
2. Earthing systems

2. EARTHING SYSTEMS

2.1. Introduction

In any medium or low voltage three-phase system there are three single-phase voltages which are measured between each phase and a common point called the "neutral point". In balanced operating conditions these three voltages are phase shifted by 120° and have the value:

$$U / \sqrt{3}$$

U being the phase-to-phase voltage measured between phases (see fig. 2-1).

From a physical point of view, the neutral is the common point of three star-connected windings. It may or may not be accessible, may or may not be distributed and may or may not be earthed, which is why we refer to the **earthing system**.

The neutral may be connected to earth either directly or via a resistor or reactor. In the first case, we say that the neutral is solidly (or directly) earthed and, in the second case, we say that the neutral is impedance-earthed.

When there is no intentional connection between the neutral point and earth, we say that the neutral is isolated or unearthed.

The earthing system plays a very important role in a network. On occurrence of an insulation fault or a phase being accidentally earthed, the values taken by the fault currents, touch voltages and overvoltages are closely related to the type of neutral earthing connection.

A solidly earthed neutral helps to limit overvoltages; however, it generates very high fault currents. On the other hand, an isolated or unearthed neutral limits fault currents to very low values but encourages the occurrence of high overvoltages.

In any installation, service continuity in the presence of an insulation fault also depends on the earthing system. An unearthed neutral allows continuity of service in medium voltage, as long as the security of persons is respected. On the other hand, a solidly earthed neutral, or low impedance-earthed neutral, requires tripping to take place on occurrence of the first insulation fault.

The extent of the damage to some equipment, such as motors and generators having an internal insulation fault, also depends on the earthing system.

In a network with a solidly earthed neutral, a machine affected by an insulation fault suffers extensive damage due to the high fault currents.

On the other hand, in an unearthed network or high impedance-earthed network, the damage is reduced, but the equipment must have an insulation level compatible with the level of overvoltages able to develop in this type of network.

The earthing system also has a considerable amount of influence on the nature and level of electromagnetic disturbances generated in an electrical installation.

Earthing systems which encourage high fault currents and their circulation in the metallic structures of buildings are highly disturbing.

On the other hand, earthing systems which tend to reduce these currents and which guarantee good equipotential bonding of exposed conductive parts and metallic structures are not very disturbing.

The choice of earthing system, as much in low voltage as in medium voltage, depends both on the type of installation and network. It is also influenced by the type of loads, the service continuity required and the limitation of the level of disturbance applied to sensitive equipment.

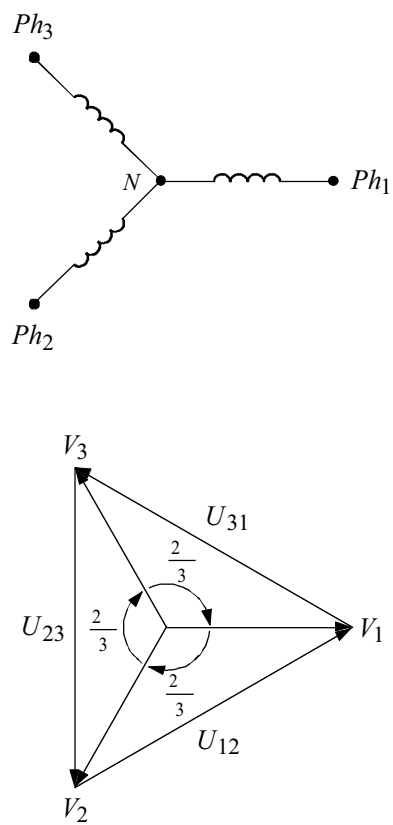


Figure 2-1: three-phase system

V_i : phase-to-neutral voltage
 U_{ij} : phase-to-phase voltage

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2.2. Different earthing systems

The different types of neutral point connection to earth are shown in table 2-1.

We can make a distinction between:

- the solidly (or directly) earthed neutral,
- the unearthed neutral, or high impedance-earthed neutral,
- resistance earthing
- reactance earthing
- Petersen coil earthing.

