic location and search for the first fault, etc.), it is the safest means of avoiding operating power cuts. ***Examples:*** - industries where service continuity takes priority to protect property or products (steel industry, food industries, etc.), - operation with priority safety circuits: very high buildings, hospitals, establishments receiving the public.	Final choice after examination: - of the installation's characteristics (type of network, type of receivers, etc., table C), - of the level of complexity of implementing each type of arrangement, - of the cost of each arrangement (design, installation, testing, operation).
NO	***No earthing arrangement is satisfactory*** due to the incompatibility between these two criteria.	***Earthed neutral (TT)*** The simplest to implement, to monitor and to operate, particularly if modifications to the installation are envisaged during operation).

Table 16: Neutral arrangement selection – Table B

Type of supply	*Arrangement*	*Remarks*
LV distribution network	**TT**	Use of lightning conductor if overhead distribution
Installation uses LV from one of the establishment's HVA/LV substations	**TT**	Recommended for little monitored or changing installations
	TN	TNS recommended for highly monitored installations which change little
	IT	Recommended if there is a service continuity requirement but be careful of the operating voltage of certain HF filters
Circuit from an LV/LV transformer with separate windings	**IT**	Recommended by NF C 15-100 § 413.5
	TNS	Recommended by the computer specialists
	TT	Equivalent to TNS but low insulation fault current
Replacement sources	**IT**	Recommended for service continuity
	TNS	Possible, but care must be taken when adjusting the protections
	TT	Recommended

Table 17: Neutral arrangement selection – Table C

special cases of networks or receivers			recomm-ended	possible
Network type	Network covering a very large area with good earth connections for the working equipment grounds (10 Ω max.)			TT, TN, IT (1) (2) or mixed
	Network covering a very large area with poor earth connections for the working equipment grounds (> 30 Ω)		TT	TNS
	Network disrupted (stormy zone) (e.g. television or radio relay)		TN	TT
	Network with high leakage currents (> 500 mA)		TN (4)	IT (4) TT (3) (4)
	Network with exterior overhead lines		TT (6)	TN (5) (6)
	Standby generator set		IT	TT (7)
Receiver type	Receivers sensitive to high fault currents (motors, etc.)			TT (8)
	Receivers with low insulation (electric furnaces, welding sets, heating tools, emersion heaters, large kitchen equipment)		TN (9)	TT (9)
	Many phase neutral single-phase receivers (mobile, semi-fixed, portable)		TT (10) TNS	
	Receivers involving a risk (hoists, conveyors, etc.)		TN (11)	TT (11)

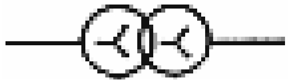
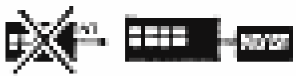
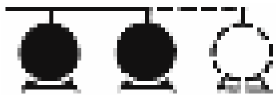
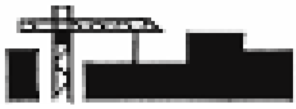
special cases of networks or receivers			recomm-ended	possible
	Numerous auxiliaries (machine tools)		TNS (12)	TNC IT (12b)
Miscellaneous	Supply via power transformer with star-star coupling		TT (13) (14)	TT without neutral
	Premises with fire risks		IT (15) TT (15)	TNS (15)
	Increase in the power of a subscriber supplied by EDF at low voltage, requiring a private transformer station		TT (16)	
	Establishment with frequent modifications		TT (17)	TNS (18)
	Installation where the continuity of the earth circuits is uncertain (worksites, old installations)		TT (19) (20)	TNS (19) (20)
	Electronic equipment: computers, programmable controllers		TN-S	TT (21)
	Command and control network for machines and effector sensors of programmable controllers		IT (22)	TN-S TT

Table 18: Neutral arrangement selection – Table D

Comments on table D – recommended / not recommended	
(1)	When it is not mandatory, the earthing arrangement is chosen according to the operating characteristics which are expected of it (service continuity essential for safety reasons or desired for productivity, etc.). Whatever the earthing arrangement, the probability of an insulation failure increases with the length of the network, it can be a good idea to divide the network, which simplifies fault-finding and in addition allows each application to have the arrangement recommended below.
(2) IT	The risks of the overvolts limiter arcing and transforming the isolated neutral into an earthed neutral. These risks mainly arise in very stormy regions or for installations supplied by overhead lines. If the IT arrangement is chosen to ensure service continuity, the designer must ensure that the conditions for the trip on the second fault are very precisely calculated.
(3) TT	Risks of spurious operation of the RCDs.
(4) TT	Whatever the earthing arrangement used, the ideal solution is to isolate the disruptive part if it can be easily located.
(5) TN	Risks of phase/earth fault rendering the equipotentiality random and risks breaking down the PEN.
(6) TT	Insulation uncertain due to the conductive humidity and dust.
(7) TN	TN is not recommended due to the risks of damaging the alternator in the event of an internal fault. Also, when the generator sets supply safety installations, they must not trip on the first fault.
(8) TN	The phase-equipment ground fault current can reach several In which risks damaging the windings of the motors and of ageing them or destroying the magnetic circuits.

Comments on table D – recommended / not recommended	
(9)	To reconcile service continuity and safety it is necessary and recommended – whatever the arrangement used – that these receivers be separated from the rest of the installation (separation transformers with local connection to neutral).
(10)	If the quality of the receivers is ignored when designing the installation, the insulation risks being rapidly reduced. The TT protection with residual current devices is the best prevention.
(11)	The mobility of these receivers generates frequent faults (sliding equipment ground contact) which must be overcome. Whatever the arrangement used, it is recommended, that the circuits be supplied by transformers with local connection to neutral.
(12)	Requires the use of transformers with local connection to neutral to prevent the risks of spurious operation or spurious shutdown on the first fault (TT) or double fault (IT).
(12b)	With double interruption of the control circuit.
(13) IT with neutral	Phase/neutral current limiting too high due to the high value of the homopolar impedance: at least 4 to 5 times the direct impedance. This arrangement must be replaced by a star-delta arrangement.
(14)	TN-C is prohibited since the high fault currents render the connection to neutral hazardous.
(15)	Whatever the earthing arrangement used, a residual current device with sensitivity I Δn i 300 mA must be used.
(16)	A low voltage installation must use a TT arrangement. Keeping this neutral arrangement is equivalent to carrying out the minimum of modifications on the existing distribution (no cable to be drawn, no protection to be changed).
(17) TT	Possible without highly competent maintenance personnel.

Comments on table D – recommended / not recommended	
(18) TNS	With recommended average residual current sensitivity.
(19)	Such installations require great conscientiousness in maintaining safety. The absence of preventive measures in the connection to neutral requires highly competent personnel to guarantee that this safety is maintained over time.
(20)	The risk of broken conductors (supply, protection) renders the equipotentiality of the equipment grounds random. NF C 15-100 imposes TT or TN-S with 30 mA RCDs. The IT arrangement can be used in very specific cases.
(21)	With lightning conductor according to the site exposure level.
(22)	This solution prevents the appearance of spurious orders during spurious earth leaks.

Table 19: Neutral arrangement selection – Table D b - comments

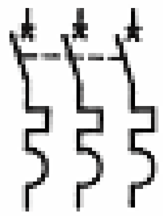
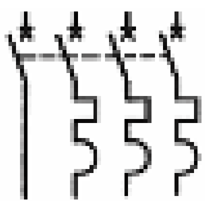
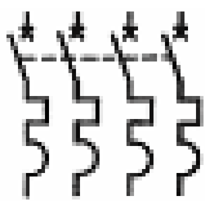
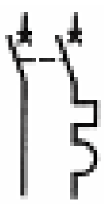
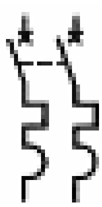
7. NEUTRAL SYSTEM PROTECTION FUNCTIONS

7.1. PROTECTION AND CROSS-SECTION OF THE NEUTRAL ACCORDING TO THE NEUTRAL SYSTEM USED

I.e. according to whether the neutral is distributed or not.

- The number of circuit breaker (or fused switch) poles to be equipped with protections
- The cross-section of the Neutral conductor according to the cross-section of the phase conductor(s). This cross-section is either equal to that of the phase conductors Sn = Sph (small cross-sections) or less than Sn < Sph (generally 0.5 Sph for large cross-sections). *It must not be confused with the cross-section of the earth conductor (PE), see paragraph 3.3.4*

The number of poles indicated in the table varies for circuit breakers performing protection, control and disconnection functions at the same time.

Distribution type	Arrangement possibilities Neutral protected or not but always disconnected – *PE independent and never disconnected*	Authorised arrangement if Sn = Sph	Authorised arrangement if Sn < Sph
TT or TN-S arrangement			
3-phase Neutral not distributed			
3-phase + N Distributed neutral	A  B 	Arrangement A and B	Arrangement B with conditions 1, 2 and 3 Arrangement A if conditions 1, 2, 3 and 5
Phase + N	A  B 	Arrangement A and B	

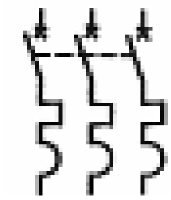
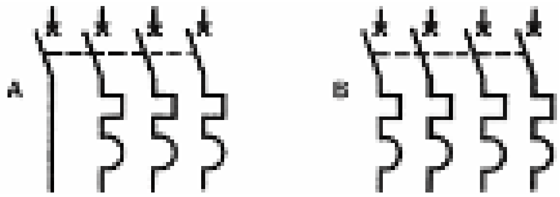
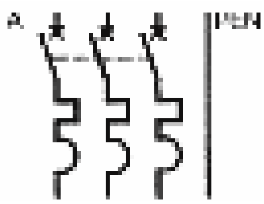
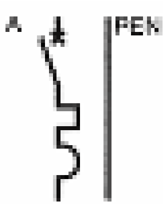
IT arrangement			
3-phase Neutral not distributed			
3-phase + N Neutral distributed		Arrangement B or arrangement A if condition 4	Arrangement B with conditions 1, 2 and 3 Arrangement A if conditions 1, 2, 3 and 4
Phase + N		Arrangement B or diagram A if condition 4	
TN-C arrangement ***Since the neutral is also the PE it is never disconnected***			
3-phase + PEN		S_{PEN}= Sph: configuration A S_{PEN} < Sph: configuration A if conditions 1, 2, 3 and 5	
Phase + PEN		S_{PEN}= Sph: configuration A	

Table 20: Protections and number of poles according to the neutral system

Explanation of the "conditions"

Condition 1

The cross-section of the conductors is > 16 mm2 Cu or > 25 mm2 Alu.

Condition 2

The absorbed power between phase an neutral is < 10 % of the total power carried by the cable.

Condition 3

The maximum current liable to flow through the neutral is less than the admissible current Iz in this conductor.

Condition 4

The circuit considered is part of an assembly of terminal circuits:

- protected by devices whose settings (or ratings) do not differ by more than twice the value
- the assembly is protected upstream by a residual current device with maximum sensitivity equal to 15 % of the lowest admissible current of the different circuits.

Condition 5

The neutral conductor is protected against short circuits by the measures taken for the phases.

7.2. TT EARTHING ARRANGEMENT

7.2.1. Standards

The NF C 15-100 standard defines the maximum disconnection time of the device protecting persons against indirect contacts in normal conditions (U_L = 50 V).

U_L is the highest contact voltage which can be maintained indefinitely without danger for persons.

A reminder of these times is given in Chapter 1 paragraph 2.4.2

In a network with a TT arrangement, the persons are protected against indirect contacts by residual current devices (RCD).

The sensitivity threshold $I_{\Delta n}$ of this device must be such that $I_{\Delta n} < U_L/R_u$ (R_u: resistance of the earth connections of the equipment grounds used).

The choice of the differential sensitivity depends on the resistance of the earth connection given in the following table.

$I_{\Delta n}$	***maximum resistance of the earth connection Ru*** (U_L = 50 V)
3 A	16 Ω
1 A	50 Ω
500 mA	100 Ω
300 mA	166 Ω
30 mA	1660 Ω

Table 21: Maximum resistance of the earth connections according to the RCD protection

When all the working equipment grounds are interconnected and connected to a single earth connection Ru, the mandatory minimum is to place an RCD at the head of the installation.

An RCD must be installed at the head of the circuits whose equipment ground or group of equipment grounds is connected to a separate earth connection.

A high sensitivity RCD (≤ 30 mA) must be installed on the outgoing lines supplying power socket circuits with assigned current ≤ 32 A, outgoing lines supplying shower rooms, pools, worksites, etc.

If several RCDs are installed, the power availability can be improved either by a vertical selectivity or a horizontal selectivity.

7.2.2. Vertical selectivity

The differential fault current is not limited (as it is for a short-circuit current) by the system impedance but by the resistance of the return circuit (earth connections of the source receivers) or, in the case where all the equipment grounds are interconnected by a main equipotential connection, by the fault loop impedance.

Therefore, the more straightforward the fault, the higher the differential current.

For a selectivity between A and B (non-trip of A for a fault downstream of B), the selectivity must be current and time-based:

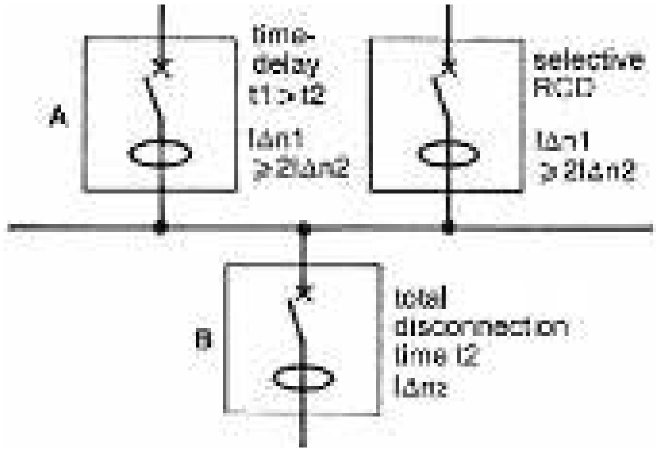


Figure 72: Vertical selectivity of RCDs

- with respect to the current, the sensitivity of the upstream device must be at least twice that of the downstream device since $I_{\Delta n}/2 \leq I_{fault} \leq I_{\Delta n}$
- with respect to time, the time-delay t1, on the operation of the upstream device must be greater than the total disconnection time t2 of the downstream device.

When a separate relay is used in conjunction with a disconnection device, the time t2 not only includes the RC relay's response time, but also the disconnection time of the associated device (generally less than 50 ms).

7.2.3. Horizontal selectivity

It is covered by the NF C 15-100 standard § 536-3-2 and eliminates the requirement for a residual current circuit breaker (RCCB) at the head of the installation when there are various circuit breakers in the same switchboard.

If there is a fault, only the faulty outgoing line is switched off, since the other RCDs do not see the fault current.

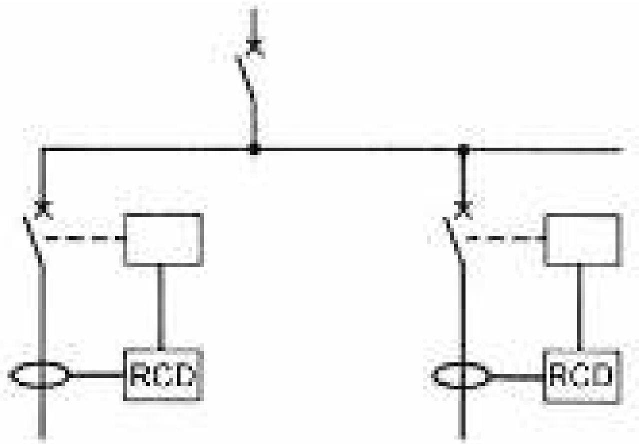


Figure 73: Horizontal selectivity of RCDs

- this configuration is only admissible if the appropriate means are put in place to protect against equipment grounding faults in the part of the installation between the main circuit breakers and the residual current devices.
- these appropriate means can result in the use of class II equipment, or the application of the protection measure "by additional insulation" against indirect contacts.

7.2.4. Typical mandatory minimum configuration for a TT arrangement

7.2.4.1. Trip on single fault

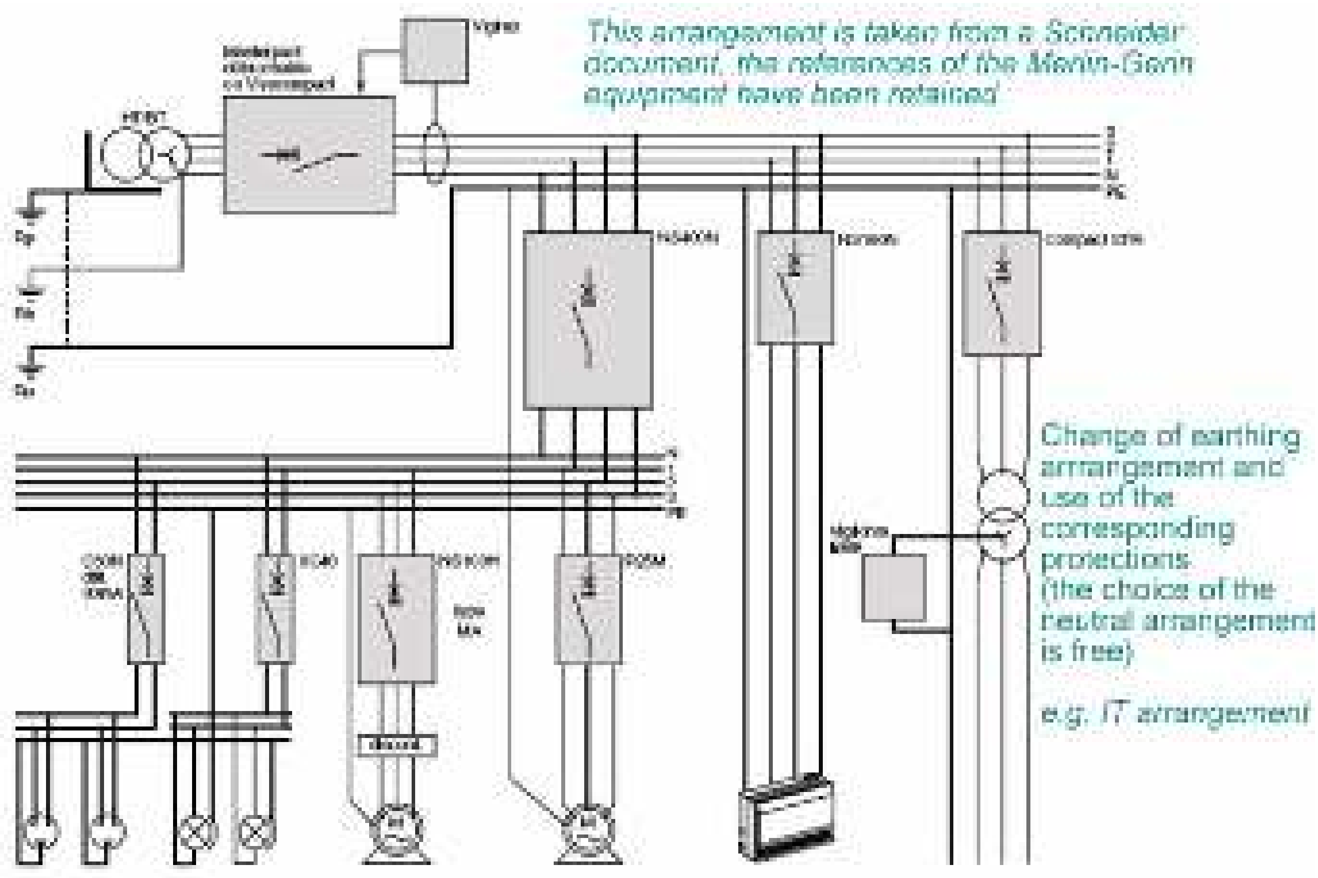


Figure 74: Typical minimum configuration for a TT arrangement

7.2.4.2. Required special measures (for some installation conditions)

a) high-sensitivity residual current device ≤ 30 mA mandatory for:

- the power socket circuits with assigned current ≤32 A (NF C 15100 chap. 53 § 532.26),
- the circuits supplying the shower rooms and pools,
- the supply of certain installations such as worksites, etc. where there is a risk of the PE being cut.

b) premises where there is a fire risk

An RCD relay (separate torus), or circuit breaker with RCD unit or a modular circuit breaker with RCD unit (threshold set to 300 mA), prevents a fault current greater than 300 mA from being maintained.

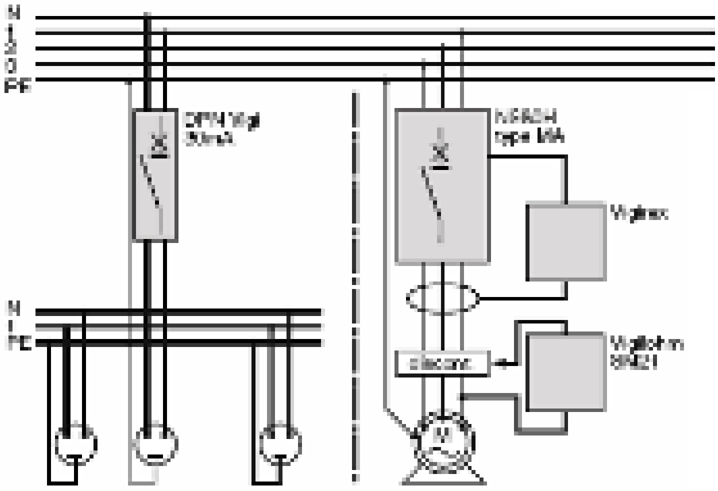
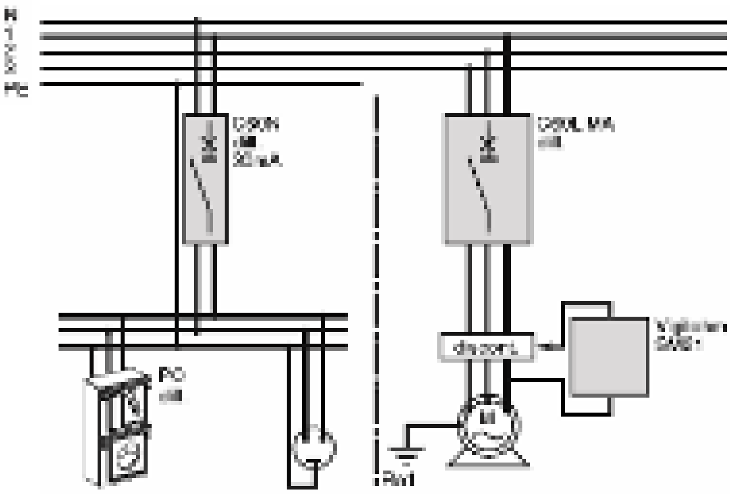


Figure 75: Special measures for RCDs for a TT arrangement

c) case where a high sensitivity device is required

Residual current device with threshold 10 mA.



d) non-interconnected distant equipment ground

The fault voltage risks being hazardous. An RCD relay (separate torus), or circuit breaker with RCD unit or a modular circuit breaker with RCD unit, threshold $\leq U_L/R_{A1}$, prevents this voltage from being maintained beyond the time imposed by the safety curve.

7.3. TN AND IT EARTHING ARRANGEMENTS

7.3.1. Protection of persons against indirect contacts

The higher the contact voltage Uc (potential difference between 2 simultaneously accessible equipment grounds or between the equipment ground and earth) the shorter must be the time taken to eliminate a fault between phase and equipment ground.

In a TN earthing arrangement or an IT impedant neutral arrangement (double fault), the protection of persons against indirect contacts is by overcurrent protection devices.

When the protection is provided by a circuit breaker, this circuit breaker must intervene:

- on the first fault, with the TN earthing arrangement
- when there are two simultaneous faults, with the IT earthing arrangement.

With circuit breakers we must ensure that Im < Id (Im: magnetic trip setting current or short time-delay, Id: phase-equipment ground fault current).

Id decreases when the length l of the cables installed downstream of the circuit breaker increases. Condition Im < Id is thus represented by l < l max.

In this case, the safety condition t = f (Uc) is met whatever the limit voltage U_L = 50 since a circuit breaker's disconnection time, which is around 10 to 20 ms, will always be sufficiently short.

Respecting the condition l < l max does not exclude calculating the voltage drop ΔU % between the origin of the installation and the operating point, and verifying: ΔU % < 5 to 8 % depending on the case.

When condition l < l max is no longer met, we can:

- **choose a type B curve circuit breaker (modular) or a type G curve circuit breaker (compact adjustable)**

  A low magnetic circuit breaker will protect persons for longer cable lengths (in the same installation conditions).

- **increase the cable cross-section**

  The length l max of cable providing the protection of persons increases with the cross-section of this cable (if the cross-section increases, the impedance decreases and Id increases to Im < Id).

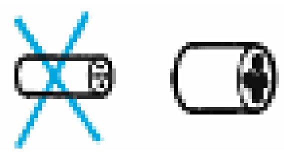


Figure 76: Increasing the cable cross-section

If the cable length is high or if the installation of a B-type or G-type curve circuit breaker is insufficient (current peak receivers (*)), increase the cross-section of the protective conductor, if it is less than that of the phases, or increase the cross-section of all conductors in all cases. This solution is the most costly and sometimes impossible to implement.

***(*)** If there are current peak receivers the cross-section of the conductor must be increased. When a motor starts it can create a voltage drop of 15 to 30 %; in this case there is a risk that the motor will not start.*

- **use a residual current device**

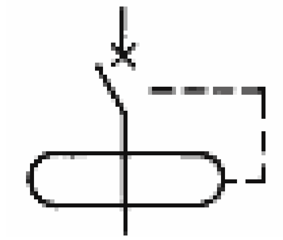


Figure 77: Using a residual current device

In all cases where the previous methods do not guarantee the protection of persons, the only solution is to use a residual current device (RCD).

Residual current protection is the only way to detect and disconnect the fault current, which has a high value in this case: a low sensitivity device (1 or 3 A) is sufficient.

This solution eliminates the need for tests. It is more especially recommended:

- for terminal circuits which are always likely to be modified on operational installations
- for terminal circuits supplying power sockets to which flexible cables, very often of unknown length and cross-section, are connected.

- **install an additional equipotential bond** between the various metal elements which are simultaneously accessible.

This reduces the contact voltage Uc and renders the contact non-hazardous (mandatory check by measurements). But it is a solution which is often difficult to implement (existing installations) and costly.

In an IT arrangement, the first fault current causes an inoffensive contact voltage.
However, the NF C 15-100 standard § 413.1.5.4 specifies that the appearance of this first fault must be indicated and eliminated.

7.3.2. Trip condition test

7.3.2.1. Precondition

The protective conductor must be in the immediate proximity of the circuit's active conductors (if this is not the case, the check can only be carried out by measurements taken once the installation is terminated).

Guide UTE C 15-105 gives a simplified calculation method, the hypotheses and results of which are given below.

Symbol meanings

L max maximum length in metres
V simple voltage = 237 V for 237/410 V network
U composite voltage in volts (400 V for 237/410 V network)
Sph cross-section of the phases in mm2
S1 Sph if the considered circuit has no neutral (IT)
S1 neutral S if the circuit has the neutral (IT)
S_{PE} cross-section of the protective conductor in mm²
ρ resistivity at normal operating temperature = 22.5 10–3Ω x mm2/m for copper
m Sph (or S1) / S_{PE}
I magn circuit breaker magnetic trip operating current (A)

7.3.2.2. Circuit distant from the source (secondary outgoing lines and terminals)

TN earthing arrangement

It consists of applying Ohm's law to the only outgoing line concerned by the fault, by making the following hypotheses:

- the voltage between the faulty phase and the PE (or PEN) at the origin of the circuit is taken to be equal to 80 % of the nominal simple voltage
- we ignore the reactances of the conductors due to their resistance (1).

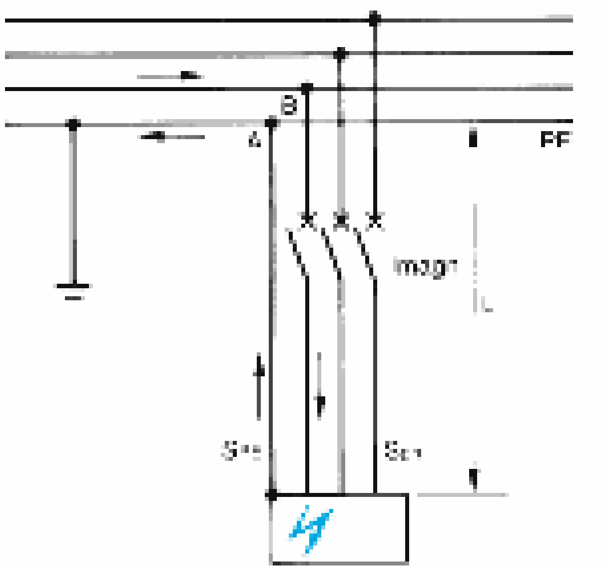


Figure 78: Trip conditions in TN arrangement

The calculation checks that the circuit length is less than the value given by the following relationship:

$$L\,max = \frac{0.8.x.V.x.Sph}{\rho(1+m).I.magn}$$

IT impedant neutral arrangement

The principle is the same as in the TN arrangement, we make the hypothesis that the sum of the voltages between the protective conductor and the origin of each faulty circuit is equal to 80 % of the normal voltage. Since, in practice, it is impossible to perform the check for each double fault configuration the calculations are performed by supposing that the voltage is identically distributed between each of the two faulty circuits (unfavourable hypothesis).

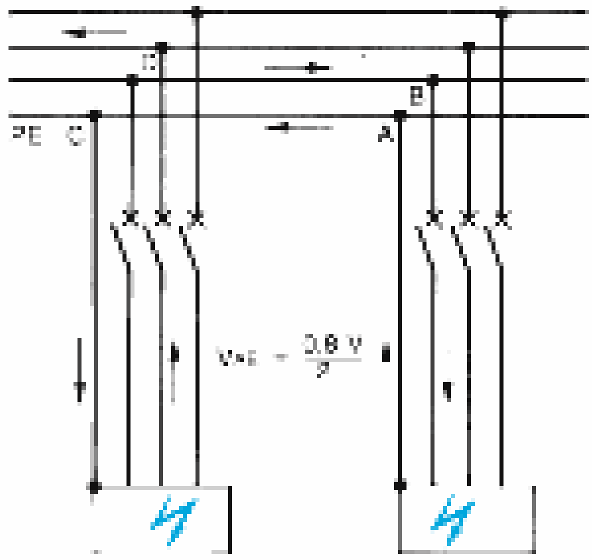


Figure 79: Trip conditions in IT arrangement

By ignoring, as in the TN arrangement, the reactances of the conductors due to their resistances(1), the calculation checks that the length of each circuit is less than the maximum value given by the following relationships:

- the neutral conductor is not distributed

$$L\,max = \frac{0.8.x.U.x.Sph}{2\rho(1+m).I.magn}$$

- if the neutral conductor is distributed (2)

$$L\,max = \frac{0.8.x.V.x.S1}{2\rho(1+m).I.magn}$$

(1) This approximation is considered to be admissible for cross-sections up to 120 mm². Beyond this value, the resistance is increased as follows (C 15-100 § 532-321):
S = 150 mm² R + 15 %, S = 185 mm² R + 20 %, S = 240 mm² R + 25 %, S = 300 mm² R + 30 %, etc. (Values not considered by the standard).

(2) The C 15-100 standard recommends that the neutral should not be distributed in a IT arrangement. One of the reasons for this advice is that the maximum lengths are relatively low.

7.3.2.3. Circuit close to the source

In this case the simplified calculation method described above gives very restrictive results which are very far from reality (in particular, the contact voltage values obtained practically prohibit all possibility of having a time-based selectivity). More precise calculations must then be carried out using the symmetrical component method and by considering, in particular, the internal impedances of the transformers.

These calculations show:

- that the contact voltage is relatively low in the case of a fault close to the source
- that it is thus possible have selectivity (the head circuit breakers can easily be given a time-delay of up to 300 or 500 ms and more)
- that the maximum cable lengths are long and very rarely reached at this stage in the distribution.

Example

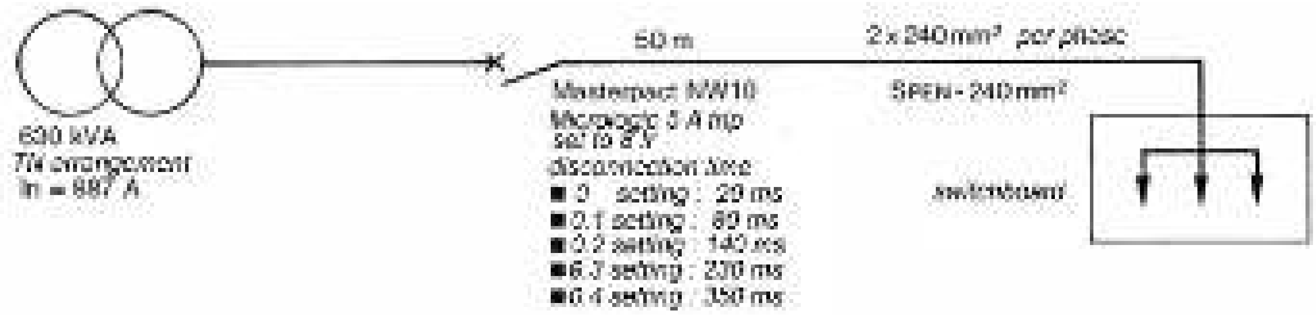


Figure 80: Trip conditions for a circuit close to the source

Results

- Fault current: approximately 11.6 kA. The 8000 A setting of the magnetic circuit breaker is therefore suitable.
- Contact voltage: approximately 75 V.

The max. disconnection time authorised by the safety curve is 600 ms, which allows all the Masterpact selectivity settings to be used without any problem (main circuit breaker).

7.3.3. Typical mandatory minimum configuration for a TN arrangement

7.3.3.1. Trip on first fault

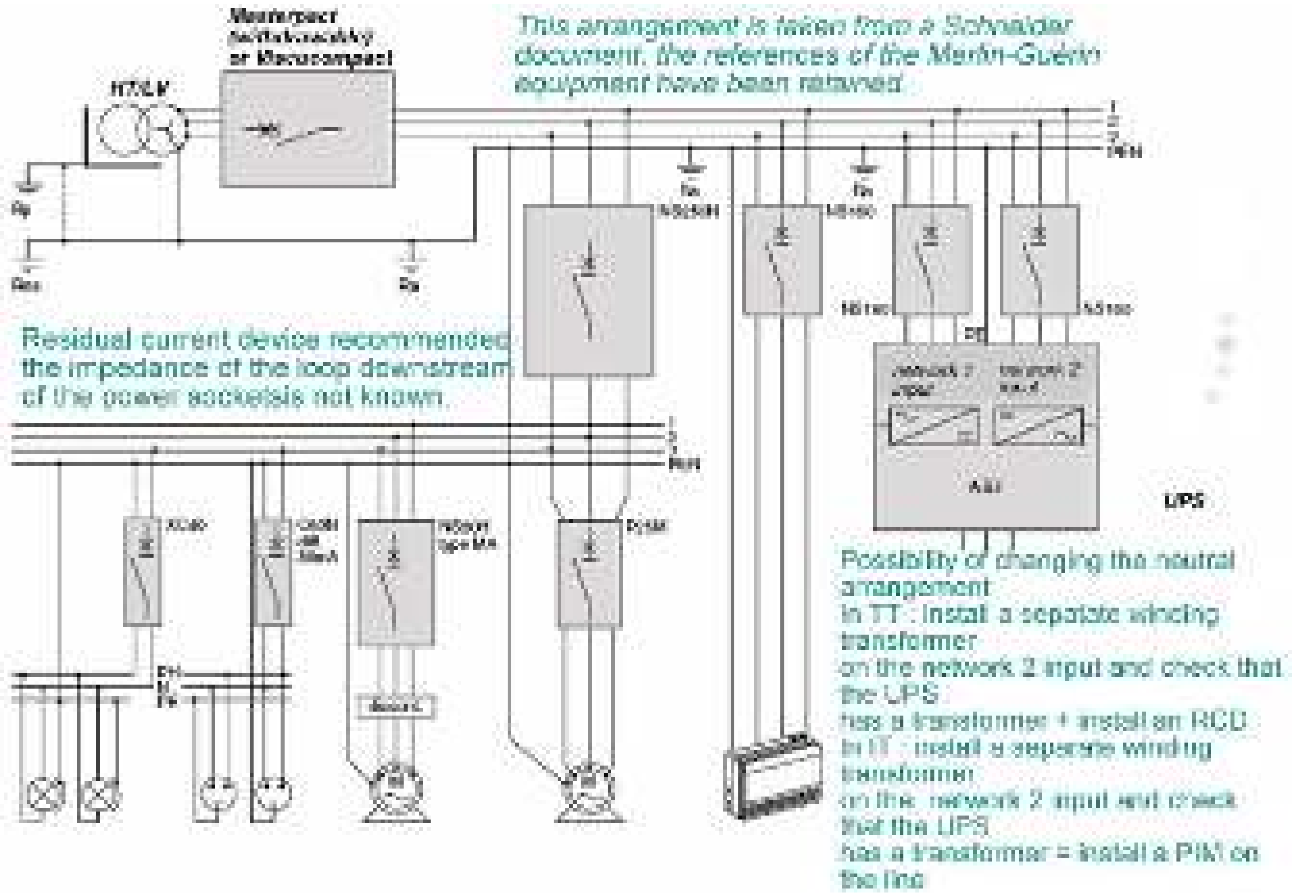


Figure 81: Typical mandatory minimum configuration for a TN arrangement

7.3.3.2. Required special measures for a TN arrangement

a) high-sensitivity residual current device ≤ 30 mA mandatory for:

- power socket circuits with assigned current i ≤ 32 A (NF C 15-100 chap. 53 § 532.26)
- the circuits supplying the shower rooms and pools,
- the supply of certain installations such as worksites, etc. where there is a risk of the PE being cut.

b) premises where there is a fire risk

An RCD relay (separate torus), or circuit breaker with RCD unit or a modular circuit breaker with RCD unit (threshold set to 300 mA), prevents a fault current greater than 300 mA from being maintained.

c) very long cable length

In this case, the fault current is limited.
Depending on the case, a Compact G-type or modular B-type curve circuit breaker; or a circuit breaker with residual current unit or separate-torus relay, threshold $I_{\Delta n}$ < I fault, performs the trip.

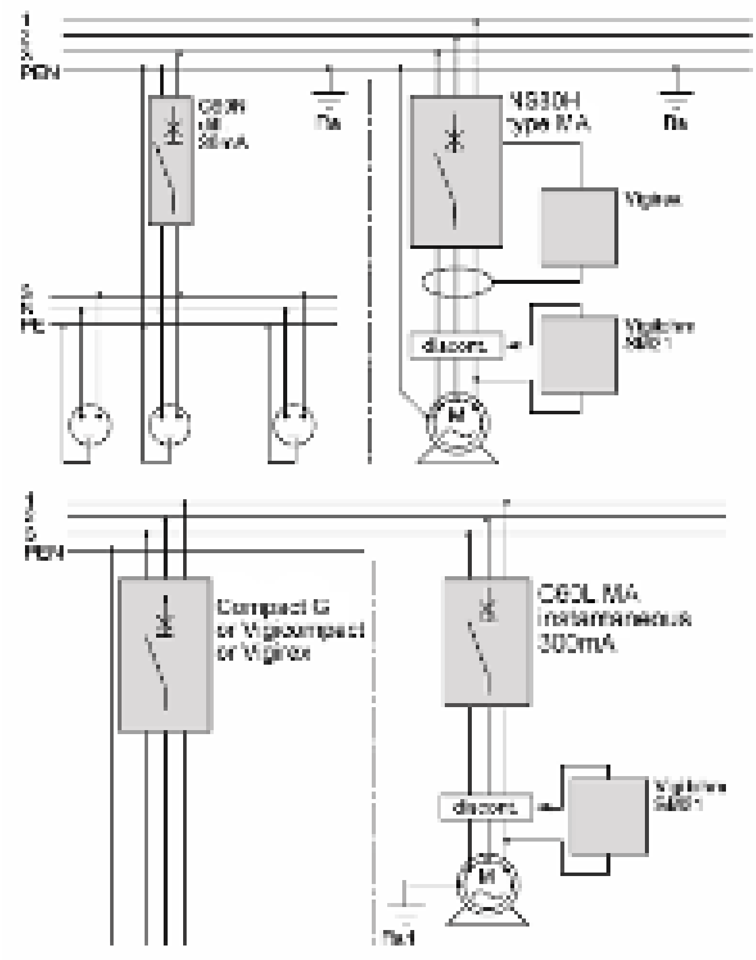


Figure 82: Special measures for RCDs for a TN arrangement

d) non-interconnected distant equipment ground

The fault voltage risks being hazardous. A separate torus relay or a circuit breaker with RCD unit or a modular residual current circuit breaker, threshold $I \leq U_L / R_{A1}$, provides the indirect contact protection.

7.3.4. Typical mandatory minimum configuration for an IT arrangement

7.3.4.1. Indication of the first fault

I.e. the possibility to maintain the operating continuity and **Trip on a double fault**

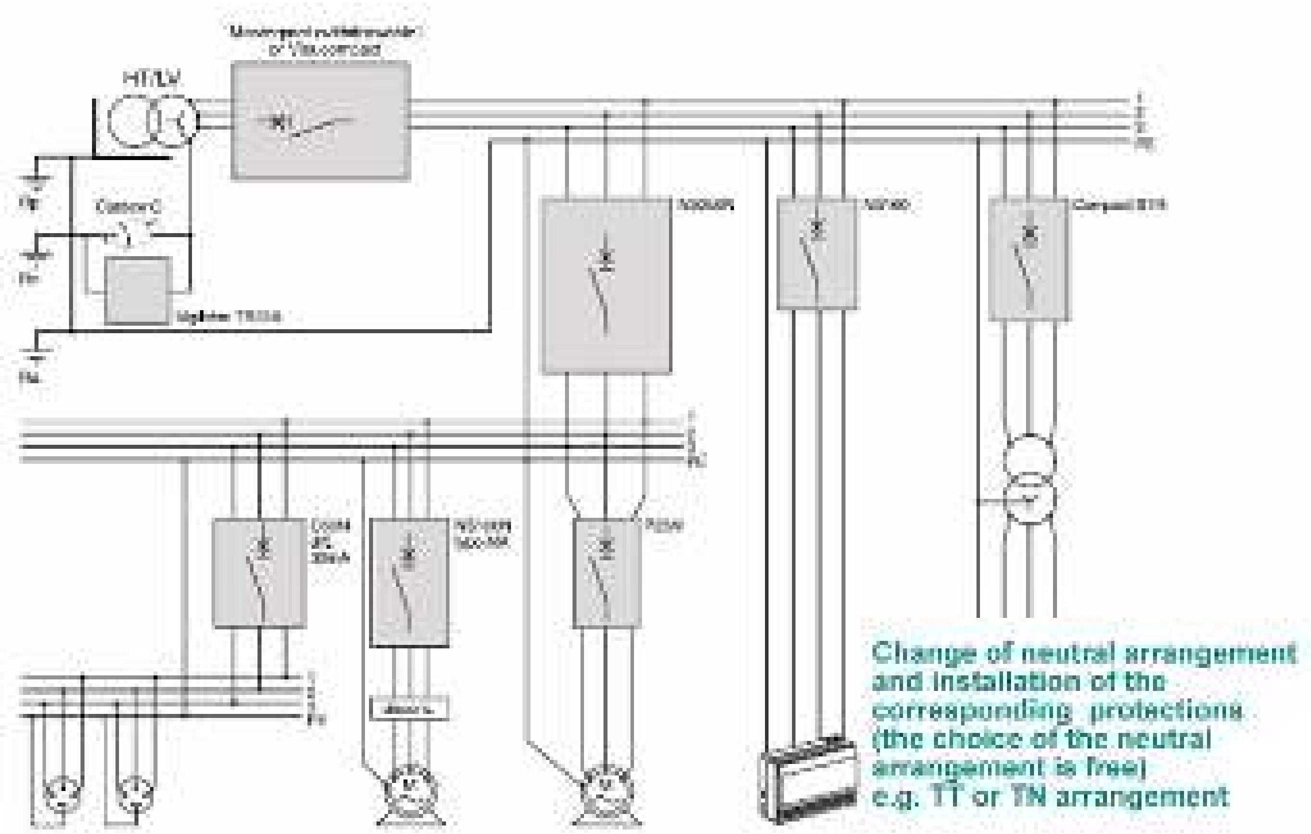


Figure 83: Typical minimum configuration for an IT arrangement

7.3.4.2. Required special measures for an IT arrangement

To perform the trip on the double fault according to the type of installation

a) high-sensitivity residual current device ≤ 30 mA mandatory for:

- power socket circuits with assigned current ≤ 32 A (NF C 15-100 chap. 53 § 532.26)
- the circuits supplying the shower rooms and pools,
- the supply of certain installations such as worksites, etc. where there is a risk of the PE being cut.

b) premises where there is a fire risk

A separate torus relay or a circuit breaker with associated RCD unit or a modular circuit breaker with RCD unit (threshold set to 300 mA), prevents a fault current greater than 300 mA from being maintained.

c) very long cable length

In this case, the fault current is limited. Depending on the case, a Compact G-type or modular B-type curve circuit breaker, or a residual current circuit breaker with RCD unit or separate torus relay, threshold $I_{\Delta n} < I_{fault}$, performs the trip.

d) non-interconnected distant equipment ground

The fault voltage risks being hazardous. A separate torus relay or a circuit breaker (compact) with RCD unit or a modular residual current circuit breaker, threshold $I_{\Delta n} \leq U_2 / R_{A1}$, provides the indirect contact protection.

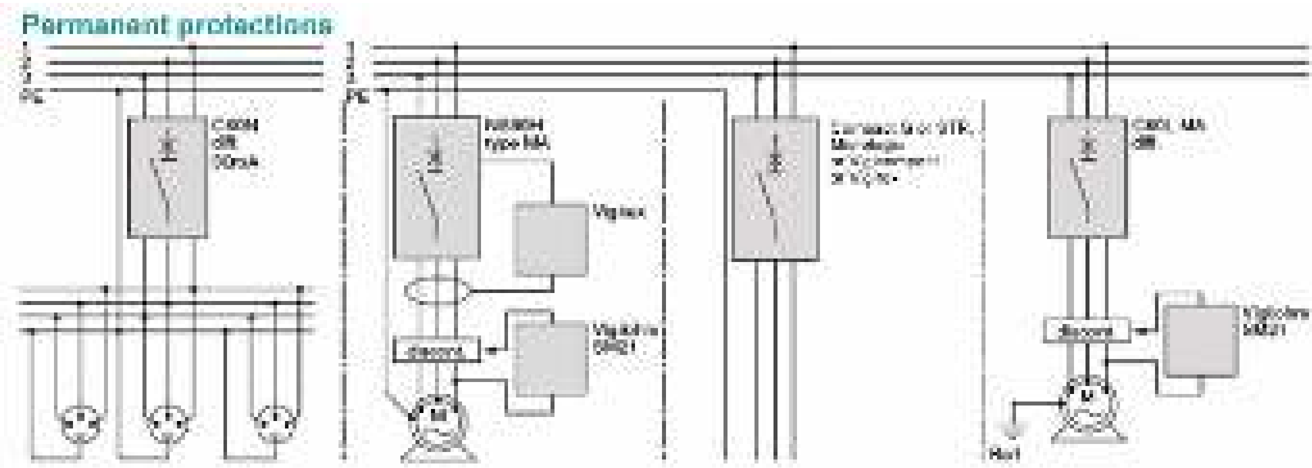


Figure 84: Special measures for an IT arrangement

7.3.5. Requirements of the standards for the PIM (IT arrangement)

According to the NFC 15-100 standard, § 532.4, the PIMs (Permanent Insulation Monitors) must be connected between earth and the neutral conductor (if the neutral conductor is accessible) and as close as possible to the origin of the installation.

The earth terminal must be as close as possible to the earth connections of the installation's equipment grounds.

7.3.5.1. Supply via a single HV/LV transformer

When the supply is via an HVA/LV transformer we recommend that the PIM be connected between the neutral point of the transformer (where it exists) and the equipotential loop of the operating equipment grounds.

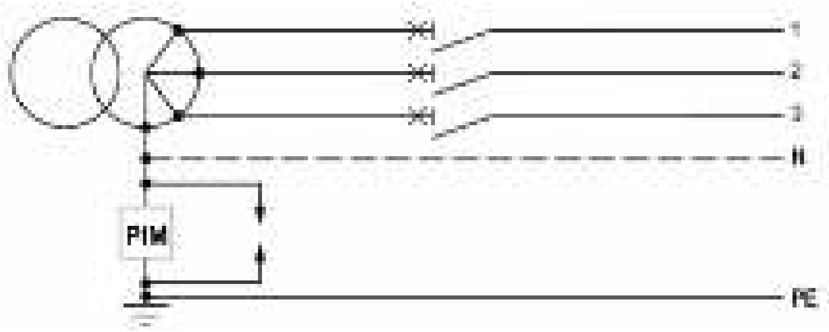


Figure 85: PIM and 1 single transformer

This configuration has the following additional advantage: if the LV incoming line main circuit breaker opens, the PIM continues to permanently monitor the transformer's secondary windings, the incoming cables and the overvoltage limiter. It is thus possible to prevent the LV installation's incoming line main circuit breaker from reclosing if an insulation fault appears upstream of this circuit breaker.
This type of connection requires 1 PIM per transformer.

7.3.5.2. Supply via several transformers in parallel (couplable)

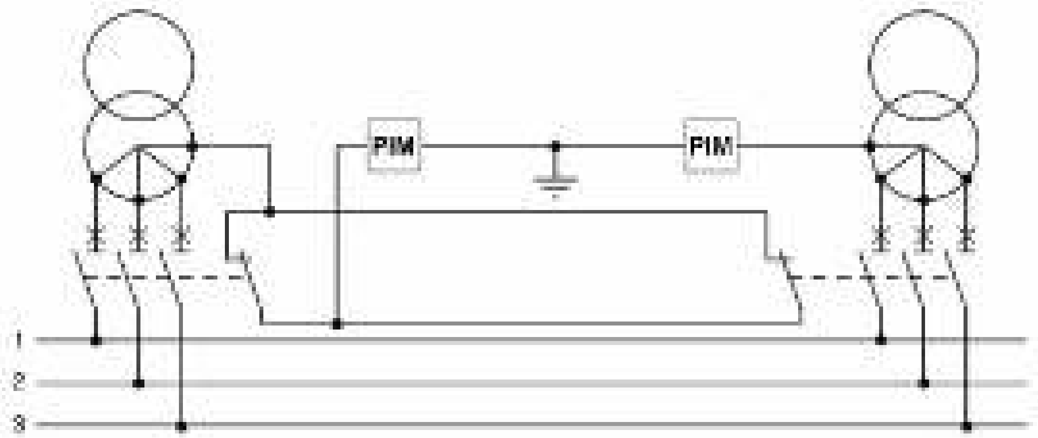


Figure 86: PIM and several couplable transformers

In the case where several transformers can be coupled in parallel, several PIMs can thus simultaneously inject on the same LV network. ***This must be absolutely prevented,*** because each PIM considers the other PIMs as an insulation fault. The PIMs mutually blind each other. The PIMs connected to each of the sources must be interlocked. The following solutions can be envisaged.

This type of arrangement can quickly become complicated when the number of sources increases and when the busbars can be divided into several sections by busbar coupling circuit breakers.

Automatic solution

This type of interlocking can be integrated in the PIMs, but requires data to be sent to the PIM on the status of the associated head circuit breaker.

The communicating PIMs can dialogue with each other and stop the injection of their signal at 2.5 Hz if there is a risk of blinding each other. This is the case with the **communicating PIMs** in the Merlin-Gerin Vigilohm System range (XM300 - XML308/316).

The limit of this system using the PIMs' internal communication is 4 PIMs.

The XAS interface supplies the communication bus. It is possible to manage networks whose main busbars can be divided into several sections by coupling circuit breakers.

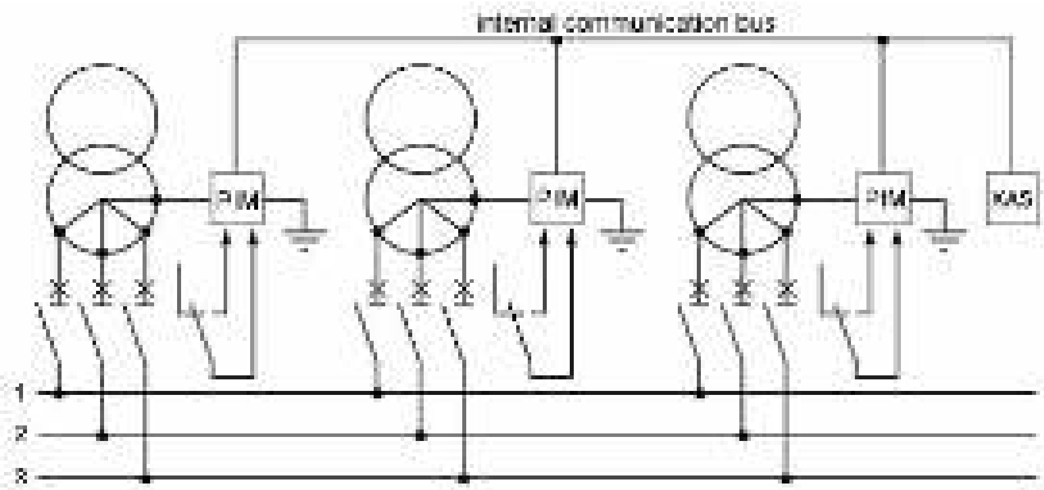


Figure 87: PIM and several couplable transformers – automatic solution

Economic solution

The PIM can be directly connected to the main busbars.

This configuration cannot monitor the transformer secondary windings, the incoming cables and the overvoltage limiters if one or more of the incoming line circuit breakers are open.

Also, in the case of a busbar coupler, there is a similar problem of PIM exclusion.