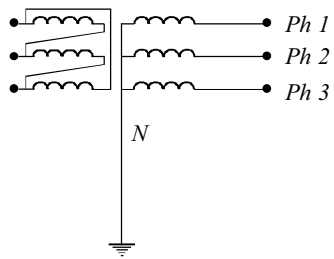
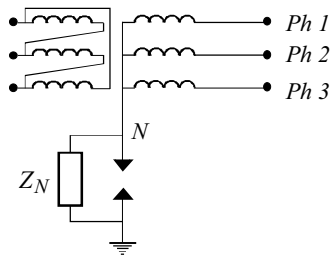
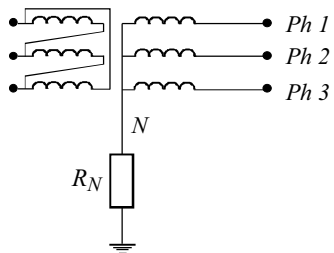
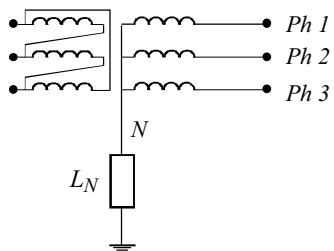
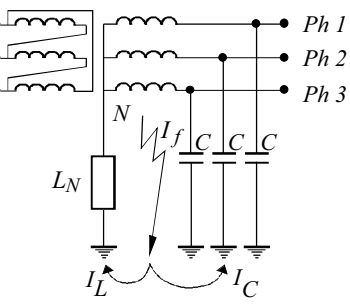
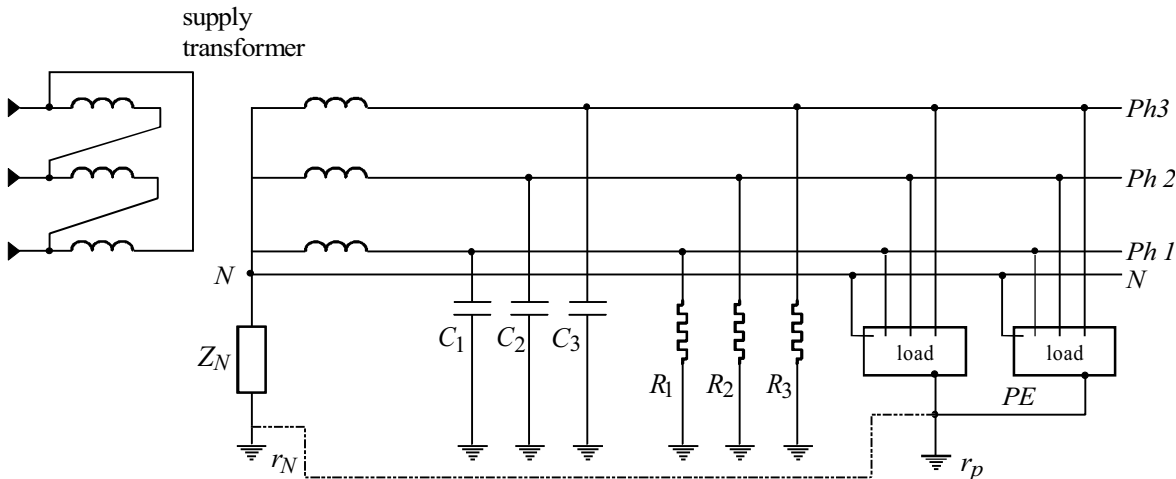
<p>Solidly earthed neutral</p> <p>An electrical connection is intentionally made between the neutral point and earth.</p>	
<p>Unearthed neutral</p> <p>There is no electrical connection between the neutral point and earth, except for measuring and protective devices.</p> <p>High impedance earthing</p> <p>A high impedance is inserted between the neutral point and earth.</p>	
<p>Resistance earthing</p> <p>A resistor is inserted between the neutral point and earth.</p>	
<p>Reactance earthing</p> <p>A reactor is inserted between the neutral point and earth.</p>	
<p>Petersen coil earthing</p> <p>A reactor tuned to the network capacitances is inserted between the neutral point and earth so that if an earth fault occurs, the fault current is zero.</p>	 <p> $\vec{I}_f = \vec{I}_L + \vec{I}_C = \vec{0}$ $I_f : \text{fault current}$ $I_L : \text{current in the neutral earthing reactor}$ $I_C : \text{current in the phase-earth capacitances}$ </p>