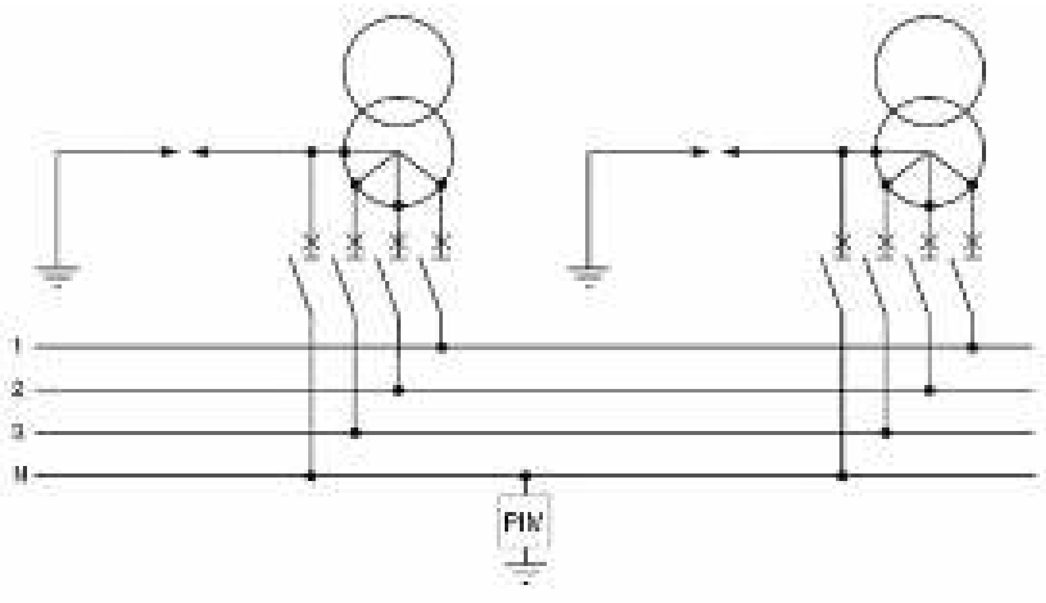


Figure 88: PIM and several couplable transformers – economic solution

7.3.6. Use of PIMs with uninterruptible power supplies (UPS)

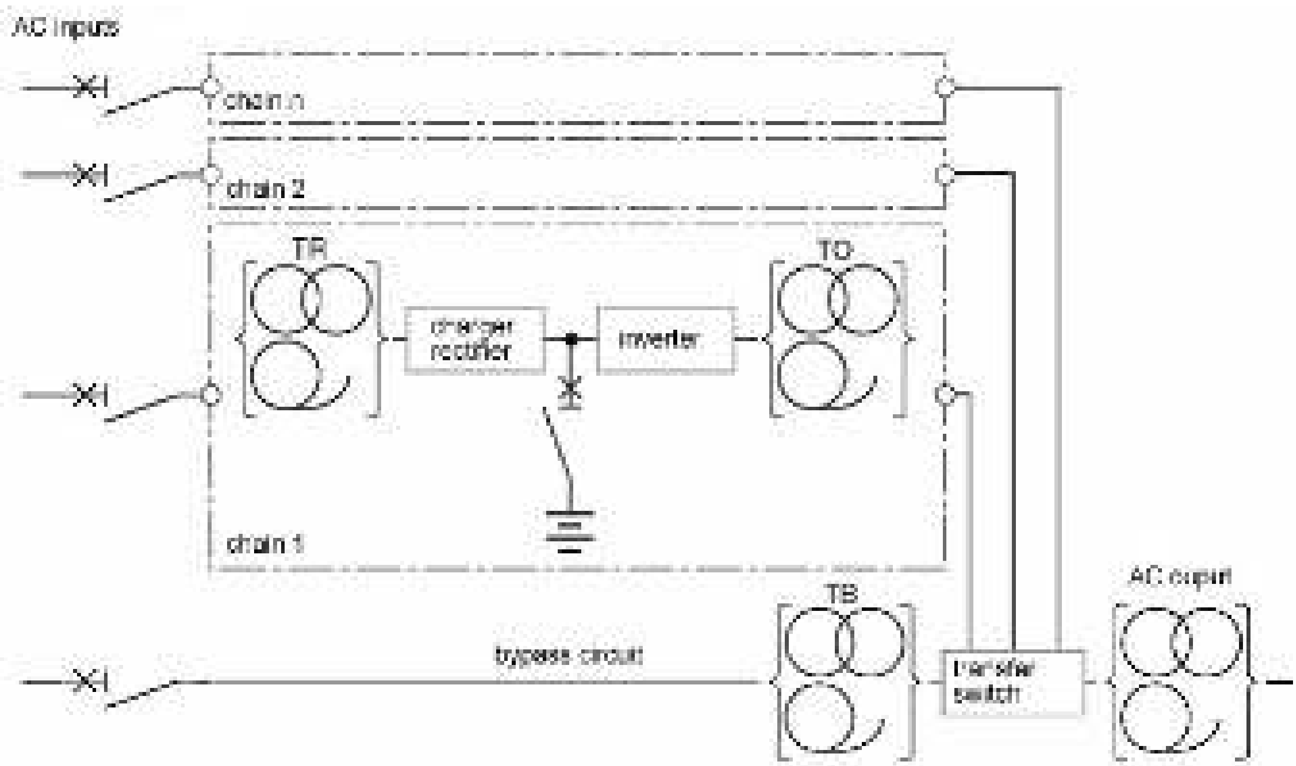


Figure 89: UPS configuration and location of the transformers which may be necessary to adapt the voltage and/or the galvanic isolation

The static uninterruptible power supplies (UPS) may have some specific requirements concerning the use of permanent insulation monitors (PIM). Two cases may arise:

- UPS without galvanic isolation between the inputs and outputs,
- UPS with galvanic isolation between the inputs and outputs. The galvanic isolation can be obtained by transformers with separate windings or either on the input or on the output of the UPS.

7.3.6.1. UPS without galvanic isolation

Two cases may arise:

This configuration is present each time the chains or the bypass are directly connected or only have an autotransformer between the upstream and downstream installations. Two cases with an absence of voltage must then be considered:

- without interruption of the circuits which provide the continuity of the supply installation's neutral,
- with interruption of the circuit causing the neutral in the supply installation to be disconnected.

Absence of voltage without interruption of the circuits which provide the continuity of the supply installation's neutral

In this first case, the initial earthing arrangement is maintained and some of the operating installation's protection devices (upstream) can be used to protect the operating installation (downstream).

Absence of voltage with interruption of the circuit causing the neutral to be cut in the main supply installation

In this second case, during the period when the neutral is disconnected, we must:

- temporarily recreate the neutral earthing arrangement downstream of the UPS, and according to the "position of the neutral with respect to the earth", implement monitoring devices,
- take measures designed to ensure that the DC circuits are monitored, where necessary (see below).

Consequence for the IT arrangement

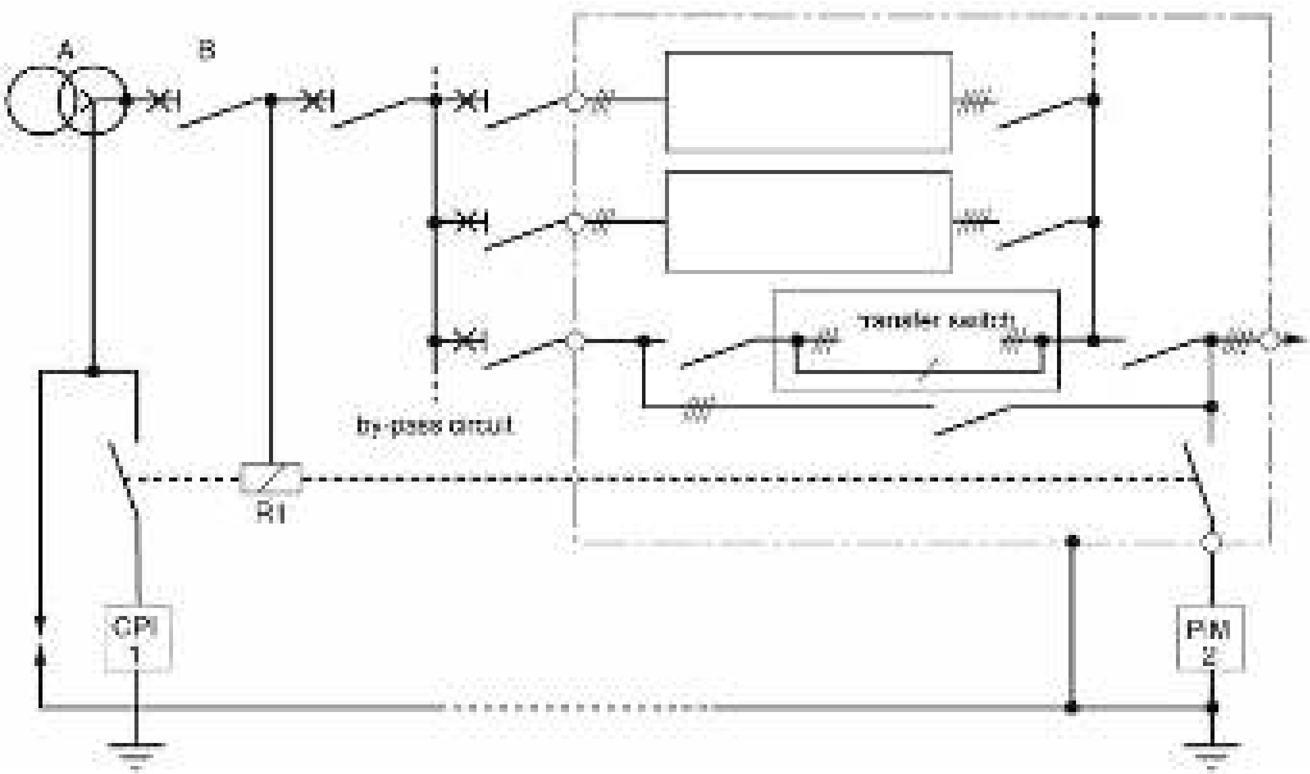


Figure 90: Devices for the protection of persons in an installation comprising a UPS without galvanic isolation

Without galvanic isolation on the input of the uninterruptible power supplies and on the backup and "bypass" network, PIM 1 located at the origin of the installation monitors everything, including the downstream side of the UPSs since the neutral is not disconnected at the transfer switch or at the bypass when this switch is closed. In the event of a voltage loss on the entries upstream of the UPS, or of circuit breaker B opening, PIM 1's injection is cut by the contact of relay R1 and PIM 2 downstream of the UPSs has its injection activated by the contact of relay R1. PIM 2 monitors the insulation downstream of the UPSs and it monitors the upstream side of the inverters via the neutral which is not disconnected at the transfer switch, the upstream side of the UPSs.

For maintenance, the bypass is closed and PIM 2 will also monitor the upstream side of the UPSs. The insulation of the UPS batteries will only be monitored by PIM 1 and PIM 2 if there are no transformers on the UPS inputs.

If PIM 1 or PIM 2 cannot monitor the insulation of the batteries, a PIM can be installed on the battery, but the battery must not be in redundancy with PIM 1 or PIM 2.

Notes:

- PIM 2 must be connected so that it is guaranteed to operate, even during maintenance on one of the parallel chains,

- When PIM 2 is in service, it then monitors all of the upstream and downstream installations up to the open upstream disconnection components,
- In practice, the rectifier-inverter chains are identical and very often have at least one isolation transformer, TR, TO, or both. Also, PIM 2's entry into service only depends on the absence of voltage upstream of the bypass and its monitoring then extends to the upstream installation except when a disconnection device on the bypass opens.

7.3.6.2. UPS with galvanic isolation

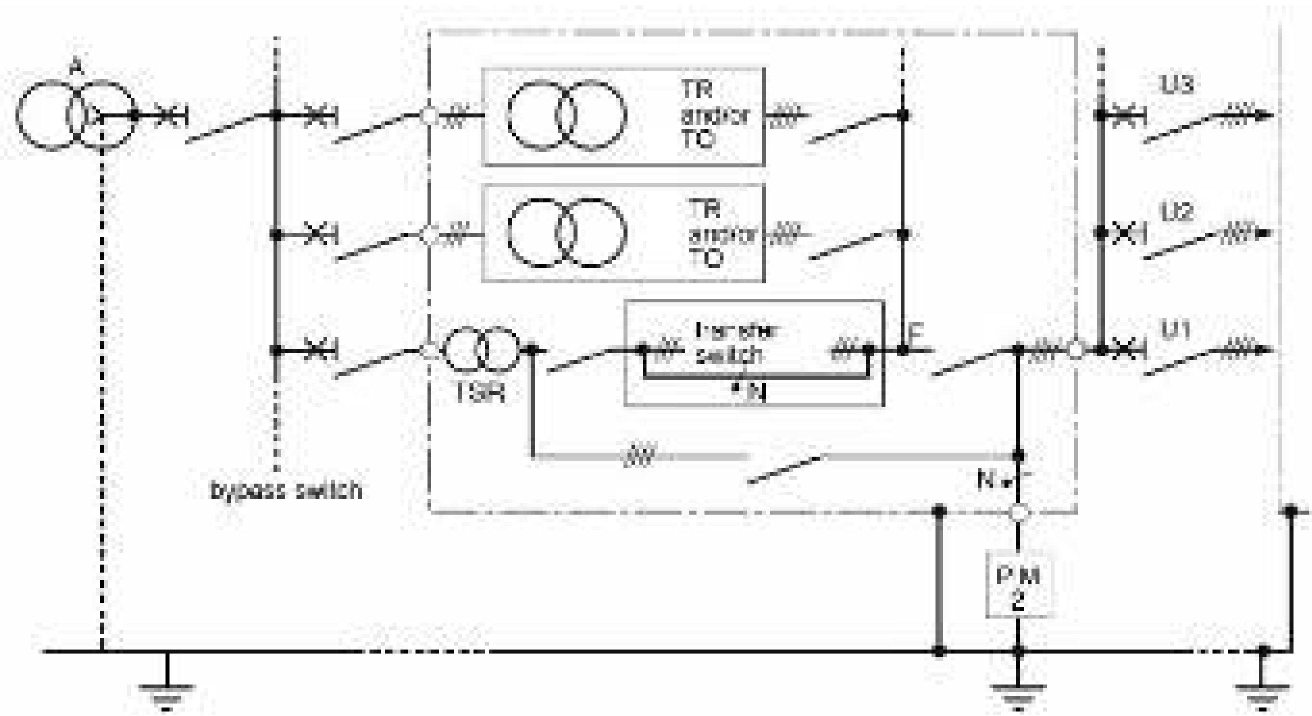


Figure 91: UPS with galvanic isolation

The upstream and downstream earthing arrangements can be separate or not.

Galvanic separation is necessary each time that the downstream operating conditions are incompatible with the upstream earthing arrangement, and vice versa. The galvanic separation is provided by the separate-winding transformers placed in each of the rectifier-inverter lines (TR or TO) and in the bypass (TSR) or by a separate-winding transformer placed downstream of the UPS.

Note: Upstream earthing arrangement with earthed neutral and downstream earthing arrangement with impedant neutral

PIM 2 monitors the insulation of the UPS output, but also the insulation of the downstream network via the non-disconnected neutral of the UPS transfer switch (static contactor).

This imposes the use of a transformer (TSR: Replacement Source Transformer) in the of "standby network" input branch of the UPS(s).

7.3.6.3. Surveillance of the battery DC circuit insulation

Only a Voltmetric balance PIM (TR5A) monitors this zone's insulation.

Note: transformers TR and TO are mandatory.

Use of a low-frequency current injection PIM (2.5 Hz)

Principle: it applies a low-frequency AC voltage source between one of the polarities of the DC circuits and earth; the appearance of an insulation fault in the DC circuits sets up a current flow which is detected by the measurement circuits (*the Vigilohms, etc.)*.

These monitors, which monitor both the mixed AC and DC networks can also find the insulation faults; they are therefore recommended if:

- there is a true DC network (several users),
- there is no galvanic isolation between the battery and the installation downstream of the UPS (rare case).

7.3.6.4. Interaction between the DC circuit monitoring devices and those of the upstream and downstream installations

This interaction is directly linked to the UPS arrangement.

In particular, it depends on:

- whether a static contactor is present or not,
- the number of UPSs, one or more in active or passive redundancy,
- whether a TR or TO galvanic isolation transformer is present or not.

This interaction directly depends on the protection devices chosen and on the neutral arrangement of the upstream and downstream installations. We can have:

- **Total interaction**

  For example, the upstream protection device also monitors the DC circuits.

- **Partial interaction**

    - between two PIMs: in the same way as for the AC circuits, two devices of the same type connected to two non-electrically separate installations mutually disrupt each other. This situation must therefore be prevented using a relay, for example, such as R1,

    - between an injection PIM and a voltmetric balance PIM: a DC or low-frequency injection PIM measures the internal resistance (R/2) of a voltmetric balance device. These PIMs are placed on either side of a power converter (rectifier or inverter) without galvanic isolation, the disturbance of one by the other will be directly dependent on the conduction level of the converter's semiconductors.

- **Zero interaction**

    - if there is a galvanic isolation between the battery and the upstream and downstream installations (AC)

    - between PIM and RCD or circuit breaker.

- **Rules**

    - a PIM's AC or DC injection cannot pass through a transformer.

    - manage the PIM exclusions when there are several PIMs in a same installation (except Vigilohm System with the interfaces).

    - DC injection is not operational on DC.

    - PIM injection cannot cause reactions by the RCD devices or circuit breakers.

7.4. DC CURRENT NETWORK ISOLATED FROM EARTH

The legislation requires a device which indicates the first fault

The traditional protections guarantee the safety of persons and property on the second fault.

7.4.1. To monitor the overall insulation and indicate the first fault

Fixed DC voltage network (bank of accumulators, etc.)

Use a PIM of the type Schneider Merlin-Gerin Vigilohm TR5A (or equivalent).

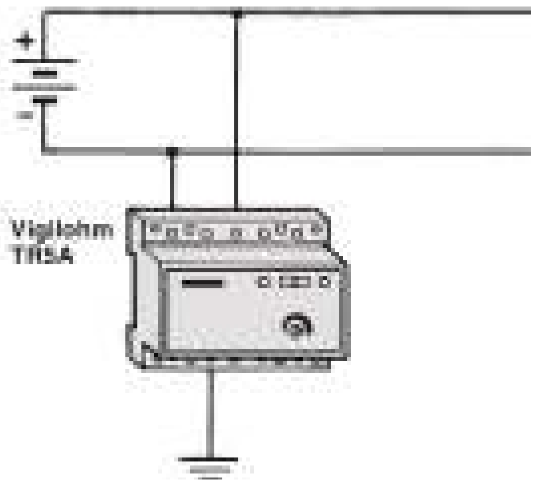


Figure 92: PIM on fixed DC voltage network

Variable DC voltage network (DC generator, thyristor rectifier transformer unit) or fixed voltage network

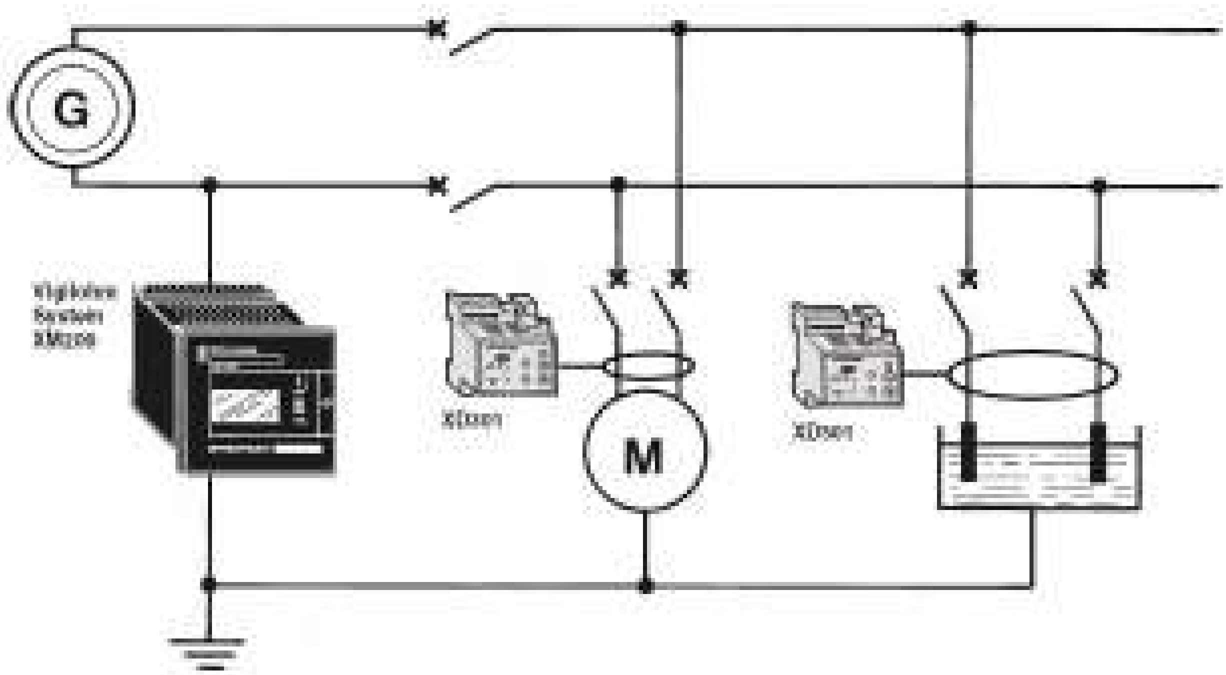


Figure 93: PIM on variable DC voltage network

Use a Vigilohm System XM200 PIM with XD301 or XD312 detectors (the XD units are "secondary detectors" returning the fault signal to the master PIM (XM200).
XM200 recommended for DC voltages ≥ 125 V.

7.4.2. For fault finding with the system energised

(Improved operating conditions).

Low frequency AC (generally 2.5 Hz) is injected:

- either by a Vigilohm system XM200 associated with XD301 or XD312 detectors on the outgoing lines,
- or by a Vigilohm System XM300 associated with XD301 or XD312 detectors or with XL308 or XL316 locators,
- or by a Vigilohm System XML308 or XML316.

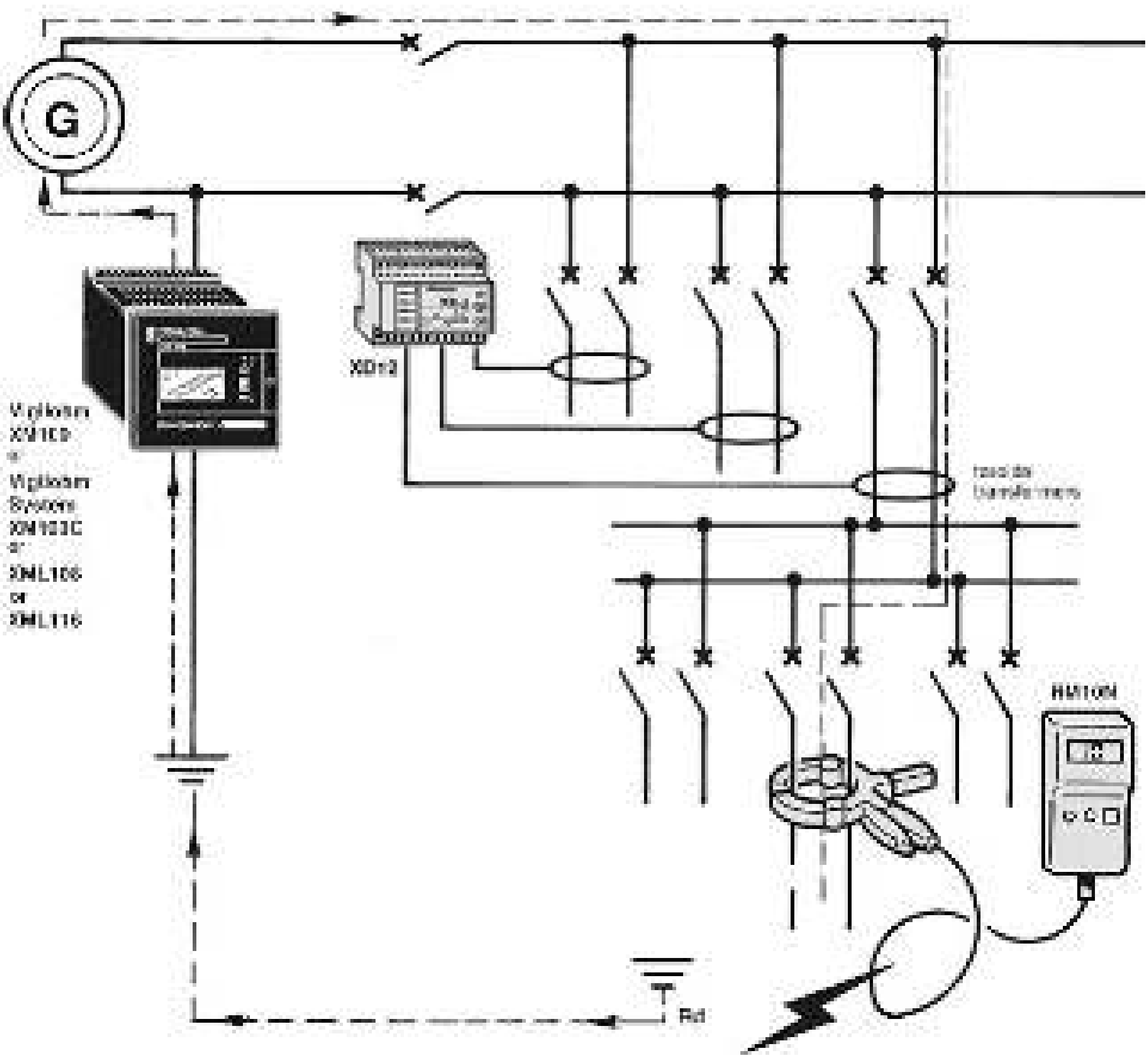


Figure 94: Fault-finding in a DC network

The fault current is detected using toroidal transformers installed on the different outgoing lines and connected to XD301 or XD312 detectors which indicate which output has the fault, or which are connected to XL308 or XL316 locators which indicate the output with the fault and measure the insulation level.

Note: the XRM portable receiver and its clip-on ammeter are compatible with all the devices in the Vigilohm series generating 2.5 Hz. *(See course on electrical protections EXP-MN-SE110 paragraph 7.2.3 and 7.2.4 for faultfinding with a PIM system).*

8. ASSOCIATED SWITCHGEAR ACCORDING TO THE NEUTRAL POINT ARRANGEMENT

8.1. ASSOCIATED SWITCHGEAR IN TT

8.1.1. Reminder

Protection of persons

- The fault current is a hazard.
- The fault current is too low to be part of the SCPDs (Short-Circuit Protection Devices).
- The protection must be almost instantaneous.

Fire protection

- The fault current is limited.
- It is naturally dealt with by the RCD for the protection of persons.

Service continuity

- Obtained by selectivity between the RCDs.

8.1.2. Correctly operating network / faulty network

See figure "Principle of a correctly operating network and of a faulty network.

8.1.3. Detection principle

Detection by a torus placed around all the active conductors.

Principle: vector sum of the currents to calculate: $\overrightarrow{I_1} + \overrightarrow{I_2} + \overrightarrow{I_3} + \overrightarrow{I_n} = \vec{I}$

I = 0 if the network is operating correctly

I ≠ 0 if there is a fault on the network

$\vec{I} = \overrightarrow{I_d} = \overrightarrow{I_{PE}}$

See figure "Detection principle"

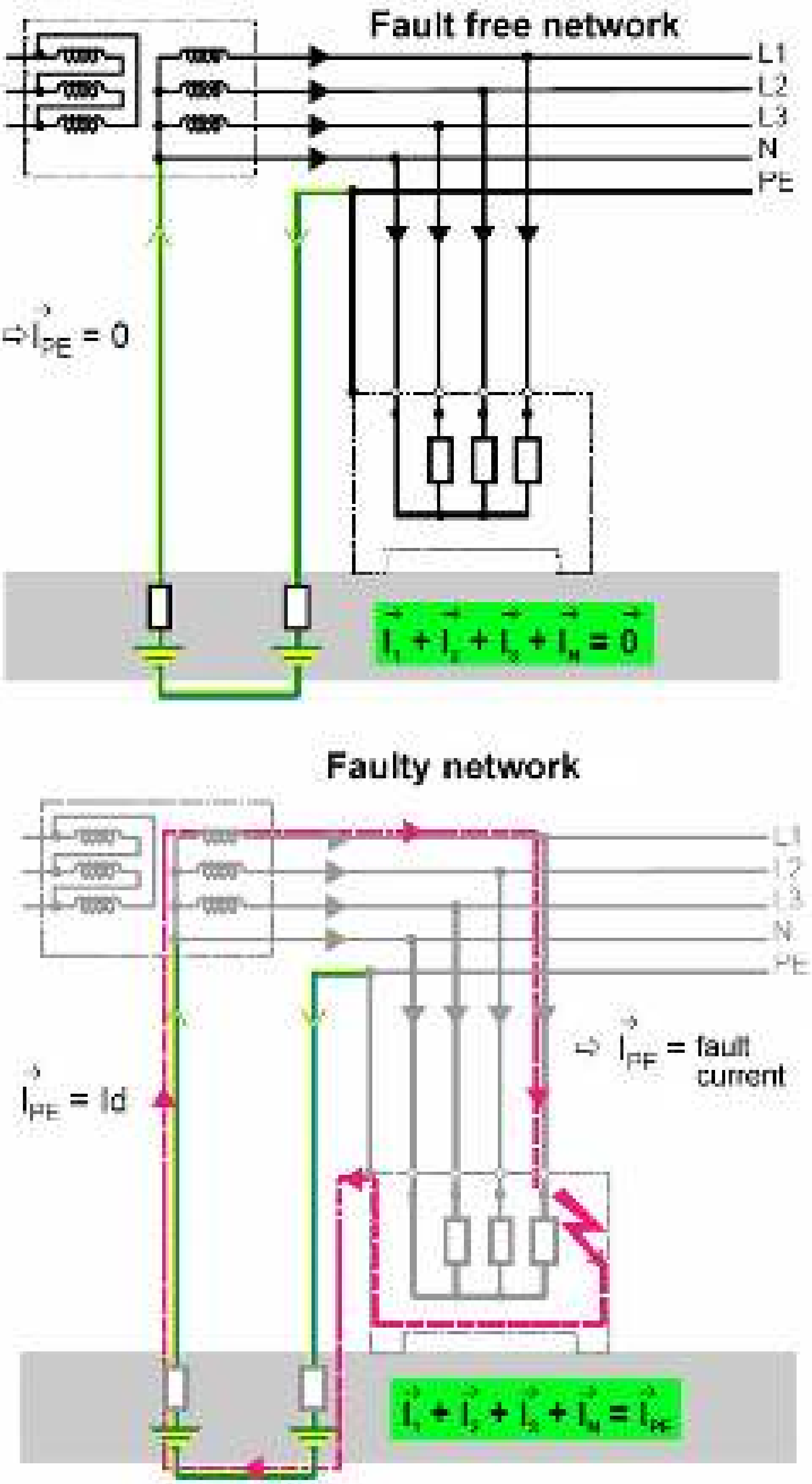


Figure 95: Principle of a correctly operating network and of a faulty network

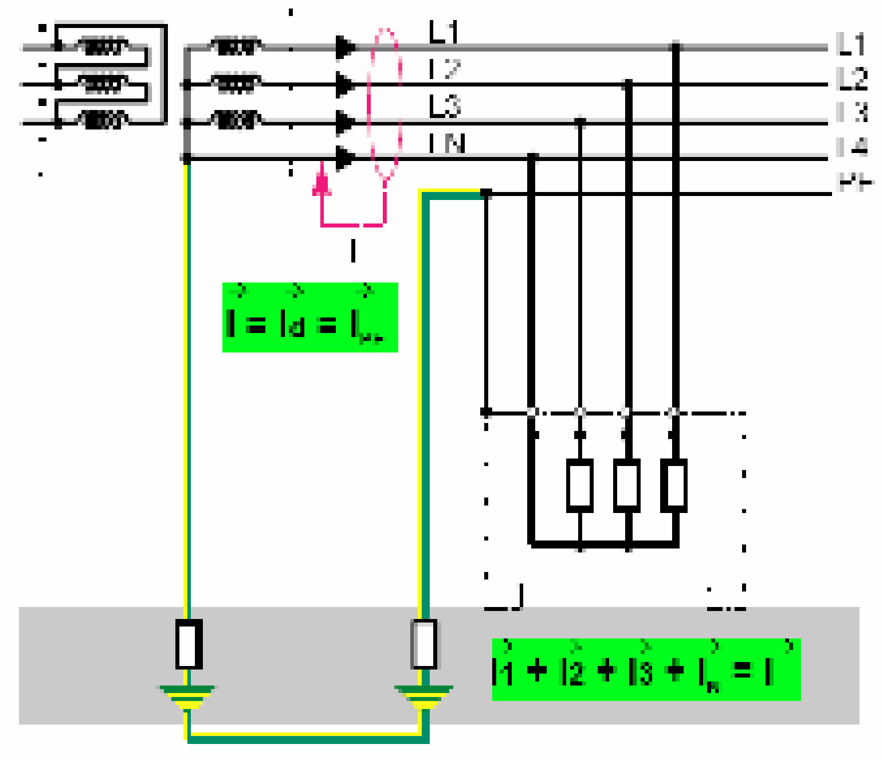


Figure 96: Detection principle

8.1.4. Residual current protection (RCD system)

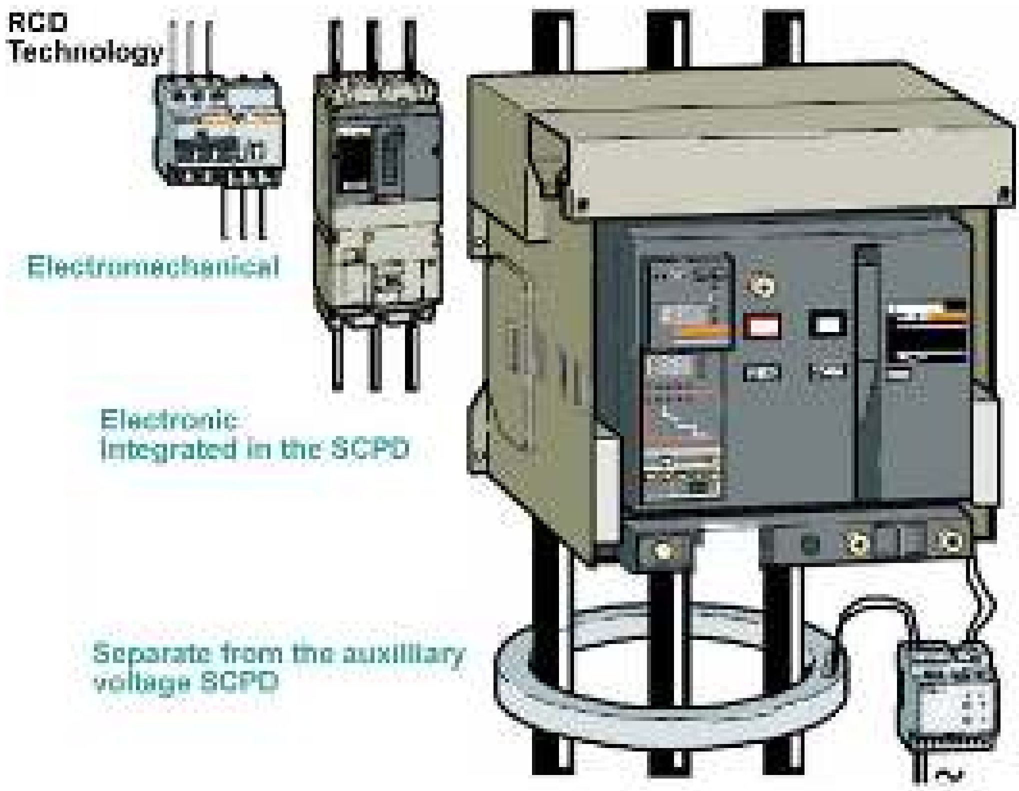


Figure 97: RCD technologies

Electromechanical (with specific current)

Electronic, integrated in the SCPD (with specific voltage)

Separate from the auxiliary voltage SCPD

Basic function

Time-delayed for upstream distribution

Instantaneous for final distribution

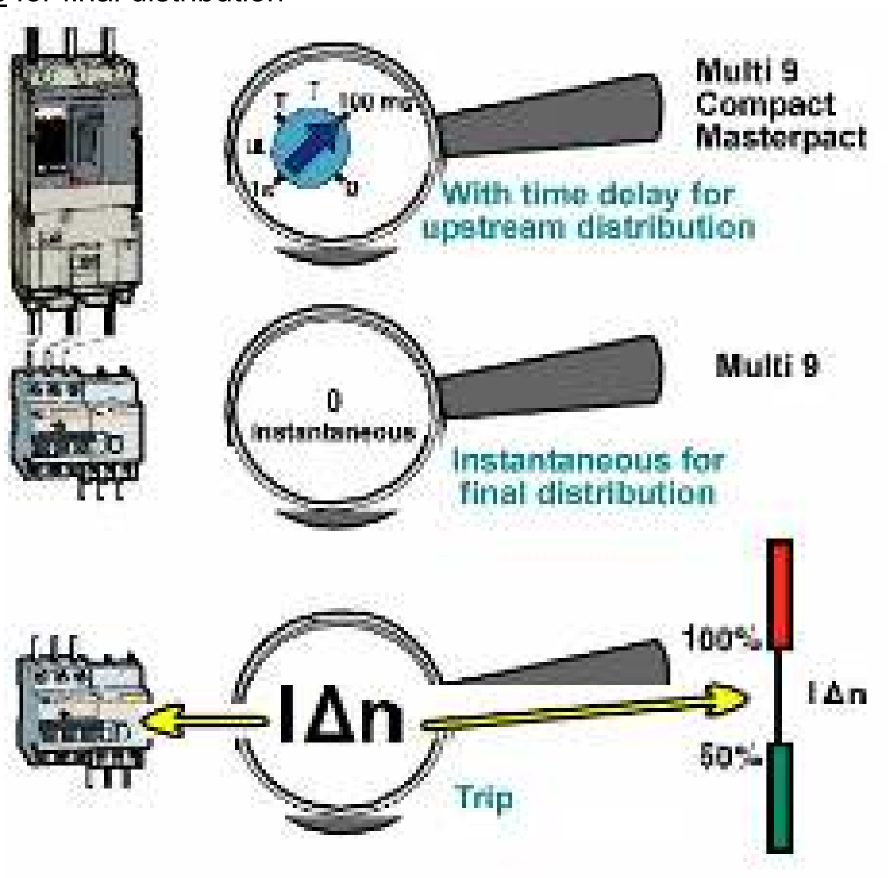


Figure 98: RCD functions

Tripping

NO at Id ≤ 50 % I^2n

YES at Id ≥ 100 % I^2n

After T if time-delay

Selectivity

Vertical selectivity

Threshold adjustment
$I\Delta n1 > 2\ I\Delta n2$

Time-delay adjustment
"RCD1" setting > "RCD2" setting

Note: where an RCD is not integrated in the SCPD, special care must be taken with the control and disconnection device (trip time-delay).

Horizontal selectivity

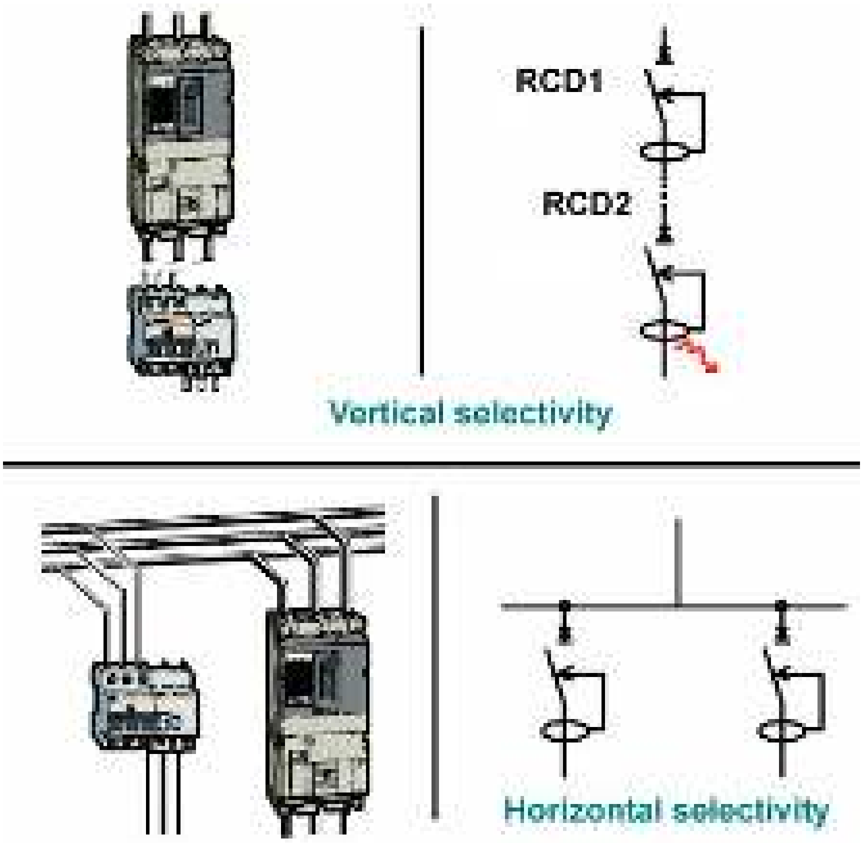


Figure 99: RCD selectivity

Immunisation

Spurious trips

Overvoltages (switching, lightning, etc.)

Capacitive circuit energisation

Types of solutions:
No DC component
= AC type

With DC component

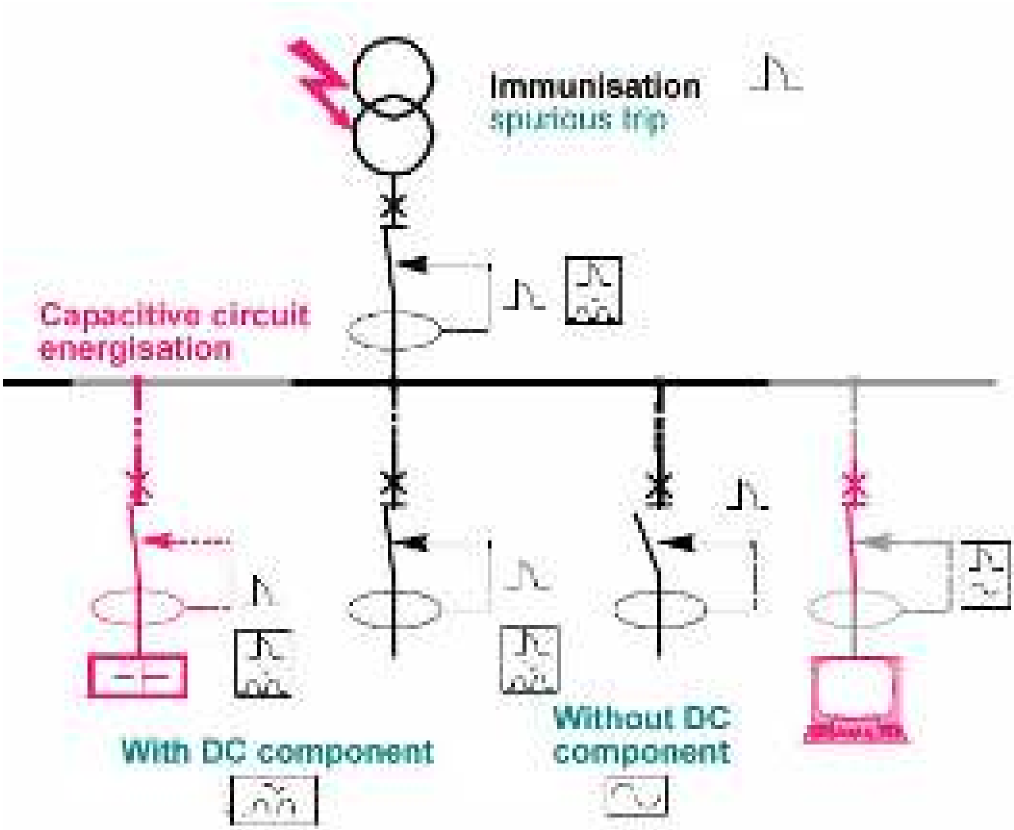


Figure 100: RCD immunisation

8.2. ASSOCIATED SWITCHGEAR IN TN-S

8.2.1. Reminder

Protection of persons

- The fault current is a hazard.
- The fault current is high and must trip the SCPD (Short-Circuit Protection Device).
- The trip is almost instantaneous.
- The protection must be provided by RCD.

Fire protection

- The fault current is high.
- It is dealt with by additional RCDs.

Service continuity

- Obtained by selectivity between the SCPDs.

8.2.2. Protection by SCPD

Protection

The fault current Id for a given cross-section / material (Cu / Al) depends on the length of the conductors.

The protection is obtained either:

- By fuses: inverse time curve, check the trip time,
- By circuit breaker: adjustment of the magnetic circuit breaker.

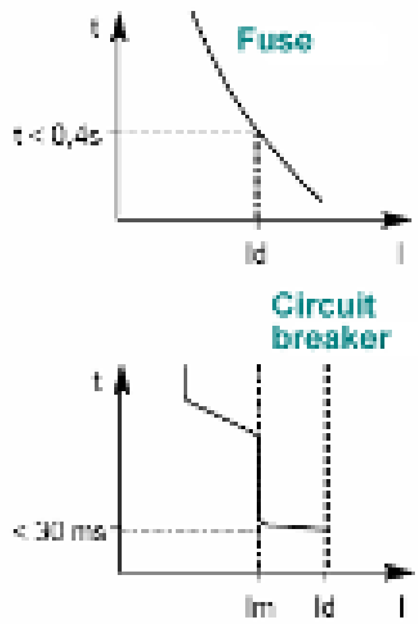


Figure 101: Protection by fuse and/or circuit breaker in TN-S

The protection condition is not fulfilled

Circuit breaker	Fuse
Low adjustment of the magnetic circuit breaker / CR	No adjustment possible
otherwise	
Install standard RCD	Difficult
otherwise	
Increase conductor cross-section	

Table 22: Protection conditions with fuses or circuit breakers

The circuit breaker selectivity is:

Current

Adjustment of the LR and CR ratings

Time

Intentional time-delay on the LR and CR upstream protection

Energy

Comparison of energies (CR)

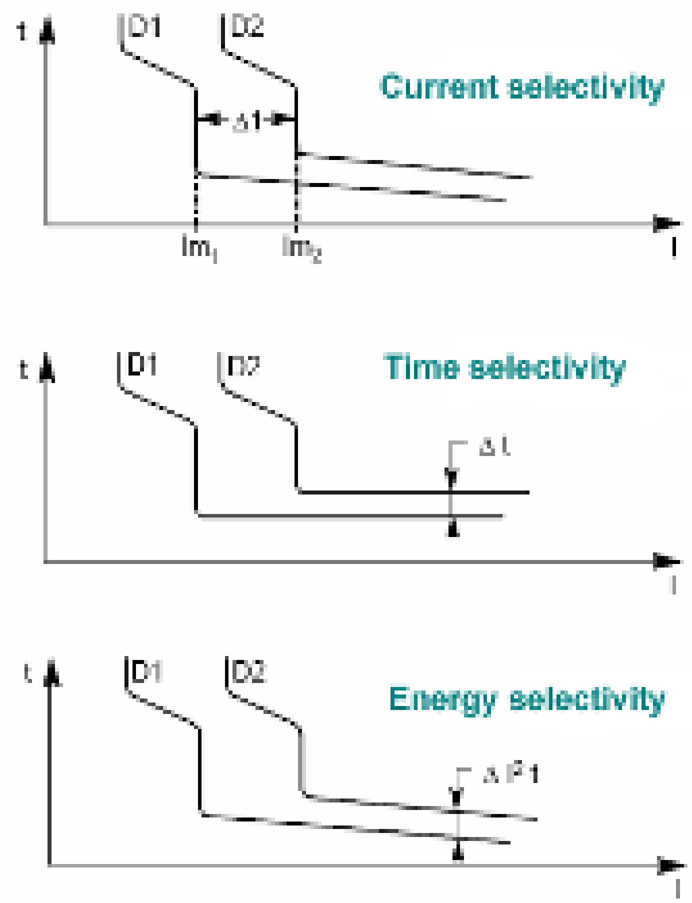


Figure 102: Circuit breaker selectivity

8.2.3. Additional protections

IEC fire protection

- Idem TT
- Provided by RCDs
- But no limitation of Id

Selectivity of RCD protections

- Idem TT
- Adjustment of IΔn thresholds
- Adjustment of the time-delays

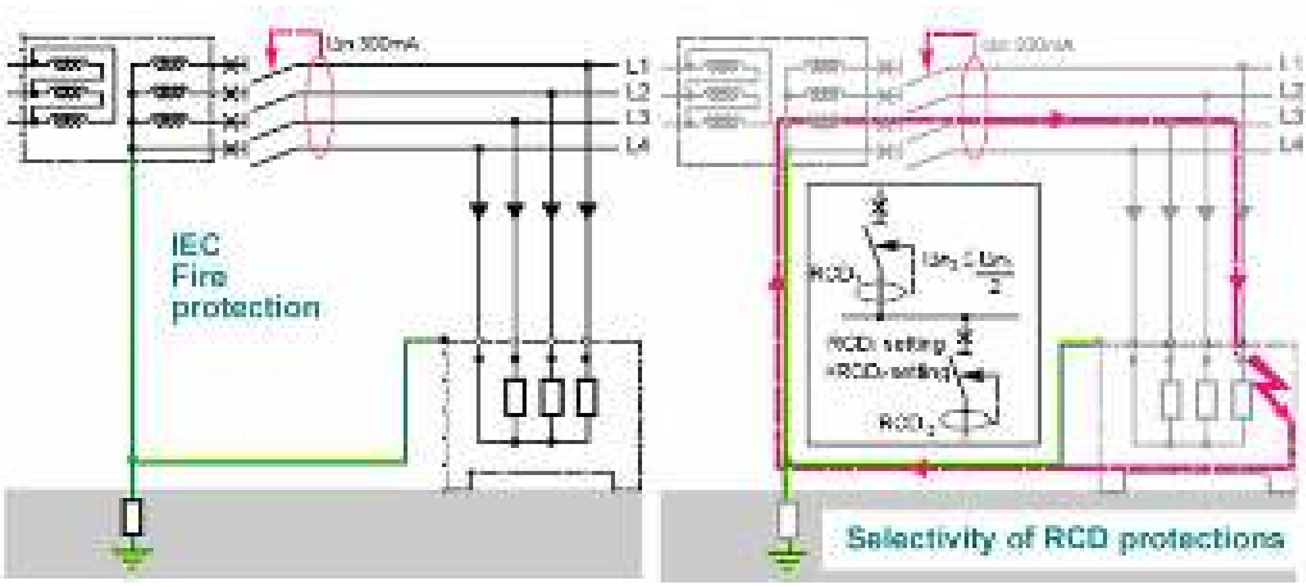


Figure 103: IEC additional protections and with RCDs

NEC fire protection

NEC = National Electrical Code (USA)

Earthing arrangement = TN -S Neutral not disconnected

Protection by GFP (GFP = Ground Fault Protection)

3 types:

1 – zero sequence (rare)

2 – source ground (at head of LV distribution, rare)

3 – residual (standard)

GFP protection selectivity

- *between GFP protections*

- *between GFP/CR protections*

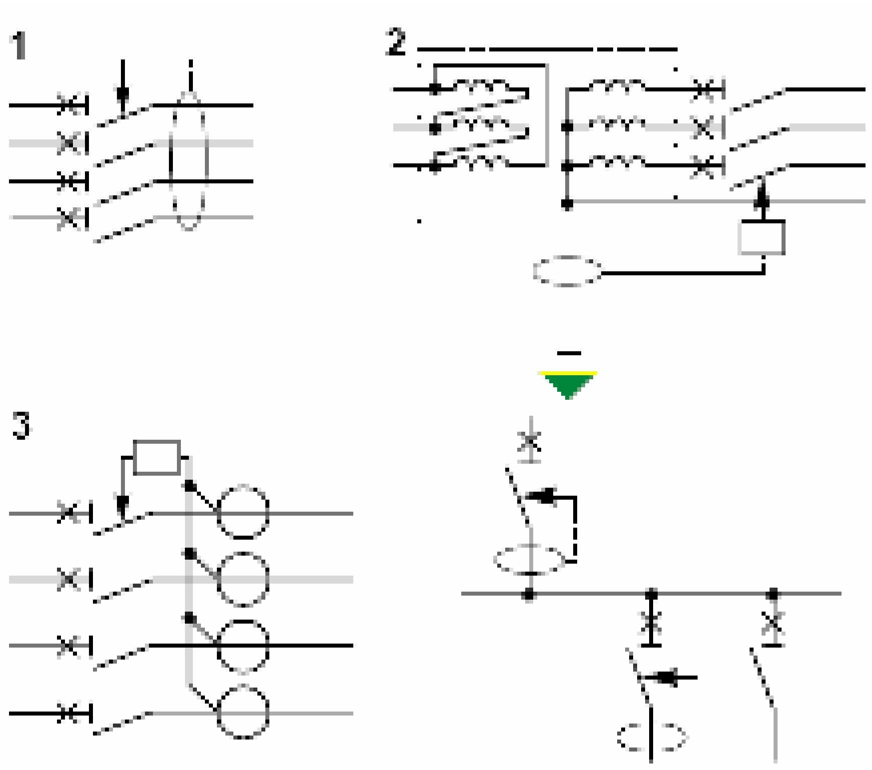


Figure 104: NEC and GFP additional protections

8.3. ASSOCIATED SWITCHGEAR IN TN-C

8.3.1. Reminder

Protection of persons

- The fault current is a hazard.
- The fault current is high and must trip the SCPDs (Short-Circuit Protection Devices).
- The trip is almost instantaneous. – idem in TN-S and TN-C
- The protection cannot be provided by RCDs.

Fire protection

- Cannot be provided

Service continuity

- Obtained by selectivity between the SCPDs - idem in TN-S and TN-C

Note: Residual current protection (RCD) cannot be installed in a TN-C earthing arrangement.

8.3.2. Protection by SCPD

Protection ranges (in TN-C and TN-S)

- "Masterpact" circuit breakers

- "Compact" circuit breakers

- Modular circuit breakers

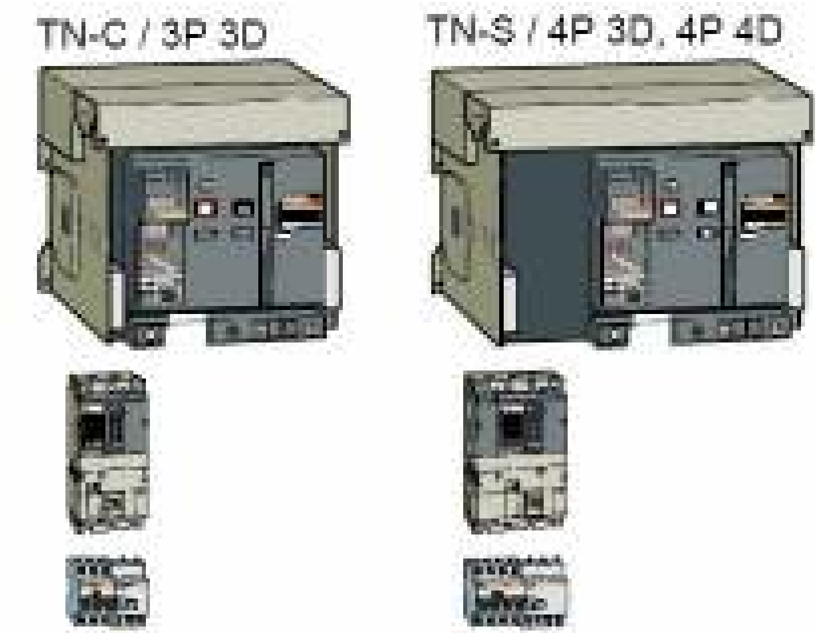


Figure 105: 3 types of circuit breakers for SCPD protection

The circuit breakers also provide overload protection for all the Low Voltage Earthing Arrangements.