Table 2-1: neutral point connection methods

2.3. Influence of the earthing system

2.3.1. Equivalent network diagram (see fig. 2-3)

■ insulation resistances and capacitances in relation to earth



- PE : protective conductor
- C_1, C_2, C_3 : phase conductor capacitances in relation to earth
- R_1, R_2, R_3 : insulation resistances, their influence is always negligible
- Z_N : neutral earthing impedance
- r_N : neutral earth electrode resistance
- r_P : earth electrode resistance of exposed conductive parts
- N : neutral

Figure 2-2: equivalent network diagram

In low voltage, as in medium voltage, a network always has a leakage resistance between each of its phases and earth . In low voltage, for a voltage below 500 volts, a network is said to be correctly earthed when the leakage resistances of the phase in relation to earth (R_1, R_2, R_3) are at least equal to 500 k Ω (IEC 364).

On a correctly earthed network, the following is always said to apply:

$$R_1 = R_2 = R_3 = R$$

As well as the leakage resistances, the capacitance presented by each phase in relation to earth must also be taken into account. Let C_1, C_2, C_3 , be these capacitances; $C_1 = C_2 = C_3 = C$ is always said to apply. The value of C is proportional to the length of the cables making up the network.

In low voltage, C is roughly $0.25 \mu\text{F}$ per kilometre of cable.

When the network feeds loads fitted with phase-to-earth connected incoming filters, the capacitance of these filters, which greatly contribute to the generation of capacitive currents, especially with computing equipment, must be taken into account.

In medium voltage, the value of these capacitances depends on the type of cables used and their type of insulating materials.

In individually screened cables, each conductor is surrounded by a screen (see fig. 2-2-a). The capacitances to be taken into account are those measured between each conductor and its earthed screen.

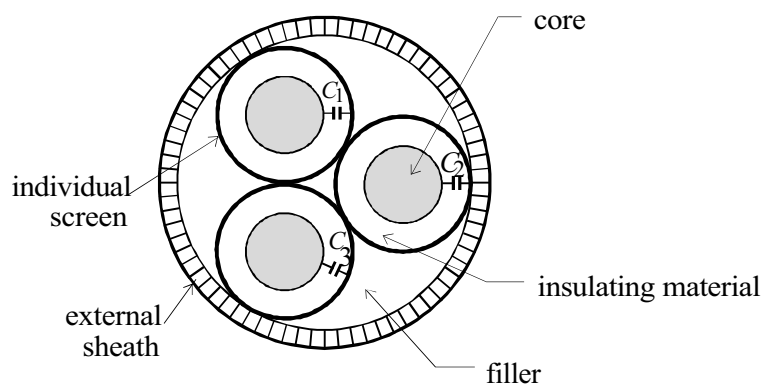


Figure 2-2-a: individually screened cable

For collectively screened cables, a single screen surrounds the three conductors (see fig. 2-2-b); there is a capacitance K between the conductors taken two by two and a capacitance C between each conductor and the earthed screen. It is the capacitances C , measured between each conductor and the screen, which must be taken into account. For this type of cable, manufacturers generally know the capacitance C_0 measured between the screen and the three grouped conductor cores. The value of the capacitance existing between each conductor and the screen is equal to $\frac{C_0}{3}$.