Protection by SCPD in TN-C-S

TN-C part: idem TN-C

TN-S part: idem TN-S

8.4. ASSOCIATED SWITCHGEAR IN IT

8.4.1. 1st fault reminder

Protection of persons

- No automatic disconnection
- Surveillance by PIM (*Permanent Insulation Monitor)*
- Fault location by FLD *(Fault Localisation Device)*

Fire protection

- No fault current = not necessary.
- Surveillance by PIM.

Service continuity

- Total.

8.4.2. 1st fault PIM

Principle

- Current injection

- Fault localisation generator

- Insulation resistance measurement

PIM

- DC: direct measurement of insulation resistance

- AC: calculation of insulation resistance

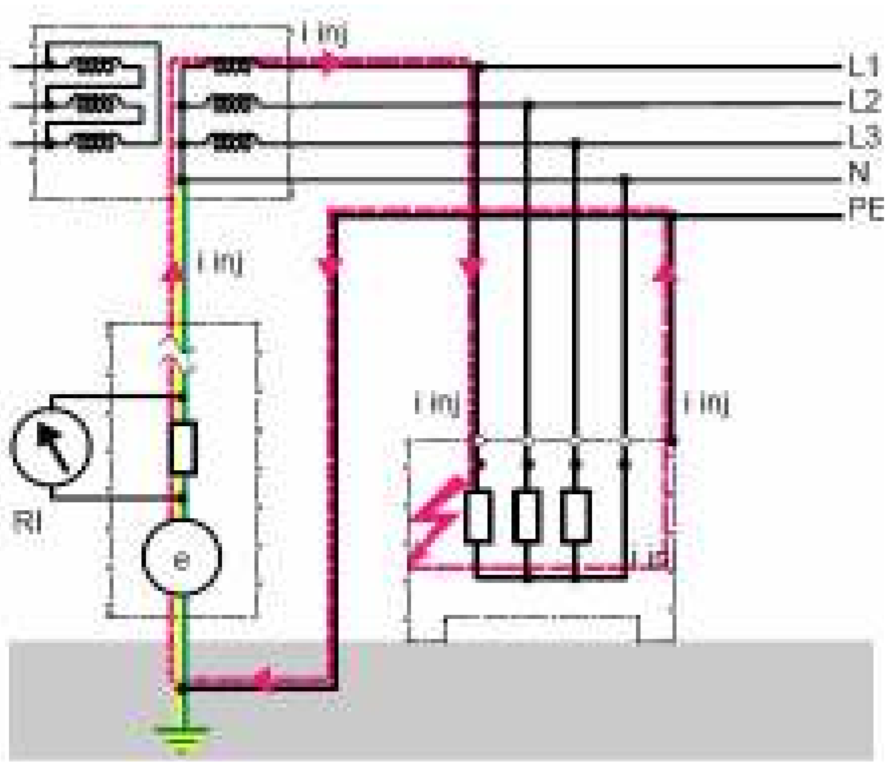
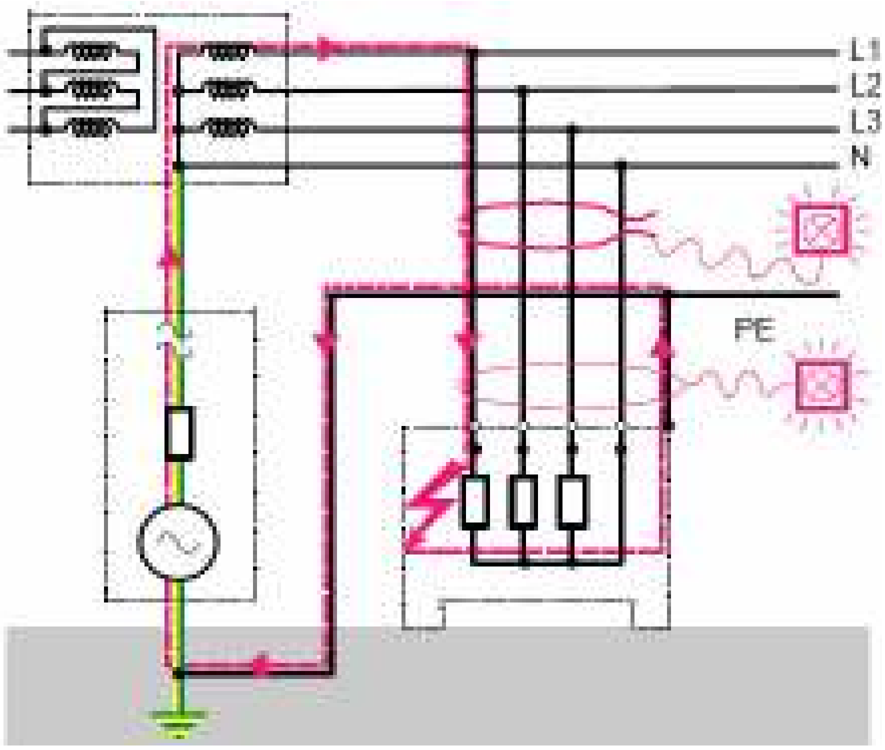


Figure 106: 1st fault detection PIM in IT arrangement

8.4.3. 1st fault FLD



FLD principle

Fault current detection

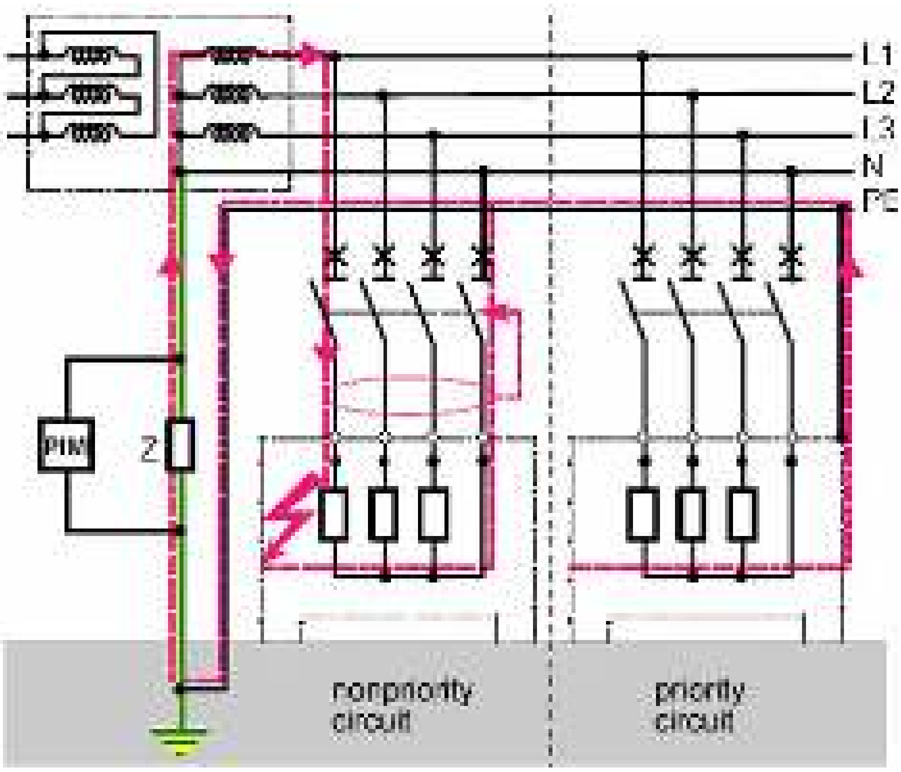
FLD type

- Mobile search

- Fixed search

Figure 107: 1st fault detection FLD in IT arrangement

8.4.4. Trip on 1st fault



50 Hz localisation

- Use of RCD and impedant IT

- Elimination of the fault = service continuity after the 1st fault

Figure 108: Trip on 1st fault in IT arrangement

8.4.5. Trip on 2nd fault

Trip on 2nd fault in IT arrangement with TT protection

- Same principle as with TT

- Protection provided by RCD = same switchgear as in TT

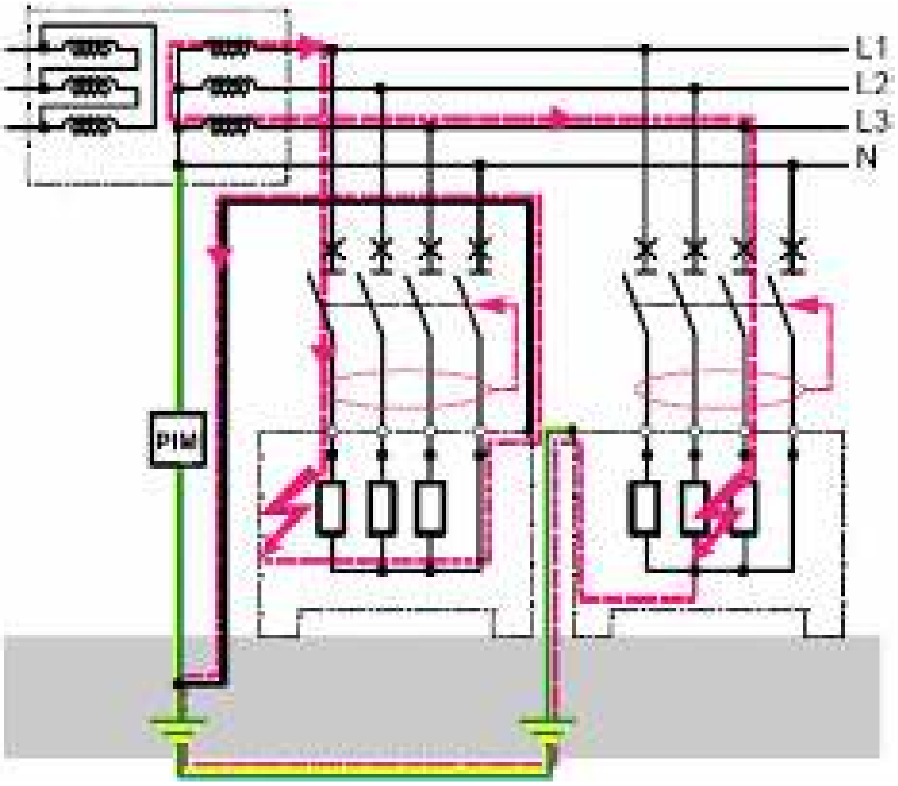


Figure 109: Trip on 2nd fault in IT arrangement with TT protection

Trip on 2nd fault in IT with TN-S protection

- Same principle as in TN-S (conductor length)

- Protection provided by same circuit breaker as in TN-S but:

* 4P – 4D mandatory
* suitable for IT = disconnect the composite voltage on 1 pole (IEC 947-2)
* No cascading

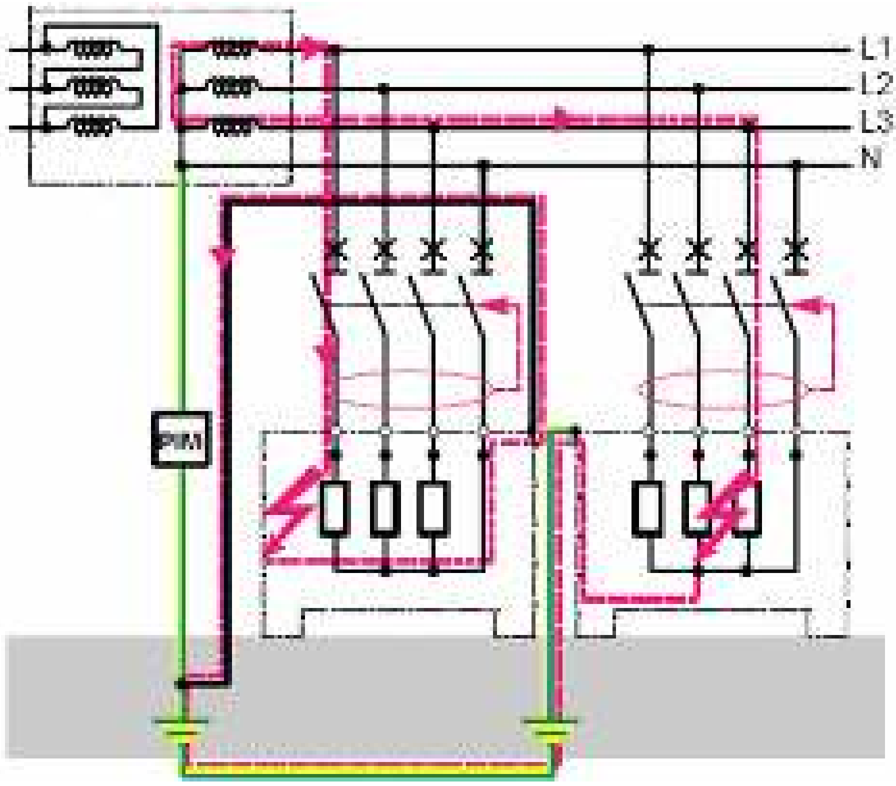


Figure 110: Trip on 2nd fault in IT arrangement with TN-S protection

8.5. COMPARISON – SUMMARY OF THE DIFFERENT ARRANGEMENTS

Criteria	TT	TN-C	TN-S	IT
Safety of persons (perfect installation)	□□□	□□□	□□□	□□□
Safety of property □ against fire risks □ protection of machines on an insulation fault	□□□ □□□	□ □	□□ □	□□□ □□□
Power availability	□□	□□	□□	□□□□
Electromagnetic compatibility	□□	□	□□	□□
For installation and maintenance □ competence □ availability	□□	□□□□ □□	□□□□ □□	□□□ □□□
□□□ □ **excellent** □□□ **good** □□ average □ poor				

Table 23: Comparison - summary of the different earthing arrangements)

After reading this document, the reader will understand the importance of making a list of all the requirements linked with the equipment used, with the environment and also the installation's design conditions as well as the later modifications before choosing an electricity distribution network's earthing arrangement.

It is essential to give a short reminder that each earthing arrangement has its advantages and disadvantages, this is the purpose of the table / summary in this paragraph.

Note: In this table, the installation cost is not covered since any additional cost for an IT arrangement (PIM, FLD) must be compared with the financial loss caused by an unscheduled operating shutdown on the first fault… which must be evaluated according to the activity.

9. EARTH NEUTRAL IN HV

The choice of neutral earthing for MV and HV networks has long been a controversial subject due to the impossibility of finding a single compromise for the different types of networks.

Experience now allows a pertinent choice to be made according to the constraints specific to each network.

This chapter describes and compares the different types of earthed neutral arrangements, which are distinguished by their neutral point connection method and their operating technique.

9.1. FIVE EARTHED NEUTRAL ARRANGEMENTS

9.1.1. Earthing impedance

The capacitors C are the cables natural earth leakage capacitors. The current Ic is the total capacitive current of the network looped through the network's fault-free phases.

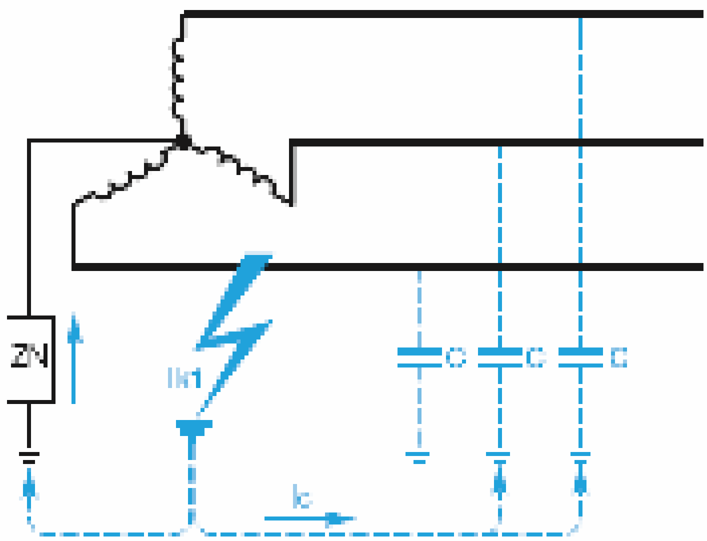


Figure 111: Equivalent diagram of a network with earthing fault

The neutral potential can be set with respect to the earth by five methods differentiated by the type (capacitor, resistance, inductance), and the value (zero to infinity) of the impedance ZN of the link which we will connect between neutral and earth:

- ZN = : **isolated neutral**, no intentional link
- ZN is a **resistance** of more or less high value
- ZN is a **reactance coil**, generally of low value
- ZN is a **compensating reactance coil**, designed to compensate for the network capacitance
- ZN = 0: the neutral is **directly connected to earth**. **(1)**

***(1)** This type of arrangement is not used in European overhead or underground HVA networks. It will not be developed here. However, it is widely used in North American overhead networks with low short-circuit power; the neutral is distributed and used as a protective conductor with earthing at each overhead electricity line pole.*

Difficulties and selection criteria

There are many aspects to the selection criteria:

- techniques (depend on the network, overvoltages, fault current, etc.),
- operating (service continuity, maintenance),
- safety,
- economic (investment costs, operating costs),
- local or national customs.

In particular, there are two major contradictory technical considerations:

Reducing the level of overvoltages

Excessively high overvoltages are the reason for the dielectric breakdown of electrical insulations, which result in short circuits.

There are many sources of overvoltages:

- lightning overvoltages which affect all overhead networks up to the delivery point to the users,
- overvoltages internal to the network, caused by switching operations and certain critical situations (resonances),
- overvoltages resulting the earth fault itself and from its elimination.

Reducing the earth fault current (Ik1) (see figure "*Equivalent diagram...*")

An excessively high fault current has a whole series of consequences:

- damage due to arcing at the fault location; in particular, melting of the magnetic circuits of the rotating machines,
- thermal resistance of the cable screens,

- size and cost of the earthing resistor,
- induction in the nearby telecommunication circuits,
- danger for persons, due to an increase in the potential of the equipment grounds.

Unfortunately, optimising one of these requirements automatically deteriorates the other. Thus, two typical neutral earthing methods accentuate this contrast:

- isolated neutral, which stops the earth fault current flowing through the neutral but generates higher overvoltages,
- directly earthed neutral, which reduces overvoltages to the minimum but produces a high fault current.

Concerning the operating considerations and depending on the method used to earth the neutral, we must note:

- the possibility or not to operate during and first maintained fault,
- the value of the contact voltages developed,
- the more or less great simplicity of implementing protection selectivity.

Therefore, an intermediate solution will often be chosen which involves earthing the neutral via an impedance.

9.1.2. Summary of the neutral arrangement characteristics

characteristics	neutral arrangements				
	isolated	compensated	resistance	reactance	direct
damps transient overvoltages	–	+ –	+	+ –	+ +
limits 50 Hz overvoltages	–	–	+	+	+
limits fault currents	+	+ +	+	+	– –
service continuity	+	+	–	–	–
(trip authorised or not on first fault)					
single selective protection	–	– –	+	+	+
qualified personnel not necessary	–	–	+	+	+
Legend: + good – poor					

Table 24: Summary of neutral arrangement characteristics

9.2. ISOLATED NEUTRAL

This system favours service continuity and does not impose a trip on an first insulation fault. This fault, however, must be located and eliminated since a 2nd fault on another phase will impose a trip.

9.2.1. Schematic diagram

There is no intentional electrical link between the neutral point and earth, with the exception of the measurement or protection devices.

9.2.2. Operating technique

In such a network, a phase-earth fault only causes a low current via the phase-earth capacitors of the fault-free phases (see figure).

We demonstrate that **Ik1** = **3 C** ω **V**

- V is the simple voltage
- C is the capacitance of one phase with respect to earth
- ω is the pulsation of the network where ω = **2** π **f**

The fault current Ik1 can remain present for a long time, in principle without damage, since it does not exceed a few amps (2 A per km approx. for a single-pole 6 kV cable with a 150 mm² cross-section and PRC insulation the capacity of which is 0.63 µF/km). It is thus not necessary to intervene to eliminate this first fault, which means that this solution has the basic advantage of maintaining service continuity.

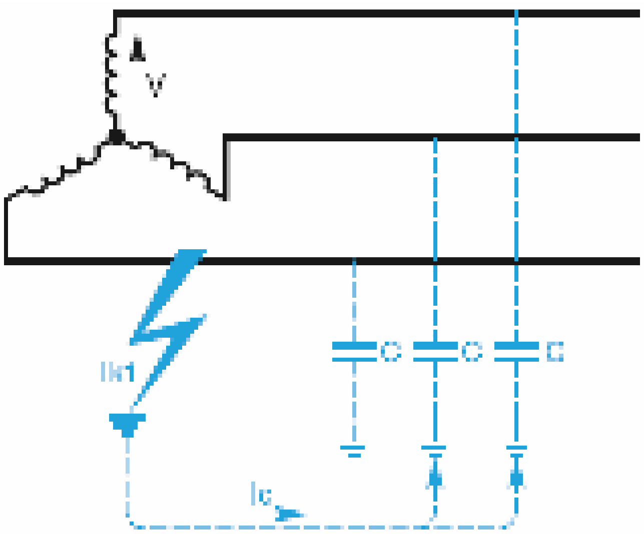


Figure 112: Capacitive fault current on isolated network

But this has the following consequences:

- the insulation must be permanently monitored, and a fault which is not yet eliminated must be indicated by **a permanent insulation monitor (PIM)** or by a maximum residual voltage protection (ANSI 59N)

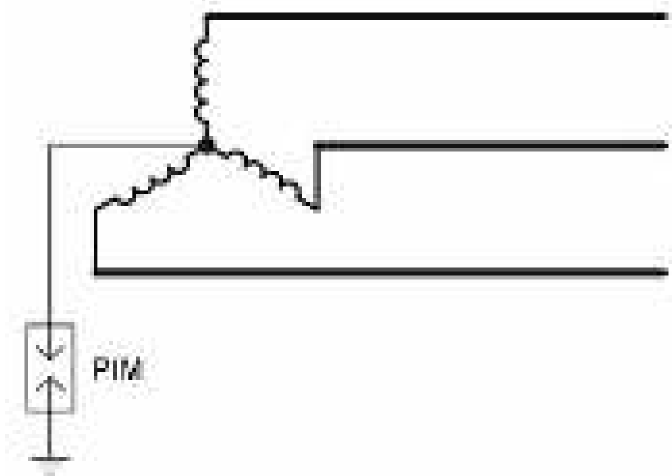


Figure 113: Permanent insulation monitor (PIM) on isolated network

- the later search to locate the fault requires more complex switchgear, since it is automatic, to quickly identify the faulty outgoing line, and a qualified maintenance service to operate it,
- if the first fault is not eliminated, a second fault appearing on another phase will result in a true two-phase short-circuit to earth, which must be eliminated by the phase protections.

9.2.3. Advantage

The main advantage is the service continuity of the faulty outgoing line because the fault current is very low and there is not an automatic trip on the first fault; it is the second fault which will require a disconnection.

9.2.4. Disadvantage

- The fact that the transient overvoltages are not eliminated by draining to earth is a major handicap if they are high.
- In addition, if one phase is earthed, the others are then at the composite voltage (U = e V with respect to earth, which reinforces the probability of a second fault. The insulation cost is higher since the composite voltage remains applied between phase and earth for a time which can be long since there is no automatic trip.
- Insulation monitoring is mandatory, and the first fault must be indicated.
- A maintenance service equipped with the appropriate equipment to quickly find the first insulation fault is necessary.
- The use of selective protections when the first fault appears is tricky.
- There are risks of overvoltages created by ferroresonance.

9.2.5. Surveillance and protections

The French Worker Protection Decree of 11 Nov. 1988 requires that the first insulation fault in a neutral arrangement IT must be detected. This first fault does not prevent the installation from operating but the standard requires it to be located and eliminated.

Permanent insulation monitor (PIM)

The PIM (e.g. Merlin-Gerin Vigilohm THR) permanently monitors the network's insulation level and indicates when it falls below a preset threshold.

Maximum residual voltage protection (ANSI 59)

This protection detects an insulation fault by measuring the neutral point shift. By using Multifunction relays, for example.

Maximum directional earth current (ANSI 67N)

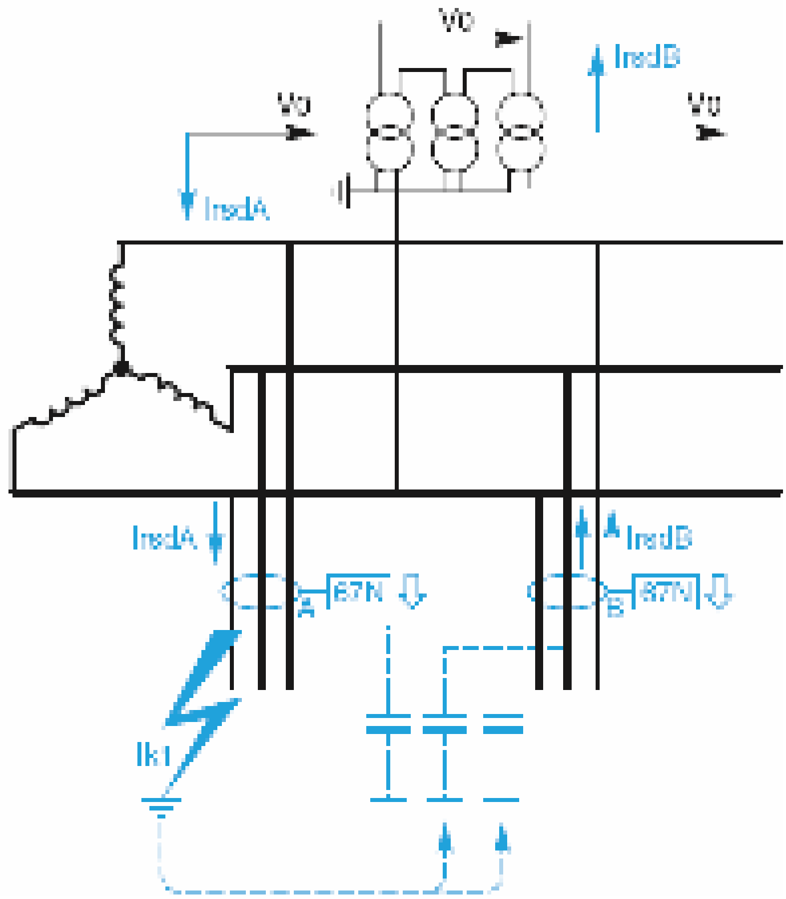


Figure 114: Detection by maximum directional earth current

This protection detects the faulty outgoing line (see figure).

The discrimination is made by comparing the phase shift angle between the residual voltage (V0) and the residual currents (Irsd), both of the faulty outgoing line and of each fault-free outgoing line.

The current is measured by a torus whose threshold is set:

- to avoid spurious trips,
- to a value less than the sum of the capacitive currents of all the other outgoing lines.

This makes detection difficult for small networks (a few hundred meters).

9.2.6. Applications

It is a solution often used for industrial networks (i 15 kV) requiring service continuity.

9.3. EARTHING VIA A RESISTOR

This arrangement limits the earth fault current and provides a good overvoltage flow, but it imposes a trip when a fault arises.

9.3.1. Schematic diagram

A resistor is voluntarily connected between the neutral point and earth.

9.3.2. Operating technique

In this type of arrangement, the resistive impedance limits the fault current to earth Ik1, while allowing a good overvoltage flow.

However, protections must intervene automatically to eliminate the first fault.

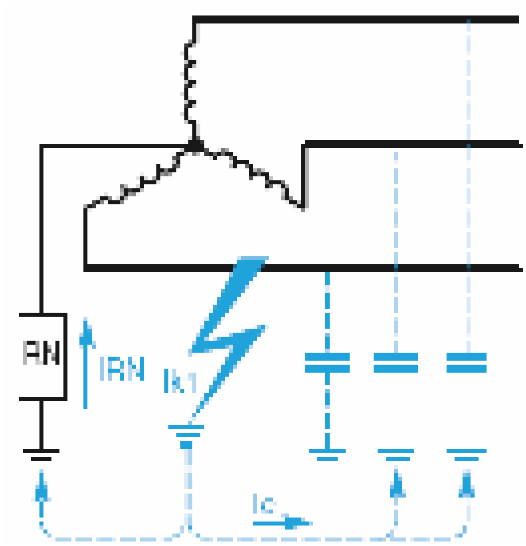


Figure 115: Earthing arrangements for accessible neutral: resistor inserted between neutral and earth

In networks supplying rotating machines, the resistance value is determined to obtain a current Ik1 of 15 to 50 A. But this low current must however validate IRN ≥ 2 Ic (where Ic: total capacitive current of the network) to reduce the switching overvoltages and allow a simple detection.

In the distribution networks, we adopt higher values (100 A to 300 A) which are easy to detect and allow the lightning pulses to drain away.

9.3.3. Advantages

- This arrangement is a good compromise between a low fault current and good overvoltage elimination flow.
- It does not require the use of equipment with an insulation level between phase and earth sized for the composite voltage.

- The protections are simple, selective and the current is limited.

9.3.4. Disadvantages

- The service continuity of the faulty outgoing line is not as good as with an isolated neutral: the earth fault must be eliminated (disconnection when the first fault appears).
- The cost of the earthing resistor increases with the voltage and the limited current.

9.3.5. Earthing the neutral point

Network neutral accessible

If the network's neutral is accessible (presence of star-coupled windings with accessible neutral), the earthing resistor can be connected:

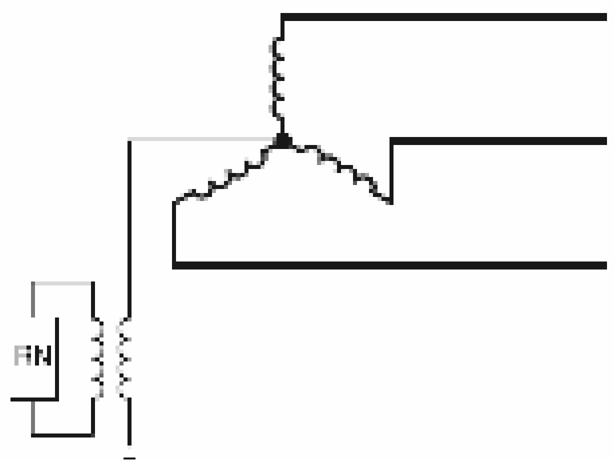


Figure 116: Earthing arrangements for accessible neutral: resistor connected to the secondary of a single-phase transformer

- either to the neutral and earth (see figure *"Earthing arrangements for accessible neutral: resistor inserted between neutral and earth"*)
- or via a single-phase transformer loaded at the secondary by an equivalent resistance (same figure as above).

Network neutral not accessible

When the neutral is not accessible (delta winding) or when the study of the protection plan demonstrates the advantage of it, we create an artificial neutral point by a **homopolar generator** connected to the busbars; this is done using a special transformer with a very low homopolar reactance:

- star delta transformer with primary neutral directly earthed, and the delta arrangement closed on the limiting resistance (LV insulation, thus less costly solution) (see left-hand figure)

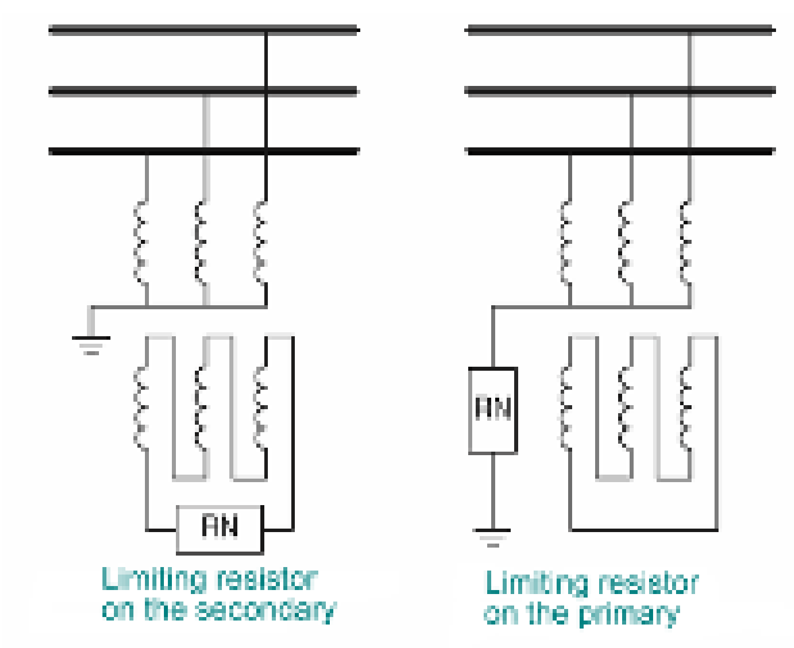


Figure 117: Earthing arrangements for inaccessible neutral

- star-delta transformer with limiting resistor (HVA insulation) between the neutral point of the primary and earth, and with the delta arrangement closed on itself; this solution is less often used (see right-hand figure).

Sizing the resistor

The resistor must withstand the permanent current flowing through it; it can be caused by an impedant fault or by a slight shift of the neutral point due to an imbalance of the capacitances of the network's 3 phases. We generally choose a permanent withstand value of Ip = Id/10 (Id = limiting current) for 2 to 5 seconds (greater than the maximum fault elimination time).

9.3.6. Protections

The detection of a low Ik1 fault current requires protections different from those for the phase overcurrent.

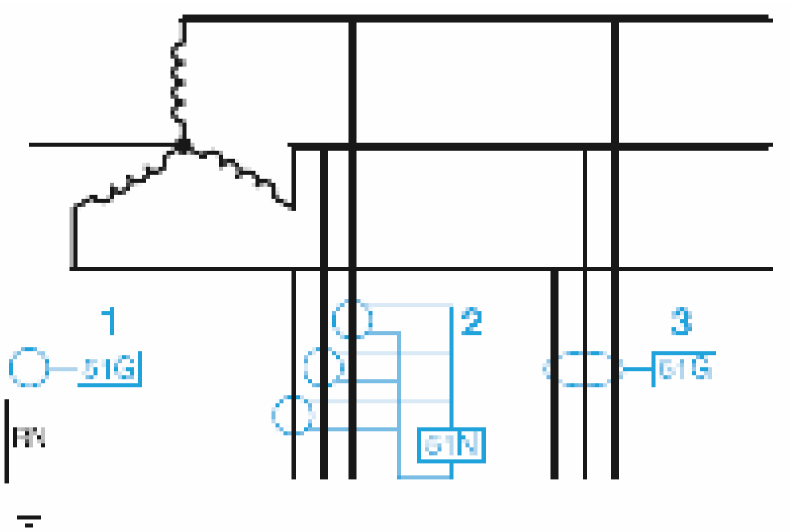


Figure 118: Earth protection solutions

These "earth" protections detect the fault current:

- either directly in the earthed neutral link **1**
- or on the network by measuring the vectoral sum of the 3 currents by using:

- either 3 phase-current sensors supplying the protections **2**

- or a torus **3**: precise measurement to be used in preference.

The threshold is set according to the fault current Ik1 calculated by neglecting the source and link homopolar impedances with respect to impedance RN and by considering the following 2 rules:

- setting > 1.3 times the capacitive I of the network downstream of the protection,
- setting of the order of 10 to 20 % of the maximum earth fault current.

In addition, if the detection is performed by 3 CTs, the setting is located (with today's technologies) between 5 and 30 % of the rating of the CTs to take into account the uncertainty due to:

- the asymmetry of the transient currents,
- the saturation of the CTs,
- the dispersion of the performances.

9.3.7. Applications

Public and industrial HVA distribution networks.

9.4. EARTHING BY LOW REACTANCE (IMPEDANT NEUTRAL)

This arrangement limits the earth fault current and provides a good overvoltage flow. But it requires a trip in the event of a fault with high values (e.g. 300 or 1000 A on the HVA neutral of the source HVB/HVA substations).

9.4.1. Schematic diagram

A reactance is voluntarily inserted between the neutral point and earth.

For networks with voltage greater than 20 kV, we prefer to use a reactance rather than a resistor due to the heat given off in the event of a fault.

Operating technique

In this type of arrangement, the inductive impedance limits the earth fault current Ik1, while allowing the overvoltages to drain away correctly.

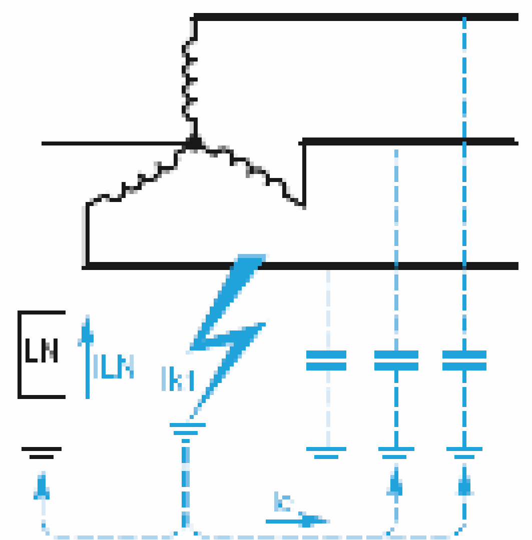


Figure 119: Earthing arrangements for accessible neutral

Therefore, the protections must automatically intervene to eliminate the first fault.

To reduce the switching overvoltages and allow a simple detection, the current ILN must be very much higher than the network's total capacitive current Ic. In distribution networks, we use high values (300 to 1000 A), which are easy to detect and allow the lightning overvoltages to drain away.

9.4.2. Advantages

- This arrangement limits the amplitude of the fault currents.
- It allows simple selective protections to be used if the limiting current is very much higher than the network's capacitive current.
- The coil, which has a low resistance, does not have to dissipate the high thermal power, which means that it can be smaller.
- In HVA, the cost of this solution is more advantageous than using a resistor.

9.4.3. Disadvantages

- The service continuity of the faulty outgoing line is not as good as with an isolated neutral: the earth fault must be eliminated (disconnection when the first fault arises).
- When eliminating earth faults, high overcurrents may appear which are due to resonances between the network's reactance and capacitance.

9.4.4. Earthing the neutral point

Accessible network neutral

If the network neutral is accessible (windings in a star arrangement with accessible neutral), the earthing resistor can be connected between neutral and earth.

Inaccessible network neutral

When the neutral is not accessible (delta winding) or when the protection plan study demonstrates the advantage of it, we use an artificial neutral point consisting of a **neutral point coil** (NPC) connected to the busbars; this is done using a zigzag coil with accessible neutral (see figure).

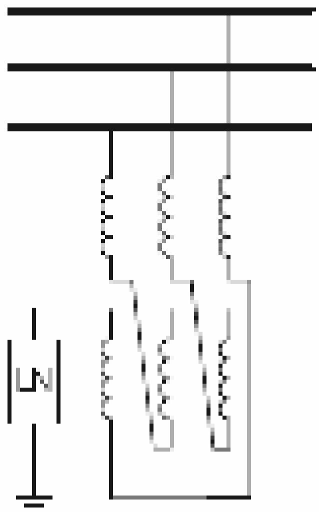


Figure 120: Earthing for inaccessible neutral

The impedance between the two parts of the winding, which is basically inductance and low, limits the current to values greater than 100 A.

The addition of a limiting resistor between the neutral point of the coil and earth reduces the fault current amplitude (HVA insulation).

Protections

- The protection is set to a level of 10 to 20 % of the maximum fault current.
- The protection is less restrictive than in the case of earthing via a resistor, and even more so because ILN is high since Ic is less than the limited current.

9.4.5. Applications

Public HVA distribution networks (currents of several hundred amps).

9.5. EARTHING BY COMPENSATING REACTANCE

(Compensated neutral)

This arrangement, called the "compensated neutral", is particularly well-adapted to HVA distribution networks with a high capacitive current Ic value.

9.5.1. Schematic diagram

A reactance tuned to the total phase-earth capacitance is inserted between the neutral point and earth so that if an earth fault arises the current in the fault is close to zero.

The reactance consists of (see figure) a resistor R in parallel with a variable inductance LN.

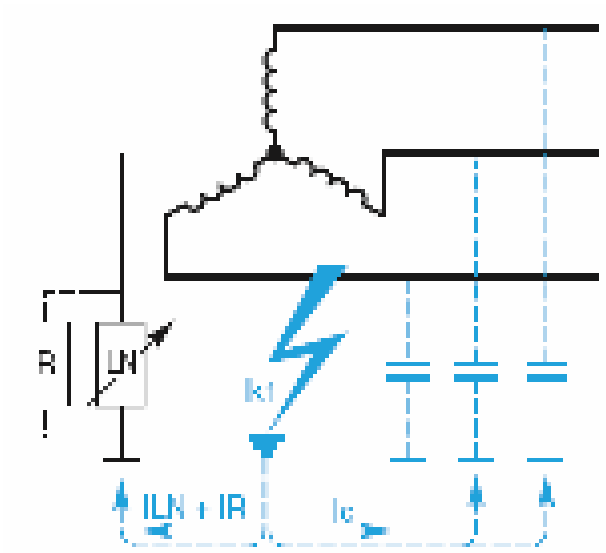


Figure 121: Earth fault in a network with earthing by compensating reactance

In the French distribution network:

- the resistor is called the fixed neutral point resistor (NPR), which provides an active current of 20 A minimum (straightforward fault)
- the inductance is called the variable neutral point coil (NPC).

9.5.2. Operating technique

This system compensates for the network's capacitive current.

The fault current is the sum of the currents which flow through:

- the earthing by reactance,
- the fault-free phase capacitors with respect to earth.

These currents compensate for each other since:

- one is inductive (in the earthing)
- the other is capacitive (in the capacitors of the fault-free phases).

They are just added to each other in phase opposition.

In practice, the low resistance value creates a small resistive current flow Ik1 of a few amps (see diagram).

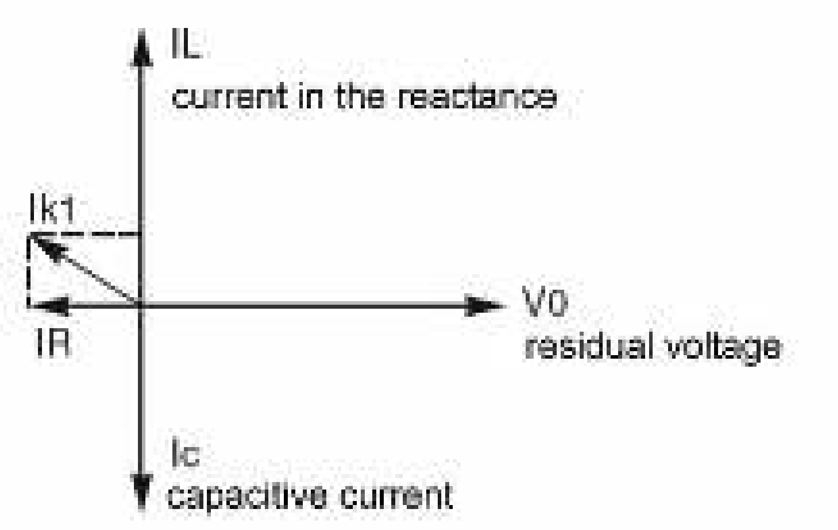


Figure 122: Vectoral diagram of the currents during the earth fault

In the French network, in the source station there is an automatic tuning system (ATS) which periodically adjusts the system to take into account the network's changing topology, the maximum authorised divergence is 40 A.

9.5.3. Advantages

- This system reduces the fault currents even if the phase-earth capacitance is high: spontaneous extinction of the non-permanent earth faults.
- At the fault location, the contact voltages are limited.
- The installation is maintained in service in spite of a permanent fault.
- The indication of the first fault is given by the detection of the current passing through the neutral point coil.

9.5.4. Disadvantages

- The cost can be high due to the necessity to modify the reactance value to adjust the compensation.
- During the fault time, we must ensure that the residual current flowing does not represent a hazard for persons and property.

- The risks of transient overvoltage on the network are high.
- The implementation of selective protections on the first fault is delicate.

9.5.5. Protection

The fault detection is based on the residual current's active component.

The fault causes residual currents to flow throughout the network, but a resistive residual current only flows through the faulty circuit.

Also, the protection devices must take account of the repetitive self-extinguishing faults (recurrent faults).

When the network's earthing reactance and capacitance are tuned (**$3 L_N C \omega^2 = 1$**)

- the fault current is at its minimum,
- it is a resistive current,
- the fault is self-extinguishing.

The reactance is then called an **extinction coil**, or a **Petersen coil**.

9.5.6. Use of the compensated neutral in France

Reasons and advantages

The compensated neutral arrangement is used in France by the distributors on part of the HVA network.

It controls the overvoltage levels of the HVA and LV earth connections during the phase-earth faults to take better account of:

- the changes in the European standards (safety of persons aspect),
- the increased sensitivity of certain loads (computer system loads, proximity of telecommunications networks),
- the insulation level of the HVA and LV equipment (e.g. HVA/LV transformer).

The compensated neutral arrangement improves the quality of the energy supply because it reduces the number of short interruptions by:

- increasing the level of transient faults ("self-extinction" of the fault without action of the upstream protection),

- reducing the number of developing faults, phase-earth faults which develop into faults between phases.

Possible problems with the present arrangements

Before 2001, which was the beginning of the deployment of the compensated neutral, the HVA network basically used 2 neutral point arrangements limiting the earth fault current to:

- 300 A for overhead - buried networks (urban and periurban),

- 1000 A for buried networks (urban networks).

Since a major part of the 20 kV overhead network was buried to improve the supply, this created two types of problems linked with:

Insufficient limiting of earth faults

The earth resistances of the HVA structures of the overhead networks can reach a value of 30 to 60 Ω. In the case of a straightforward earthing fault the sum of the capacitive currents of all the source station's outgoing lines (around 3A/km for 20kV cables) is added to the fault current (300 A or 1000 A limiting current).

With the added lengths of the buried cables, this total capacitive current sharply increased, making the limiting insufficient.

Increase in potential of the HVA and LV equipment grounds

When an earth fault appears near or in an HVA/LV station, the fault current creates a potential increase in the earth connections. The higher the network's overall homopolar capacitance, the higher this potential.

The increase in cable lengths will thus increase the potential increase with repercussions on the clients by:

- possible arcing of the HVA to the LV leading to the flow of an earth fault current in the LV neutral,

- coupling of the earth connections of the LV clients or of the LV neutral with the HVA/LV station's earth connection, thus generating overvoltages.

The use of a compensated neutral arrangement on networks presenting these risks reduces the earth fault current and this rise in potential.

Compensation method used

The neutral is earthed by a variable compensation impedance (VCI) and its automatic tuning system (ATS). The fault current is very low (< 40 A), the arc voltage perpendicular to the fault is minimal, which allows the dielectric insulation to be spontaneously re-established ("self-extinguishing" fault).

9.5.7. Consequence of using the compensated neutral on HVA stations

With the compensated neutral point arrangement, the **Wattmetric Homopolar Protections** - **WHP** (67N) complete the Maximum residual current protections (51N) at the level of:

- the outgoing lines of the source stations,
- the general NF C13-100 protections,
- the part of the HVA installation which may be dependent on NF C 13-200 standard.

Depending on the network supplied by the source station, 3 cases may arise:

- Underground network (urban station): the present neutral point arrangement is retained, limited neutral 300 A or 1000 A.
- Overhead - underground network majoritarily underground (mainly periurban station): modification of the current neutral point arrangement by the addition of a fixed coil in the neutral point to limit the current to 150 A. This change has no effect on the C 13-100 protection or on the HVA client's protections.
- Overhead - underground network majoritarily overhead (mainly rural stations): modification of the current neutral point arrangement to change to compensated neutral point arrangement. In this case a Wattmetric Homopolar Protection WHP(1) protection is necessary at the level of the HVA delivery station.

This change is summarised in the following tables.

<table>
<tr><th colspan="3">Impact on the general C 13-100 protection</th></tr>
<tr><td colspan="3">delivery station with LV metering: protection by fuses unchanged</td></tr>
<tr><td colspan="3">delivery station with HVA metering with general protection by circuit breaker: depending on the case</td></tr>
<tr><th>supply of the station</th><th>without auxiliary supply</th><th>with auxiliary supply</th></tr>
<tr><td>relay to be installed</td><td>- existing relay retained (function 51 only)
- addition of a relay performing functions 51N and WHP</td><td>- replacement of the existing relay by a relay performing functions 51, 51N and WHP</td></tr>
<tr><th colspan="3">impact on the HVA installation's "earth" protection plan C 13-200</th></tr>
<tr><td rowspan="3">installation type</td><td>non-sensitive application</td><td>sensitive application (process industry, hospital, etc.) outgoing line</td></tr>
<tr><td>fused switch protection outgoing lines</td><td>HVA circuit breaker protection</td></tr>
<tr><td>local HVA network</td><td>large area HVA network</td></tr>
<tr><td rowspan="3">protection plan</td><td>- keep the 51N in place</td><td>- addition of 67NC on the outgoing lines</td></tr>
<tr><td>- addition of 51N on fused switch outgoing lines</td><td>- configure 51N with the normal settings (selective with 51N of the C13 100 general protection)</td></tr>
<tr><td>- logic or time selectivity</td><td>- logic or time selectivity</td></tr>
<tr><td>impact on sensors</td><td>- protection on torus (improved sensitivity)</td><td>- protection on torus, otherwise sum of 3 CTs + torus
PT for the Vresidual measurement, (PT with 2 secondary windings: 1 protection and 1 metering)</td></tr>
<tr><td>products</td><td>- Torus and RCD relay on fused switch outgoing lines</td><td>- Multifunction relays (applications with 67N)
- Multifunction relays (specific application)</td></tr>
<tr><td>remarks on selectivity</td><td>Partial selectivity on:
- resistive faults
- recurrent faults (non-detection)</td><td>Total selectivity with C 13-100 protection, and with the source station according to the configuration of the 67N</td></tr>
<tr><td colspan="3">1) WHP: With the compensated neutral point arrangement, the residual current in the faulty outgoing line can be lower than the capacitive current in the fault-free outgoing lines. It becomes impossible to use maximum residual current protections. The use of earth directional protections provides an insensitivity to the capacitive current flowing in the fault-free outgoing lines.</td></tr>
<tr><td colspan="3">It thus authorises a sensitive setting to detect the residual current's active component which is only present in the faulty outgoing line. However, the directional criterion is insufficient, the protection must be capable of detecting the recurrent faults characterised by a series of short restriking overvoltages.
The WHP (67N) integrates the earth directional and the recurrent fault detection.</td></tr>
</table>

Table 25: Consequence of using compensated neutral on HVA stations

10. USING NEUTRAL POINT ARRANGEMENTS IN HV

I found this document "interesting" so I have added it as a bonus for anyone it may interest…

10.1. CONTEXT

An electric power network's performance depends on the way in which it is designed, constructed, maintained and operated.

These networks were originally designed to meet the safety requirements for energy supply. Their design and their operation then consisted of finding the economic optimum to control the technical constraints.

Today, with the opening up of the market and the traditional distributors in competition with each other, the designers and operators must take into account the users' expectations and meet the requirements of the regulations and standards. In this context, since almost 80% of the faults are short-circuits to earth, the choice of the neutral point arrangement has become a strategic decision. It is now the result of a compromise between three requirements:

- Cost control;
- Safety of persons and property;
- Quality of service for the users.

To meet the safety and quality obligations, the engineer must design a coherent architecture. The voltage plan and short-circuit power of this architecture must be compliant with the expected quality of service. Its neutral point arrangement must be able to handle the constraints created by the homopolar imbalances. The whole assembly must be consolidated by a protection plan to quickly eliminate short circuits.

Since the choice of a power network's neutral point arrangement requires the use of coherent and costly technical measures, it is based on objective decision elements:

- role of the network,
- topology,
- short-circuit powers,
- expected services,
- respect for the obligations.

In addition, it must be closely associated with a safe and selective protection plan.

The network's architecture is chosen to meet the operating unknowns. In normal operating conditions or in disrupted operating conditions, the quality of the electricity product supplied by the network must be compliant with the agreements.

During a short-circuit to earth, the neutral point arrangement controls the rises in potential in the earth terminals, for example. It maintains the system of voltages coherent with the network's insulation coordination and the expected quality of service.

In addition, it guarantees the selective operation of the associated protection plan.

There are two ways to design a neutral point arrangement.

In Europe, we try to limit the values of the short-circuit currents to earth and we coordinate the insulation in the network's common mode.

In countries under Anglo-Saxon influence, we limit the dynamic overvoltage levels and we try to control the rises in potential of the earth connections. This solution is also widely used on networks supplying imbalanced loads.

However, there are cases where a standard solution (1) which has been tried and tested elsewhere cannot be used. We must also beware of technical, commercial and geopolitical influences. The choice of a neutral point arrangement must be the result of a coherence study.

(1) The neutral point arrangements used in continental networks may, for example, be unsuitable for certain insular networks.

10.2. MANAGEMENT OF THE NEUTRALS

The management of an electrical power network's neutrals is an operating task which consists of:

- finding the right compromise between controlling the short-circuit currents to earth and maintaining the earthing factor within a given interval;
- guaranteeing the method of connecting the neutral to the earth;
- establishing the operating arrangement of the network's neutrals which guarantees that the protection plan functions at all times.

We usually classify the neutral point arrangements according to their method of connection to earth. However, we must not confuse the neutral point arrangement and the neutral's earthing system (2)

(2) Impedant neutral and neutral impedance, for example.

Isolated neutrals.

The network's neutral is physically isolated from earth. However, there is a virtual link consisting of the network's transversal homopolar capacitive reactances.

Directly earthed neutrals.

The network's neutral can be distributed or not.

- In the first case, there is a neutral conductor which interconnects the network's earth connections. The homopolar imbalance current is then shared between the earth and the neutral conductor.
- In the second case the network's neutral is only earthed at the source. The homopolar imbalance current only transits via the earth.

Impedant neutrals.

At the source, the neutral is connected to earth via an impedance. With the exception of the interconnected networks, other earthing points are generally not admissible.

Due to its method of connection, the compensated neutral belongs to the category of impedant neutrals. However, the operation of the electrical system is very close to that of the isolated neutral.

10.3. NEUTRAL POINT ARRANGEMENTS AND THEIR CONNECTION METHOD

These two classification methods must be differentiated.

If a homopolar imbalance is present, the network's operation is fixed by the neutral point arrangement. This neutral point arrangement depends on three parameters:

- the method of connecting the neutral to earth;
- the homopolar capacitance value;
- the profile of the network's short-circuit powers.