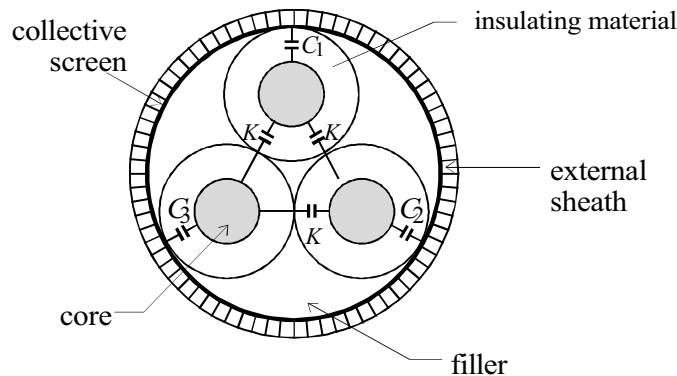


Figure 2-2-b: three-core collectively screened cable

For example, we might take the following values of the phase-to-earth cable capacitances.

■ EPR-insulated MV individually screened cables

□ 5.5 kV voltage

35 mm ² cable	0.29 μF/km
70 mm ² cable	0.35 μF/km
120 mm ² cable	0.44 μF/km
240 mm ² cable	0.58 μF/km

□ 10 kV voltage

35 mm ² cable	0.21 μF/km
70 mm ² cable	0.26 μF/km
120 mm ² cable	0.31 μF/km
240 mm ² cable	0.41 μF/km

□ tension 20 kV

70 mm ² cable	0.17 μF/km
120 mm ² cable	0.20 μF/km
240 mm ² cable	0.26 μF/km

■ PE-insulated MV individually screened cables

□ 5.5 kV voltage

35 mm ² cable	0.27 μF/km
70 mm ² cable	0.34 μF/km
120 mm ² cable	0.42 μF/km
240 mm ² cable	0.54 μF/km

□ 10 kV voltage

35 mm ² cable	0.17 μF/km
70 mm ² cable	0.21 μF/km
120 mm ² cable	0.26 μF/km
240 mm ² cable	0.34 μF/km

□ 20 kV voltage

70 mm ² cable	0.14 μF/km
120 mm ² cable	0.17 μF/km
240 mm ² cable	0.21 μF/km

■ PVC-insulated MV collectively screened cables

□ 3.2 kV voltage

10 mm ² cable	0.16 μF/km
25 mm ² cable	0.18 μF/km
35 mm ² cable	0.17 μF/km

□ 6 kV voltage

16 mm ² cable	0.14 μF/km
50 mm ² cable	0.21 μF/km
95 mm ² cable	0.30 μF/km

■ PVC-insulated low voltage cables

16 mm ² cable	0.2 μF/km
35 mm ² cable	0.16 μF/km

■ earth electrode and earth resistance

When the neutral of a network is earthed, whether solidly or via an impedance, it is connected to an earth electrode, called the neutral earth electrode, having a non zero resistance r_N .

In any electrical installation, whether low or medium voltage, the exposed conductive parts of loads are generally interconnected. Interconnection may be total or through groups of loads. Each interconnected group is connected to an earth electrode having the value r_P . One or several exposed conductive parts may also be individually connected to earth. The earth electrodes of the exposed conductive parts and the neutral may or may not be interconnected and are sometimes common. The conductor interconnecting exposed conductive parts is called the protective conductor and is indicated by the letters *PE* or *PEN*.

A low or medium voltage network is thus always characterised by:

- an insulation resistance R
- a capacitance C between each phase and earth
- a neutral earth electrode having the value r_N
- one or several earth electrodes of exposed conductive parts having the value r_P .

2.3.2. Earthing system and fault current

Let us consider a low or high voltage three-phase network (see fig. 2-4). The neutral may or may not be earthed. The earthing system depends on the value and nature of impedance Z_N .

If Z_N is zero, the neutral is solidly earthed.