The neutral point arrangement is defined by an indicator called the "**Earthing factor**" which takes into account these parameters.

A neutral connected to the earth via a 40+40j impedance will, in Europe, provide an impedant neutral point arrangement whereas with the same configuration, an insular network in Polynesia will behave as a directly earthed neutral point arrangement.

10.4. NEUTRAL POINT ARRANGEMENTS AND THE ELECTRICAL SYSTEM

10.4.1. Parameters

Let us consider a single-phase short circuit on an HVA network whose neutral is earthed via the power transformer. In our example, there is no connection between the homopolar impedances of the 63 kV and 20 kV networks.

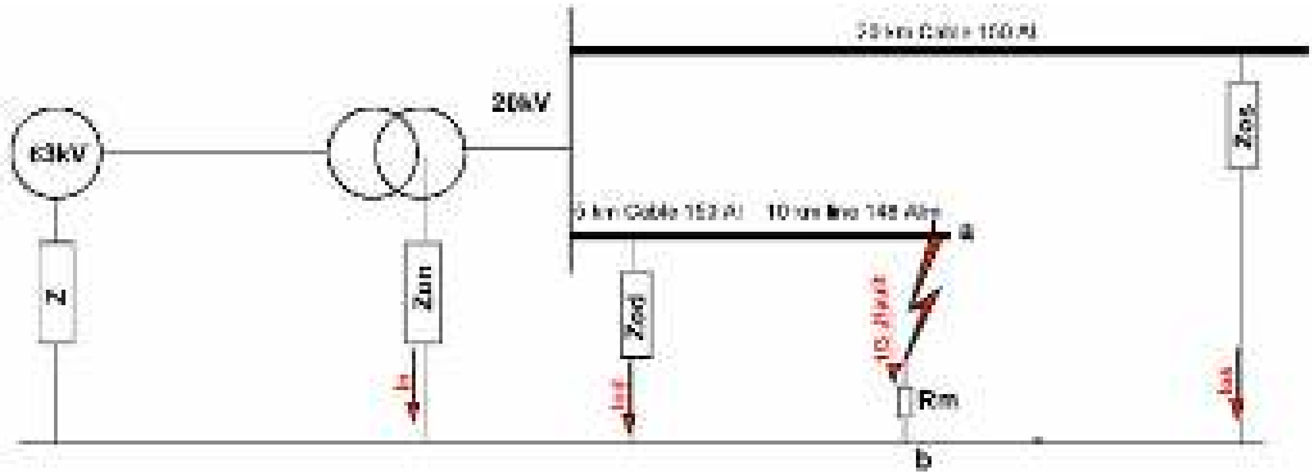


Figure 123: Short circuit on HVA network

At the fault location, the parameters are represented in the equivalent diagram.

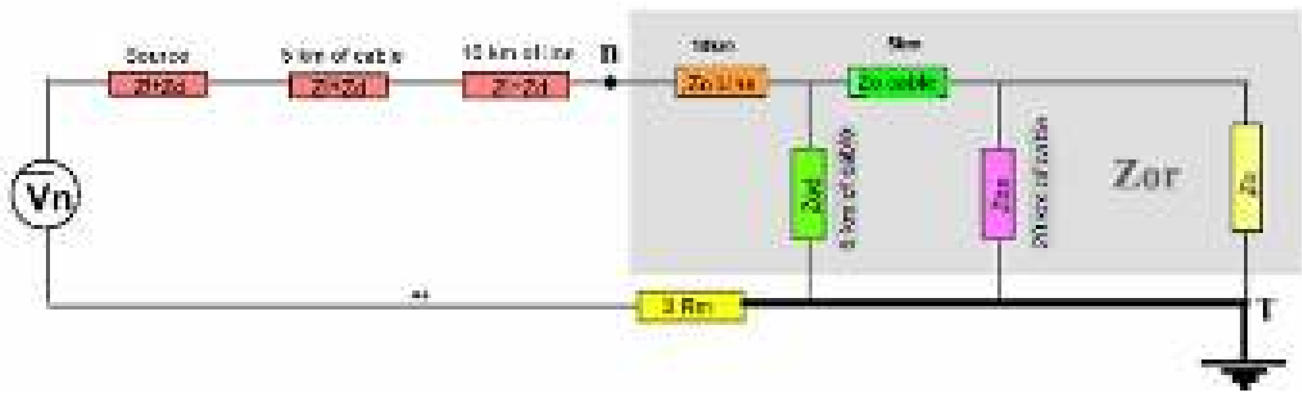


Figure 124: Short circuit on HVA network - equivalent diagram

Zo is the homopolar impedance of the physical device for earthing the network's neutral.

Zod and Zos correspond to the network's homopolar capacitances.

Zo line and Zo cable are the longitudinal homopolar impedances of the faulty output line.

All these impedances form the network's homopolar impedance (Zor)

$\overline{Zd} = \overline{Zd}_{source} + \overline{Zd}_{cable} + \overline{Zd}_{ligne}$ is the direct impedance of the network. It is approximately equal to the inverse impedance Zi of the network *(Zd # Zi if the fault location is electrically close to production units).*

The ratio $F = \frac{Zo}{Zd}$ is the network's earthing factor

It strongly depends on the neutral point arrangement.

- Isolated neutral → F > 300
- Directly earthed neutral → F ≤ 3
- Impedant neutral 3 < F < 300

If there is a homopolar imbalance, the network's performance depends on this factor.

Knowing this factor allows the dielectric constraints at the fundamental frequency to be evaluated as well as the performance of the protection plan.

10.4.2. Imbalances

10.4.2.1. Description

These are caused by short circuits and dissymmetrical loads. When they are present the balance of the electrical values in play is modified.

The homopolar imbalance affects the simple voltage system. It modifies the efficiency of the single-phase loads. A homopolar imbalance induces inverse imbalance.

The inverse imbalance affects the composite voltage system. It disrupts the efficiency of the loads connected between phases.

The value of the inverse imbalance induced by the homopolar imbalance depends on the electrical system's neutral point arrangement (*). The lower the short-circuit power and the higher the dissymmetrical load, the higher the inverse component level.

(*) The size of the inverse imbalance thus depends on the fault current value. It follows that a high earth fault current is likely to create a high inverse imbalance. This will be the case, for example, of a fault affecting a network with directly earthed neutral.

Finally, to clarify the concepts of inverse imbalance and homopolar imbalance, we will look at some examples

Example 1: Load imbalance on a low voltage network with distributed neutral.

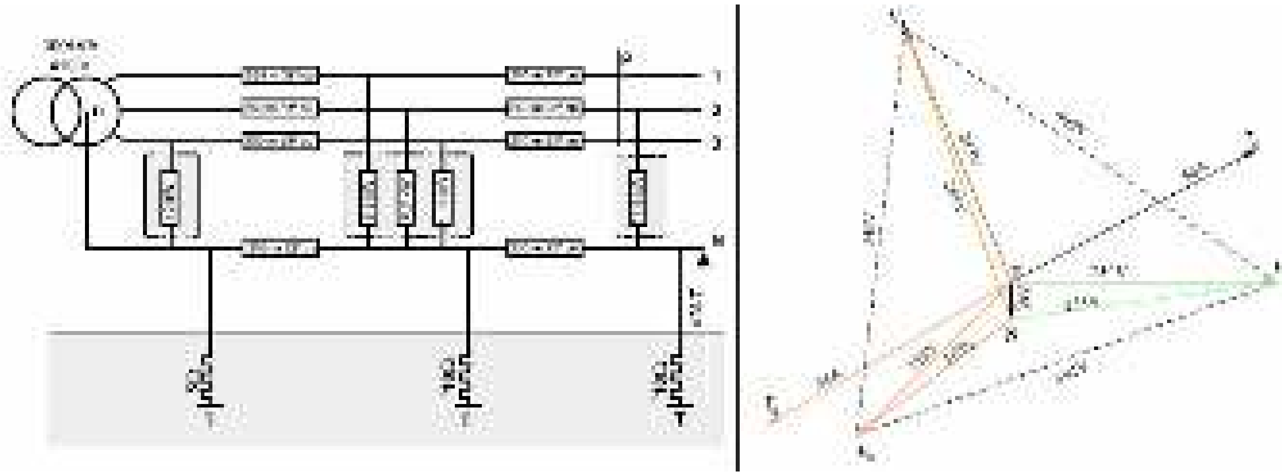


Figure 125: Load imbalance – LV network – distributed neutral

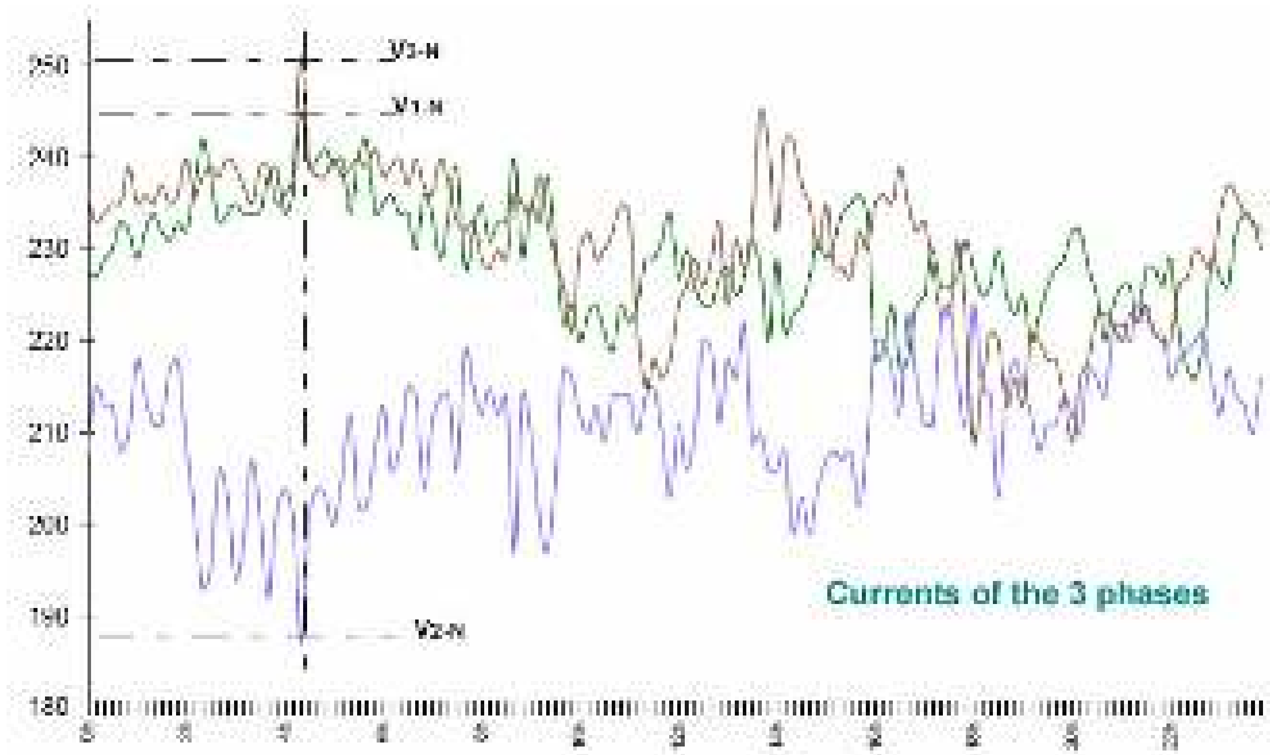
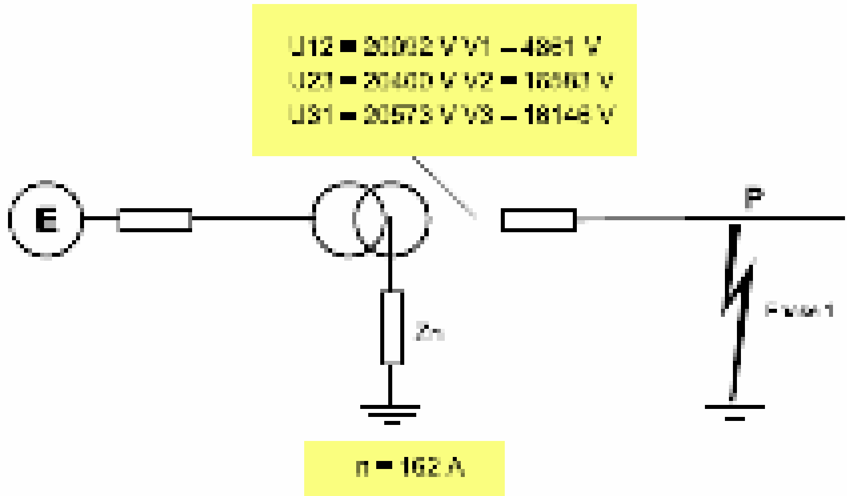


Figure 126: Change in current on each of the phases over time

There is a current in the neutral and a displacement of the neutral point V_{N-T}.
The balance of the simple voltages is affected. A homopolar imbalance is present.

The composite voltages are slightly imbalanced, there is also a slight inverse imbalance in the network.

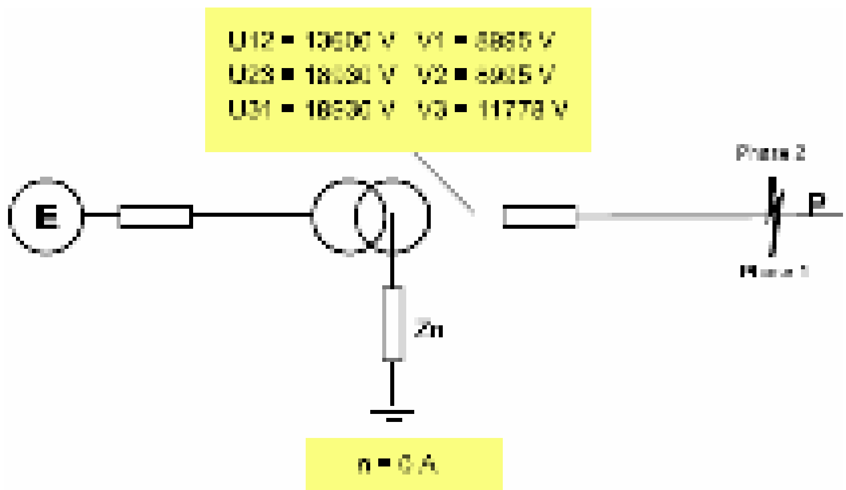
Example 2 :Short circuits on a 20 kV network.

<table>
<tr><th colspan="2">Single-phase short circuit</th></tr>
<tr><td>
</td><td>This is a homopolar imbalance

The simple voltages are imbalanced.

There is a current in the neutral.

The composite voltages are less imbalanced.

There is thus a slight inverse imbalance.</td></tr>
<tr><th colspan="2">Two-phase short circuit</th></tr>
<tr><td>
</td><td>This is an inverse imbalance

The composite voltages are highly imbalanced.

This results in an imbalance of the simple voltages.

There is no current in the neutral.

There is thus no homopolar imbalance.</td></tr>
</table>

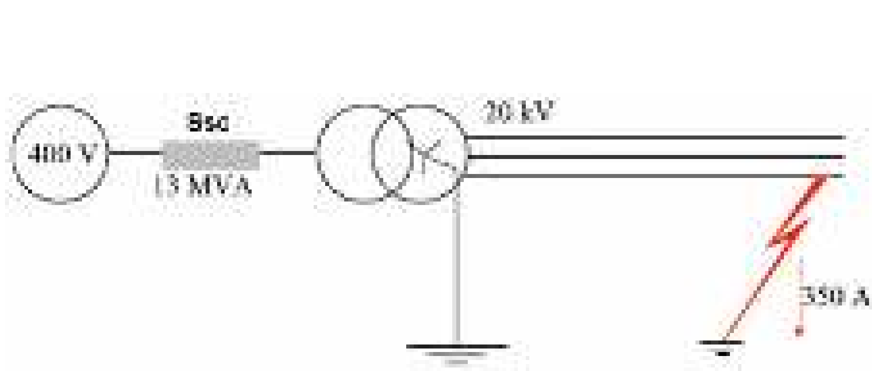
Table 26: Short circuits on a 20 kV network

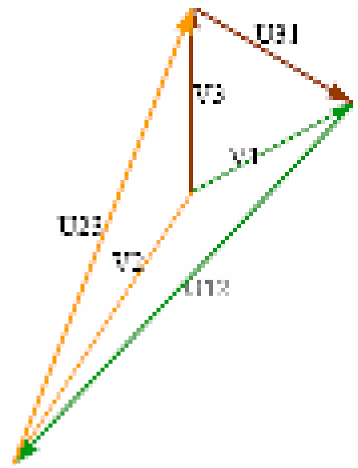
In conclusion: A homopolar imbalance is identified by the presence of homopolar components the amplitude of which depends on the choice of the neutral point arrangement.

10.4.2.2. Action of the neutral point arrangement on the imbalances

Let us consider the case of an insular network with very low short-circuit power and let us examine the performance of the electrical system when there is a single-phase short circuit.

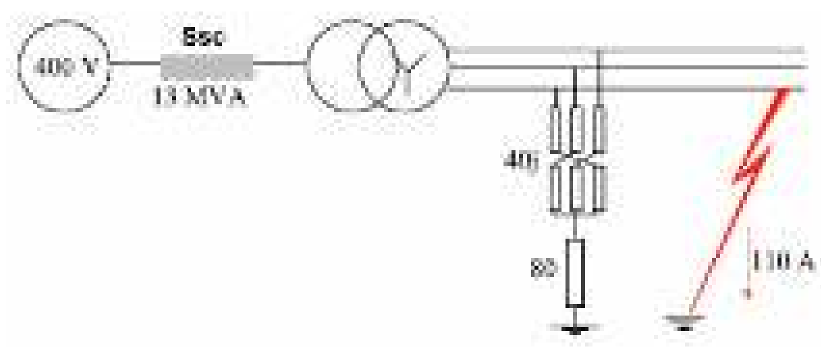
The 20 kV neutral is directly earthed

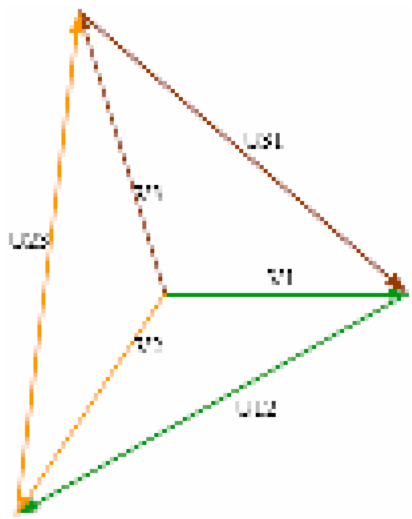




The inverse component level at the terminals of the 400V generators is 32 %.
The fault current is 350 A.

We install an 80+j40 Ω impedance





The inverse component level at the terminals of the 400V generators is 10 %.
The fault current is 110 A.

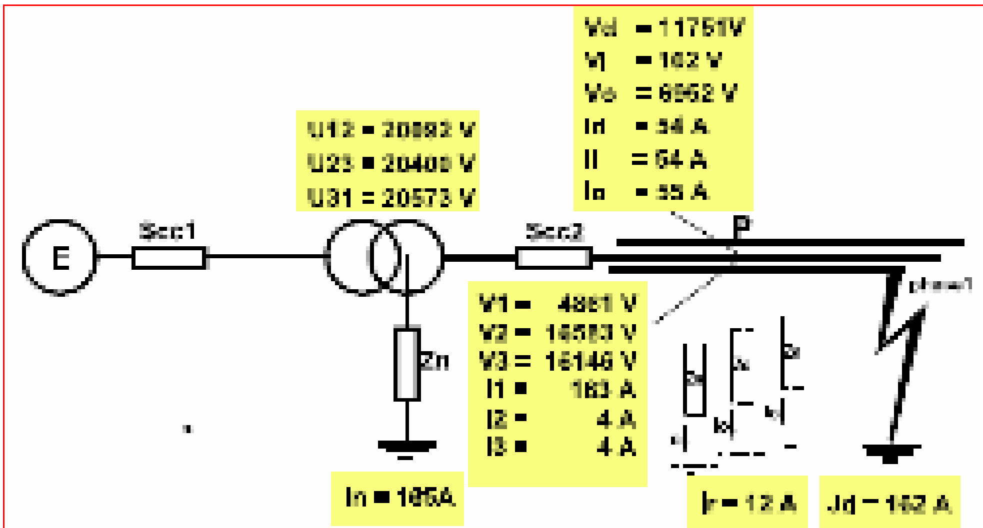
Table 27 Action of the neutral point arrangement on the imbalances

In conclusion: By increasing the network's homopolar impedance we reduce the fault current value and the inverse component level.

10.4.3. Dynamic overvoltages

They are created by the homopolar imbalances. Since they only last for the time of the event, they depend on the neutral point arrangement and the amount of homopolar imbalance.

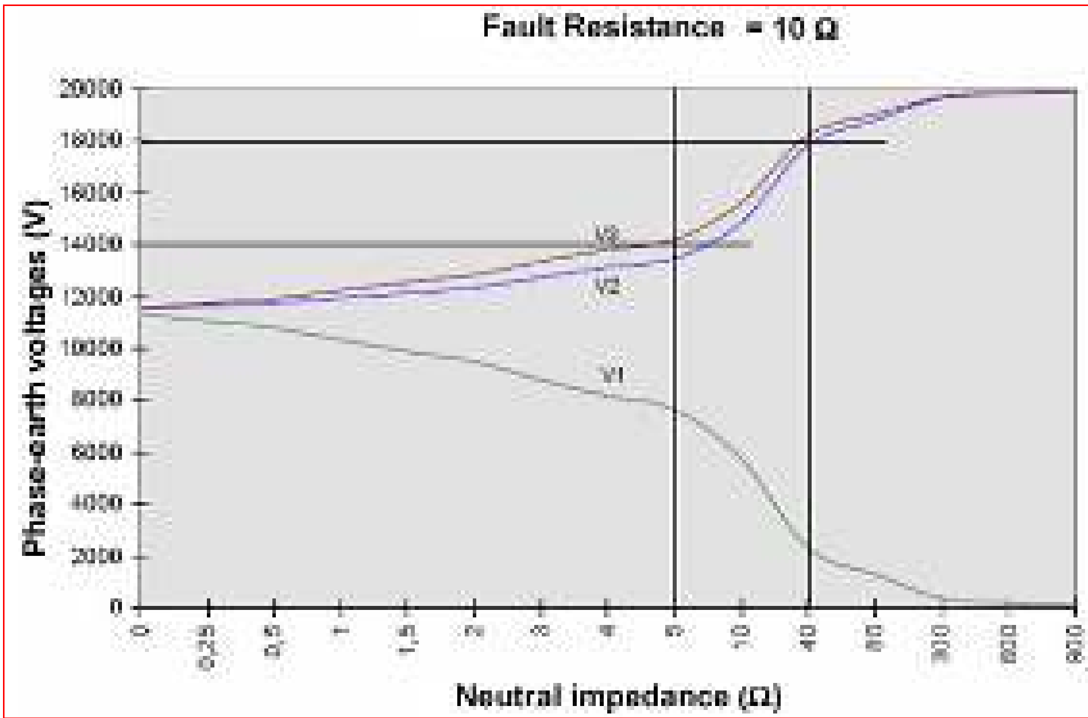
Let us examine the case of a single-phase fault affecting phase 1 of a 20kV network.



The simulation shows that there is an overvoltage on phases 2 and 3. Voltage V1 is equal to the increase in potential of the earth connection at the fault location. The composite voltages are only slightly modified. The neutral point is displaced.

Figure 127: Single-phase fault on a 20 kV network

Let us fix the fault resistance value at 10 Ω and vary the neutral's earthing impedance.



The dynamic overvoltages greatly increase from a neutral point impedance of 5 Ω. For this value, the earthing factor F is equal to 3.

Figure 128: Overvoltages according to the neutral's earthing impedance

The dynamic overvoltage values appearing on the fault-free phases at the fault location depend on the value of the earthing factor at this point.

When an Operator wishes to control the dynamic overvoltages on a network, he must maintain the earthing factor at a value less than 3 (*).

(*)We consider that a network's neutral is directly earthed if, at all points, F ≤ 3. For this value, the overvoltages are limited to 1.4 times the network's simple voltage.

10.4.4. Homopolar capacitance

This is the current derived by the homopolar capacitive reactances of the lines and cables.

The homopolar capacitive current amplify the fault currents and are likely to disrupt the protection plan selectivity.

For a ratio $\frac{Zo}{Zd} \geq 1.4$ the homopolar capacitive current is close to its maximum value.

The IEC 909 standard specifies that the homopolar capacitances must be taken into account in the studies if the earthing factor is greater than or equal to 1.4.

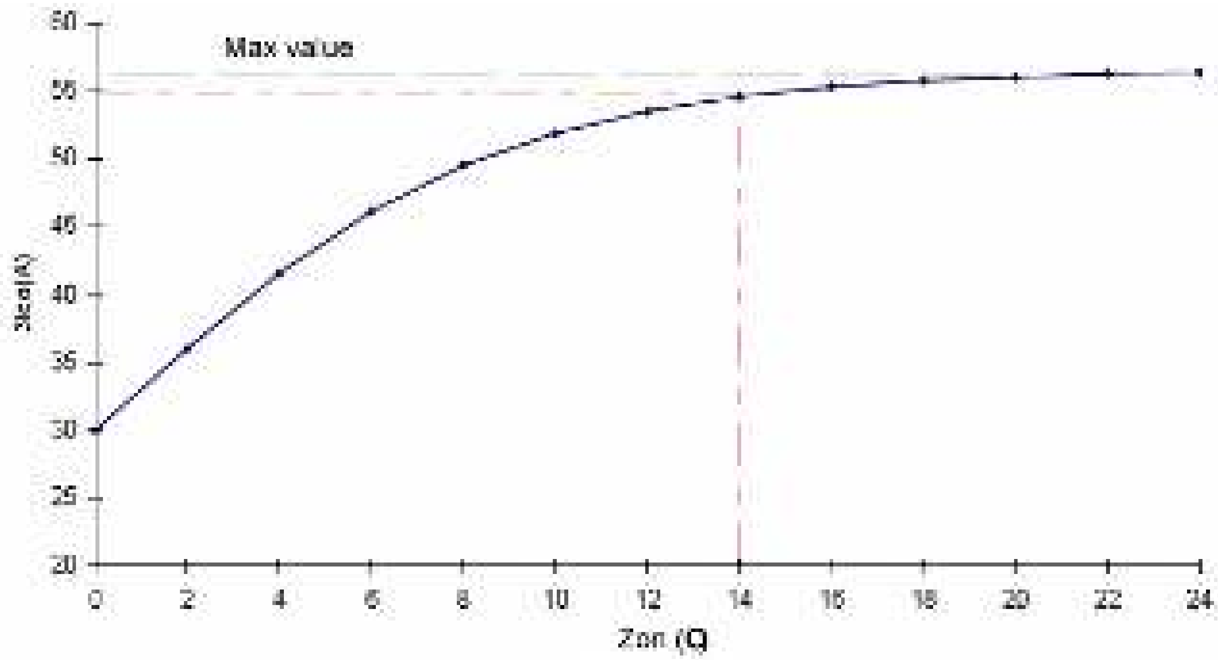


Figure 129: Network homopolar capacitance 3Ico=f(Zon) for Zd= 10j

10.4.5. Fault currents

We have seen that the fault currents depend on the neutral point arrangement. In the case of the directly earthed neutral (F ≤ 3) the network performance, in the presence of a homopolar imbalance, has a specific feature which we will now examine.

Let us consider a 20 kV network. We study the earth fault current for a two-phase earth fault. We compare this current to that produced by a single-phase fault for different values of F (see figure).

When the earthing factor is less than 1 (North American networks), the maximum earth fault current is obtained for a two-phase short circuit to earth.

The ratio of the fault currents to earth varies greatly with the value of the earthing factor (see figure).

$$2 > \frac{J_{2-phase\ fault}}{J_{\sin gle-phase\ fault}} > 0.5$$

The Operator must take these properties into account when adjusting the protections against insulation faults to ground (switchboard, tank, etc.) and for sizing the earth circuits.

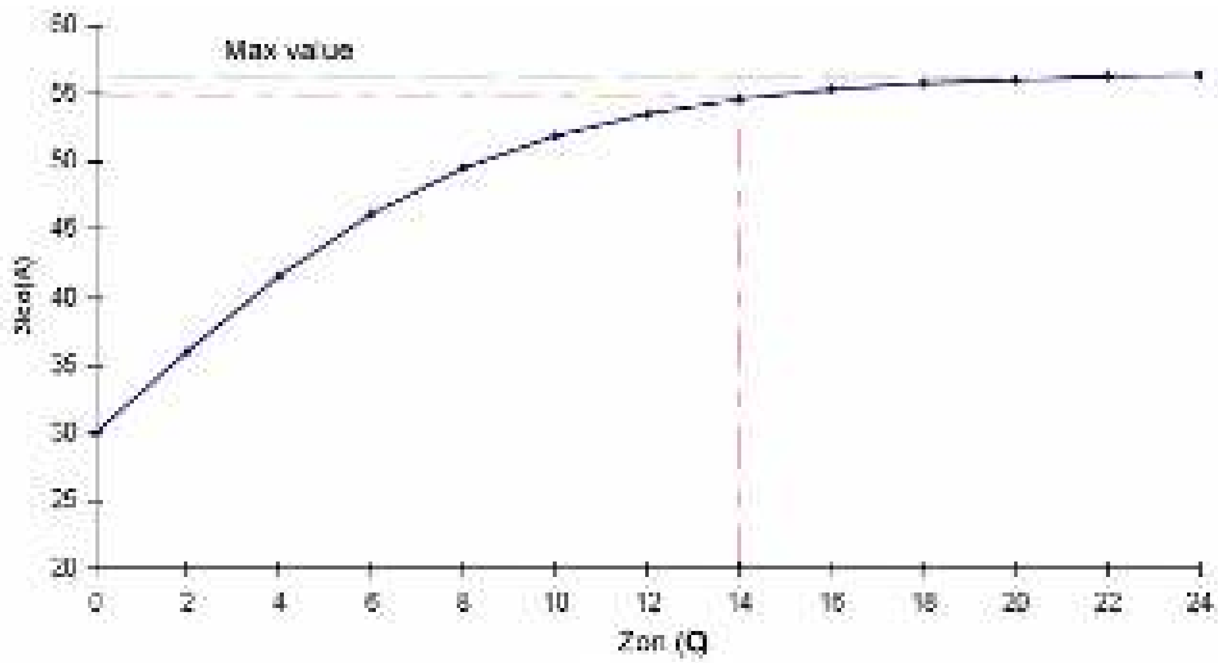


Figure 130: Earth fault current Jfault= g(F) on a 20kV network (Psc= 200 MVA)

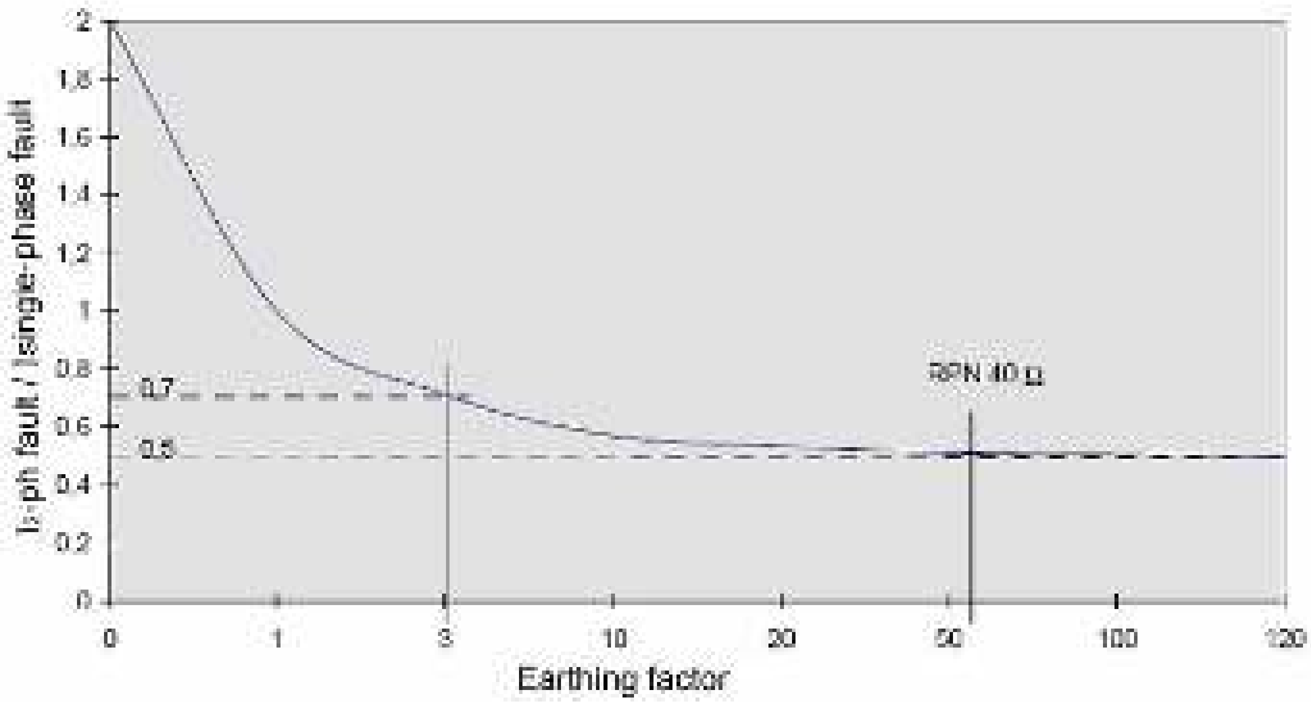


Figure 131: Ratio of the earth current values

10.5. EQUIPMENT FOR EARTHING THE NEUTRALS

10.5.1. Transformers

The table summarises the use of the different transformers.

Neutral point arrangement		Coupling	Uses
Direct or slightly impedant neutral	F ≤ 3	**Δ.yn**	Generator set transformer Low voltage distribution
	F ≤ 3	**Y.zn,** Yn.zn	Low powers
	F ≤ 1	**Y.yn.d**	HVA, HVB, VHV Interconnection North American networks
Moderately or highly impedant neutral		**Yn.yn Forced flow** and all couplings	All voltage levels and all powers

Table 28: Uses of the different neutral earthing transformers

10.5.2. Neutral point resistances

When we wish to greatly limit the current in the network's neutral, we often use a neutral point resistor connected between the network's neutral and earth.

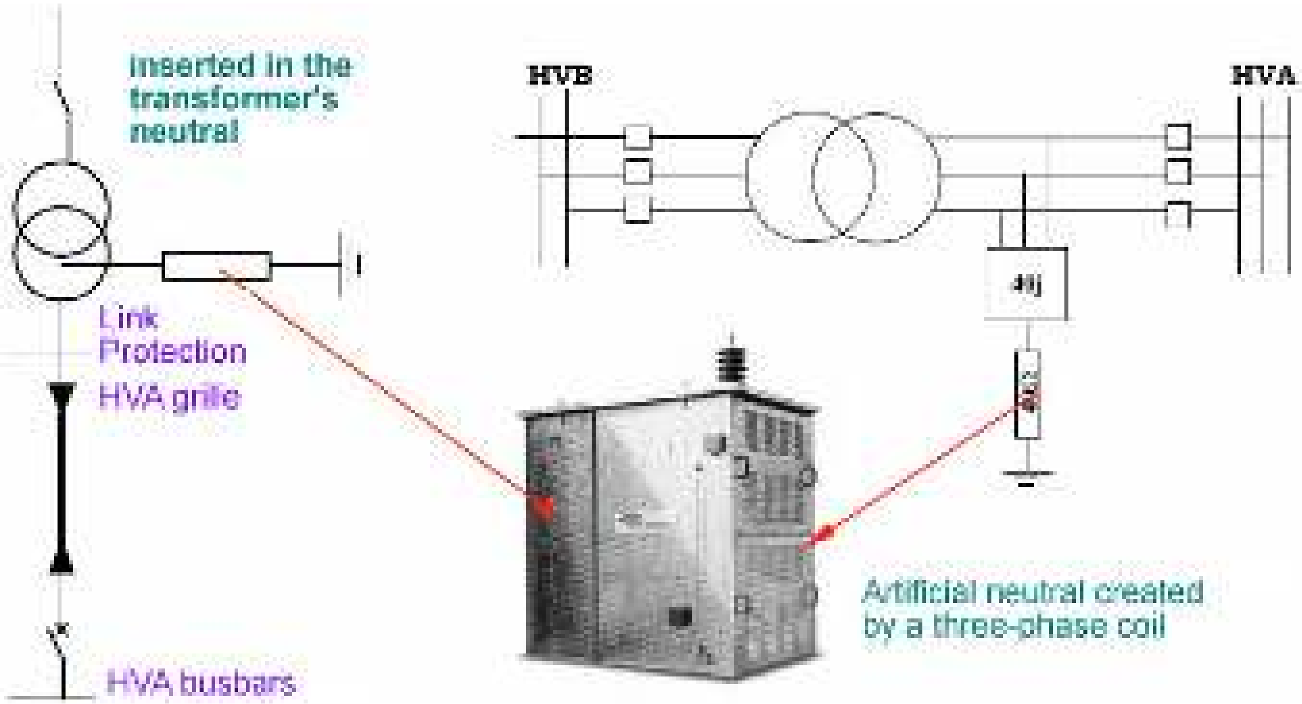


Figure 132: Neutral earthing resistor

10.5.3. Neutral point inductances

An inductance is defined by its thermal resistance and by the maximum admissible continuous current. It must also resist the dynamic effects of the fault currents.

If a high homopolar capacitance is present, the use of a pure inductance risks causing a malfunction of a protection plan consisting of maximum residual current relays. Such a practice is reserved for majoritarily overhead networks or when we have a very low impedant neutral point arrangement (*).

(*) The British HVA networks use these devices to limit the current in the neutral to 4000 A.

10.5.3.1. Single-phase inductances

They are inserted in the transformer neutral earthing connections. Compared to the resistors, they have the advantage of being more robust, smaller and low-maintenance. Their operating cost is much lower.

The simplest of these consists of a solenoid wound around a non-magnetic support.

To be able to install these inductances on the ground while guaranteeing the safety of persons, the inductance can be immersed in a tank filled with a dielectric liquid.

Figure 133: Example of single-phase neutral point inductance

The attachment devices then consist of magnetic shunts whose job it is to preserve the tank from the circulation of the flux produced by the coil.

10.5.3.2. Three-phase inductances

The best-known of these is the zigzag coil.

These devices are installed in priority when we wish to:

- limit the amplitude of certain disturbances,
- eliminate the homopolar coupling between two networks connected to a same transformer,
- earth the neutral at the level of the busbars.
- etc.

In a highly capacitive network, a neutral point resistor must be inserted in the neutral's earthing connection.

Figure 134: Example of three-phase neutral point inductance

When correctly sized, this combination has the advantage of partially compensating the network's homopolar capacitance and of being able to be associated with a protection plan consisting of homopolar current relays.

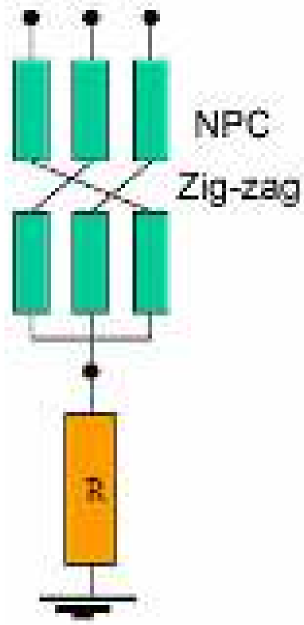


Figure 135: Connection of a zigzag three-phase inductance

Operating principle

The figure shows a single-phase fault affecting a 20 kV network.

The neutral earthing consist of a j40 Ω inductance with a quality factor of 6.

The homopolar impedance of such a device is: Zo=20+120 j.

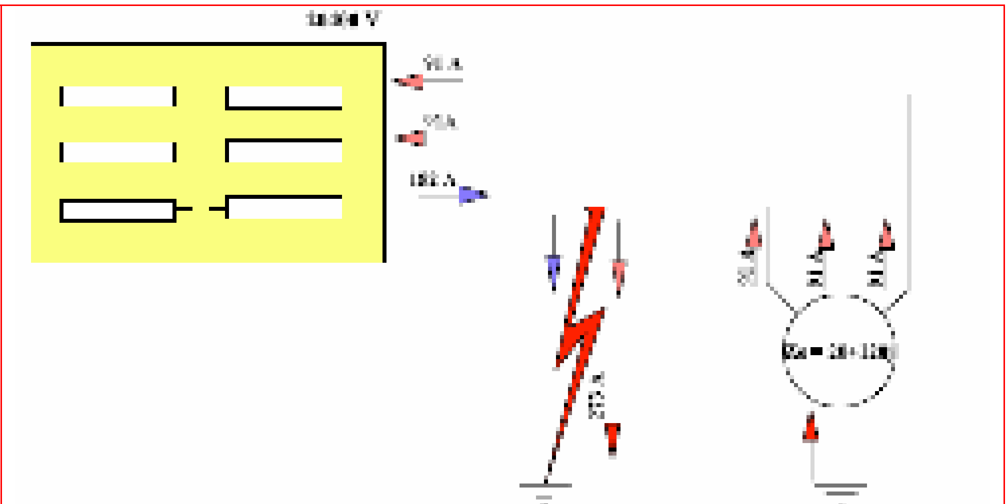


Figure 136: Single-phase fault on a 20 kV network with neutral three-phase inductance

The system behaves like a homopolar current generator.

10.5.3.3. Homopolar generators

To limit the extent of the damage caused to production units by equipment ground faults, the Operators limit the earth fault currents to around 10 Amps. They often use a device connected to the main distribution busbars, this device is incorrectly called a "homopolar generator" (*).

(*) This term is often given to all the devices used to create an artificial neutral point.

Transformer with a delta-coupled winding loaded by a resistor. The assembly thus behaves like a resistor.

The CT placed in the neutral's earth supplies the stator ground protection of the generator sets connected to the busbars.

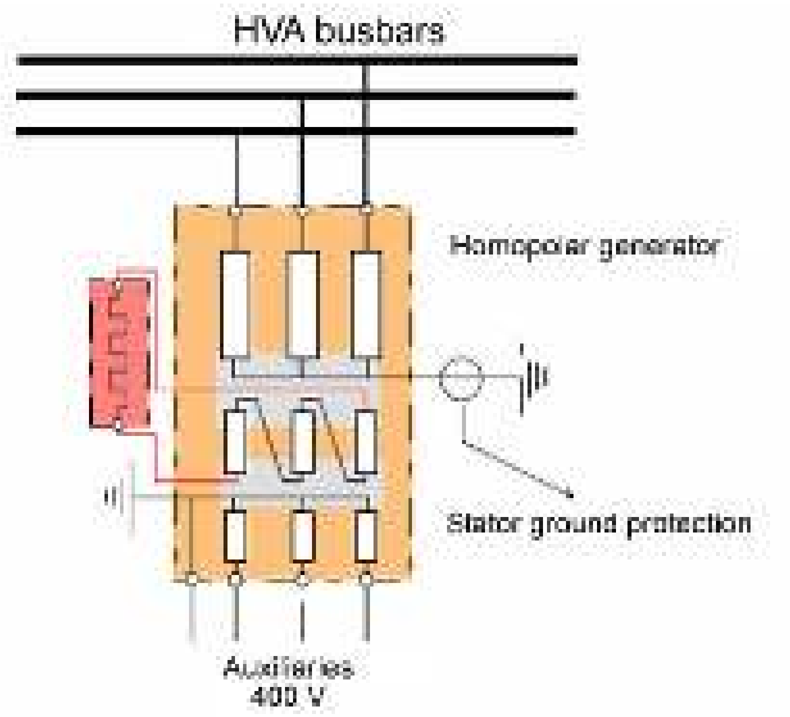


Figure 137: Homopolar generator

This device must have a free flux magnetic circuit or consist of three single-phase power transformers. Voltage transformers are also used.

In this last case, the homopolar generator can supply the measurement and protection circuits. The device can have a star-coupled tertiary device to supply the auxiliaries. (However this solution is not recommended).

10.5.3.4. Compensation impedances

Principle

The principle of the extinction coil was presented by Professor PETERSEN at the beginning of the 20th century. It consists of inductances tuned to the network's capacitance and associated with a high-value resistor.

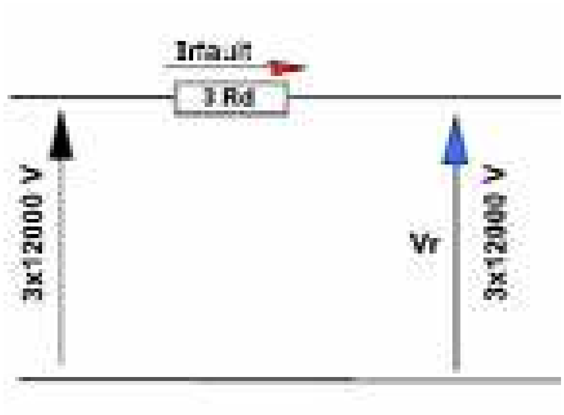


Figure 138: Compensation impedance – schematic diagram

When tuned, the network's homopolar impedance is fixed by the value of the resistor.

The fault current is then very low (15 to 40 A).

With the reserve that it is correctly tuned to the network's homopolar capacitance, an extinction coil, by its action on the amplitude of the fault current, provides the following functions:

- It converts some transient faults into self-extinguishing faults.

- It reduces the earth connection potential rises.

Figure 139: Petersen compensation coil (Alstom)

The performance of the network with a compensated neutral is very similar to those operated with an isolated neutral.

The use of an extinction coil must be associated with a protection plan containing homopolar active power relays (WHP),specified for compensated networks.

The system is completed by maximum homopolar voltage relays the role of which is to detect the resistive faults.

Composition

The artificial neutral point is created by a zigzag coil.

The adjustment inductance consists of a combination of four steps controlled by an automatic control device, itself controlled by a tuning system.

Inserting a high value resistor in parallel on the adjustment inductance allows an active component to be injected into the homopolar circuit and which is detected by the protection plan consisting of WHP relays.

In the French 20 kV networks operating with a compensated neutral, the fault current value is limited to 40 A with an active component greater than 20 A. To reach these objectives, the resistance value is approximately 600 Ω, the mismatch is then limited to 35 A.

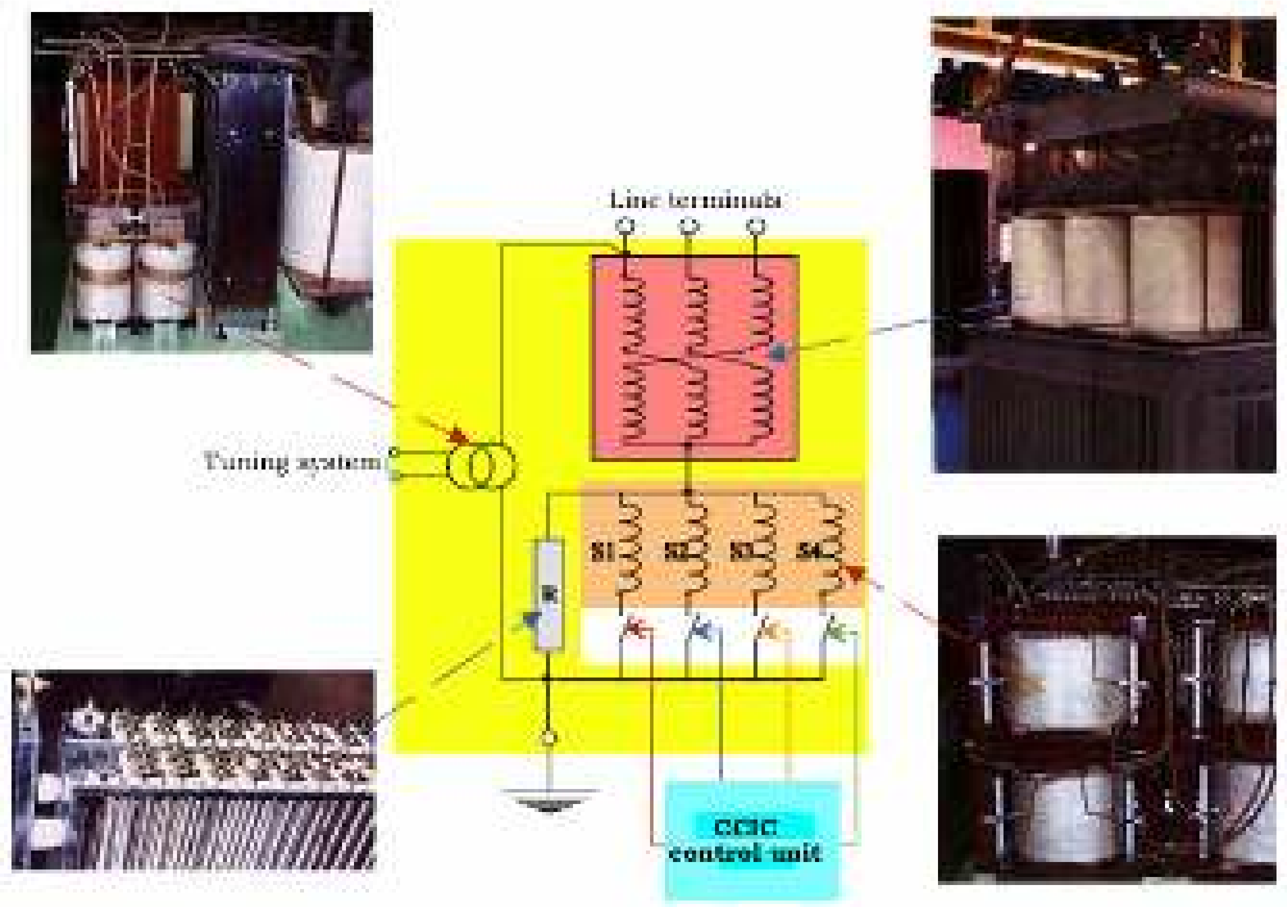


Figure 140: Composition of a compensation impedance

10.6. PROTECTION PLANS

They must respect the following general principles:

- To preserve the safety of persons and the integrity of the electrical equipment, all faults arising on a network component or connected to the network must be rapidly detected and eliminated by the protection plan.
- To meet the electrical energy supply continuity obligations, the fault elimination process must respect the selectivity principles.
- The users and the industrial processes must be able to benefit at all times from the services which are defined contractually and covered by the regulations (*).
- The definition of a protection plan must be studied in coherence with the neutral point arrangement.

(*) The essential services concern quality of service, neutral point arrangement, voltage plan, short-circuit power, electric wave purity, etc.

As an indication, the earth fault detection criteria are summarised in the following table.

Neutral point arrange-ment	**Single-phase short-circuit protection criteria * pending (study) ** recommended *** essential**									
	Max Ur	**Max Ir**	**Max Pr**	**Max Qr**	**Max Sr ∠φ**	**Min. Z**	**Min. X**	**Max Ir ∠φ**	**ΔI**	**ΔIr**
Isolated	***			**				* (study)		
Direct		***			***	***	***	***	***	***
Impedant R+jX		**	***		**	***	***	***	* (study)	**
Impedant jX		* (study)				***	***	***	* (study)	**
Compen-sated	**		***							

Table 29: Fault selection criteria according to the neutral point arrangement

10.7. IS THERE A RIGHT NEUTRAL POINT ARRANGEMENT?

The answer is a complex one. To be convinced, we just have to take part in a meeting of experts on the subject.

"If there was a neutral point arrangement representing a low investment, a low operating cost and an excellent quality of service, we would know it".

However, we can express the following opinions:

- In networks with a low homopolar capacitance, the use of the isolated neutral gives a good quality of service but poses the problem of protection plan selectivity.

- The compensated neutral provides a good quality of service, the protection plan is selective but costly to implement. The cost of the accessories to operate the network is high.

  In these networks, the level of dynamic overvoltages is at its maximum. The equipment must absolutely be isolated in common mode for the composite voltage (24 kV in 20 kV networks).

- In networks where the neutral is directly earthed, the level of dynamic overvoltages is controlled ($F \leq 3$). The common mode isolation of the equipment can be reduced.

  These networks are well-adapted to supplying single-phase loads when the neutral is distributed. The protection plans are simple and selective. The resistive fault detection, however, is difficult to obtain. The quality of service is poor, it requires a careful and costly implementation of the circuits and of the earth connections.

Neutral point arrangements in public networks

On such networks, the choice of the neutral point arrangement is based on historical reasons.

Its development depends on the country's development level, its geography and on the distribution of its population. However, the geopolitical influences can lead to a disregard for the technical and economic criteria. The errors may then be costly.

For the purposes of comparison we often examine the performance of networks currently operated throughout the world by different electricity companies. We then discover that, whatever their neutral point arrangement, these networks operate relatively correctly.

Today, the trend is as follows:

High voltage (HVB)		Impedant neutral or directly earthed neutral
Medium voltage (HVA)	EUROPE	Impedant or compensated neutral
	UNITED STATES AUSTRALIA ASIA	Directly earthed neutral
	AFRICA	Depends on influences
Low voltage		Directly earthed neutral

Table 30: Use of neutral point arrangements worldwide

Some countries still operate isolated neutral HVA networks: ITALY, IRELAND, RUSSIA, JAPAN, GERMANY, etc.

In GREAT BRITAIN the HVA networks are operated with directly earthed neutrals or low impedance neutrals.

On GERMAN HVA networks, the practice is as follows:

		10kV	20kV	30kV
Isolated neutral	9.6%	30,409 km	655 km	1,052 km
Compensated neutral	85.7%	86,779 km	184,097 km	14,110 km
Impedant neutral	4.7%	11,480 km	3,988 km	11 km

Table 31: Neutral point arrangements on German HVA networks

However, some GERMAN electricity companies are looking into the opportunity of changing over to the low impedance neutral on their ageing cable networks.

The FRENCH HVA networks are currently operated with an impedant and resistive neutral. To meet the quality and safety requirements, EDF is migrating rural networks to the compensated neutral system.

The approaches initiated by FRANCE and certain GERMAN companies may seem contradictory. However, they can be explained by the history and composition of their HVA networks.

"In GERMANY, the HVA networks are majoritarily underground and are beginning to age. The reduction in homopolar impedance would reduce the dielectric constraints and thus postpone the renewal of the dilapidated cables. In FRANCE, the HVA networks consisting of overhead lines and underground cables have been greatly improved over the last few years. The increasing proportion of underground cables has led to a sharp increase in the earth fault currents and therefore increases in the earth connection potential which are difficult to control in the present system".

In a few tens of years the French Operator should perhaps think about migrating its neutral point arrangement to a low impedance arrangement.

11. GLOSSAIRE

12. FIGURES

13. TABLES