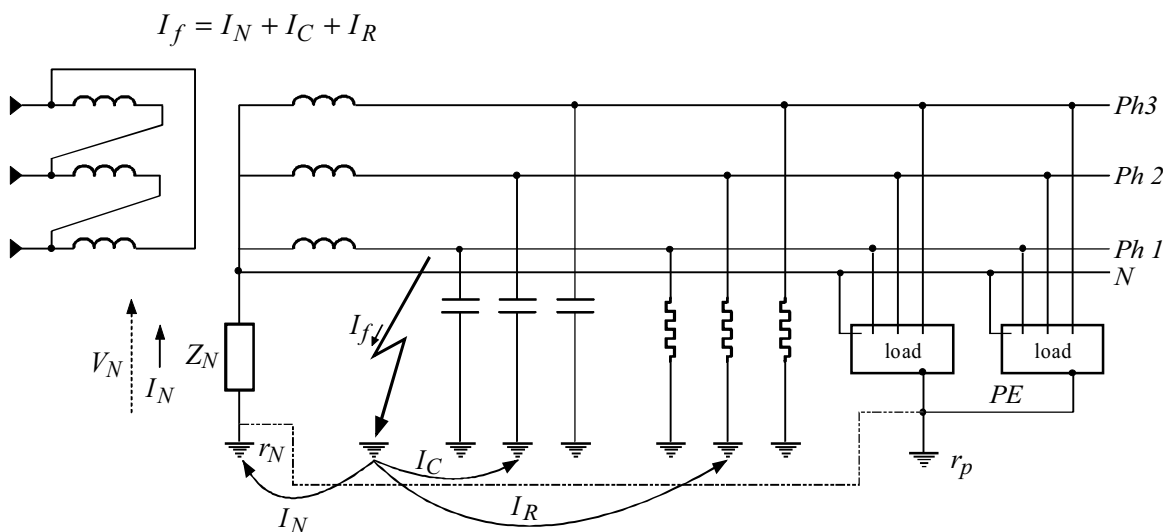
If Z_N is very high, the neutral is unearthed or highly impeditant.

If Z_N is different from zero, but of a low value (from several dozen to several hundred ohms in high voltage, depending on the voltage level and the type of network), the network is said to have impedance earthing. The impedance Z_N may be a resistance or a reactance.

If there is no fault, currents circulate in the network resistances and leakage capacitances. With these currents being balanced, none of them circulates in the impedance Z_N and the neutral point is at the same potential as the earth:

$$V_N = -Z_N I_N = 0$$

When a phase is put in contact with the earth, a current I_f is established between the faulty phase and earth, and it returns via the impedance Z_N as well as via the healthy phase leakage capacitances and resistances:



I_f : fault current

I_N : current returning via the neutral earthing impedance

I_C : current returning via the network phase-earth capacitances

I_R : current returning via the network insulation resistances, this current is always negligible

V_N : rise in neutral point potential

Z_N : neutral earthing impedance

Figure 2-4: rise in neutral point potential

The neutral point is thus raised to a potential of:

$$-Z I$$

The leakage current I_R , which is always low, can be neglected.

If the neutral is solidly earthed, the current I_N is very high and the current I_C may be neglected:

- if the neutral is unearthed:

$$I_f = I_C$$

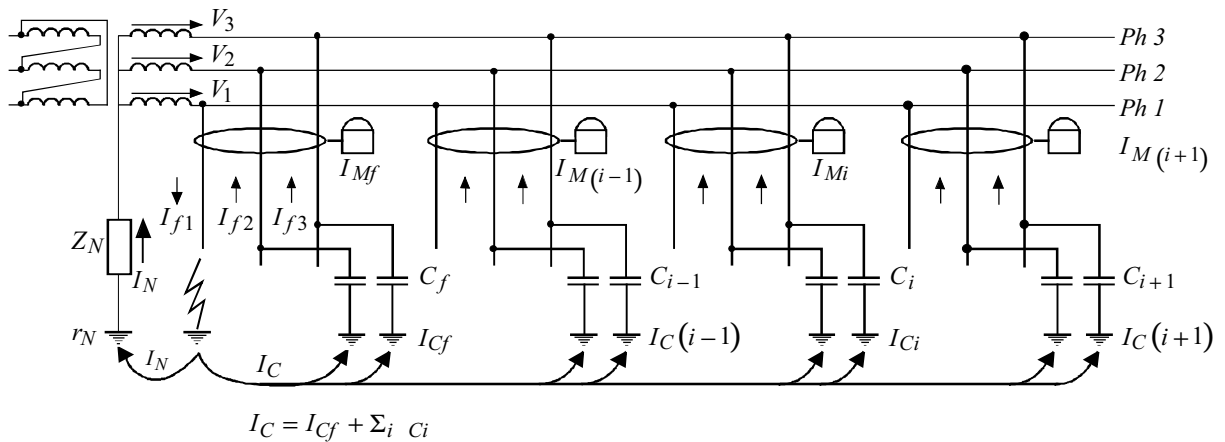
- if the neutral is impedant:

$$I_f = I_N + I_C$$

Figure 2-5 gives the current spread in a general case.

Table 2-2 gives the current values in the case of a solid fault (fault resistance = 0).

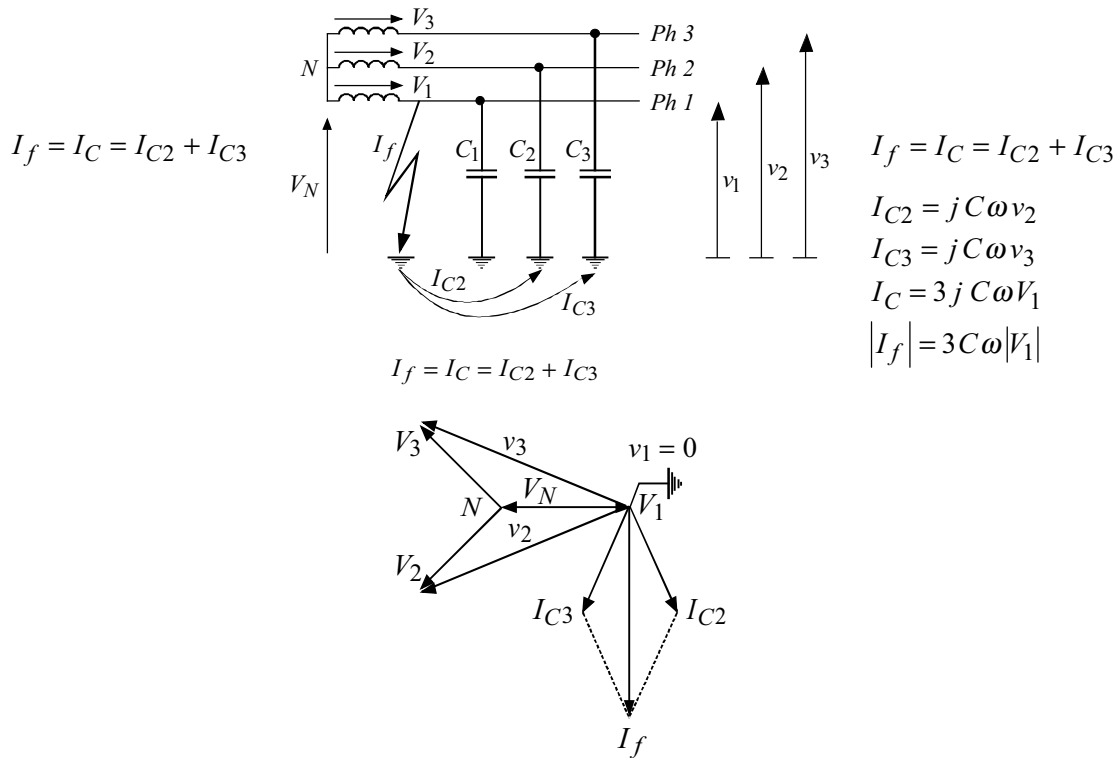
For further details on fault currents, refer to chapter 4.3. of the *Industrial network protection guide*.



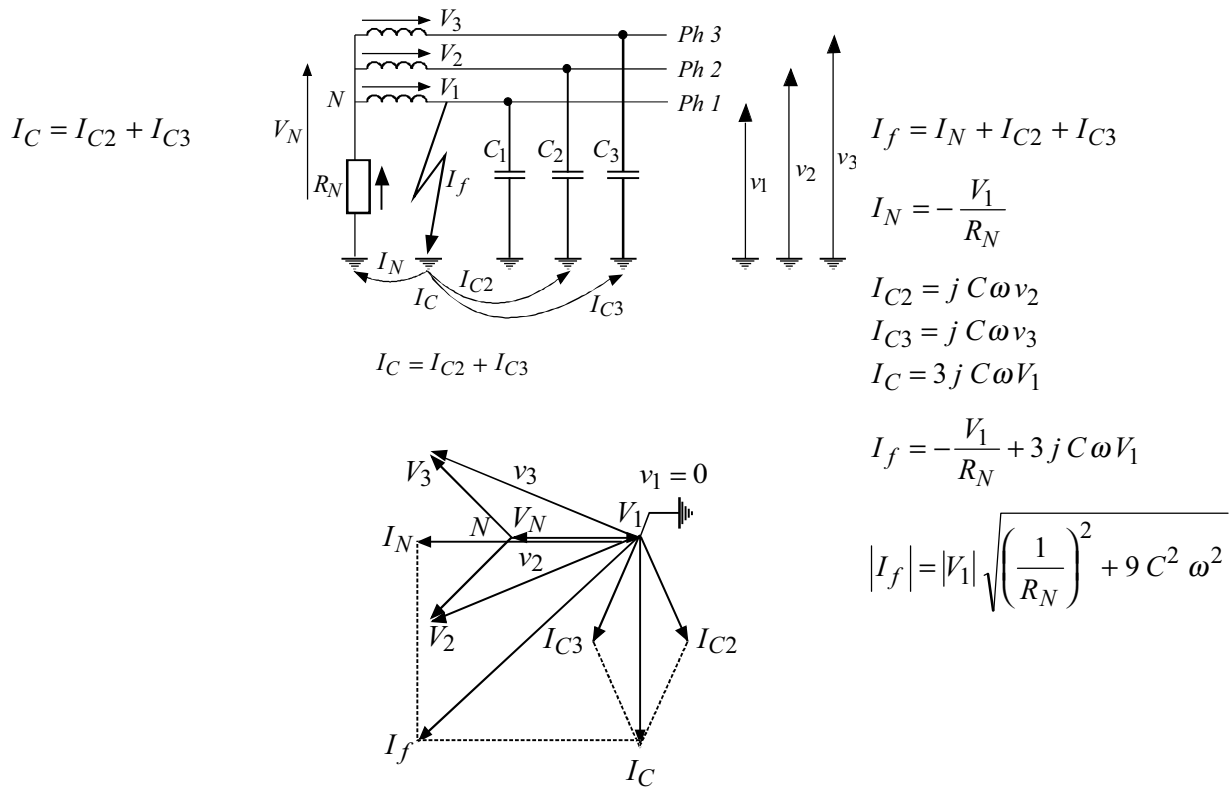
- I_{f1} : current circulating in the fault
- I_N : current circulating in the neutral earthing impedance
- I_C : capacitive current returning via the network phase-earth capacitances
- I_{Cf} : capacitive current returning via the healthy phases of the faulty outgoing feeder
- I_{Ci} : capacitive current returning via the healthy phases of the healthy outgoing feeders
- I_{Mf} : residual current measured on the faulty outgoing feeder
- I_{Mi} : residual currents measured on the healthy outgoing feeders
- V_1, V_2, V_3 : network single-phase voltages

Figure 2-5: current spread on occurrence of a phase-earth fault

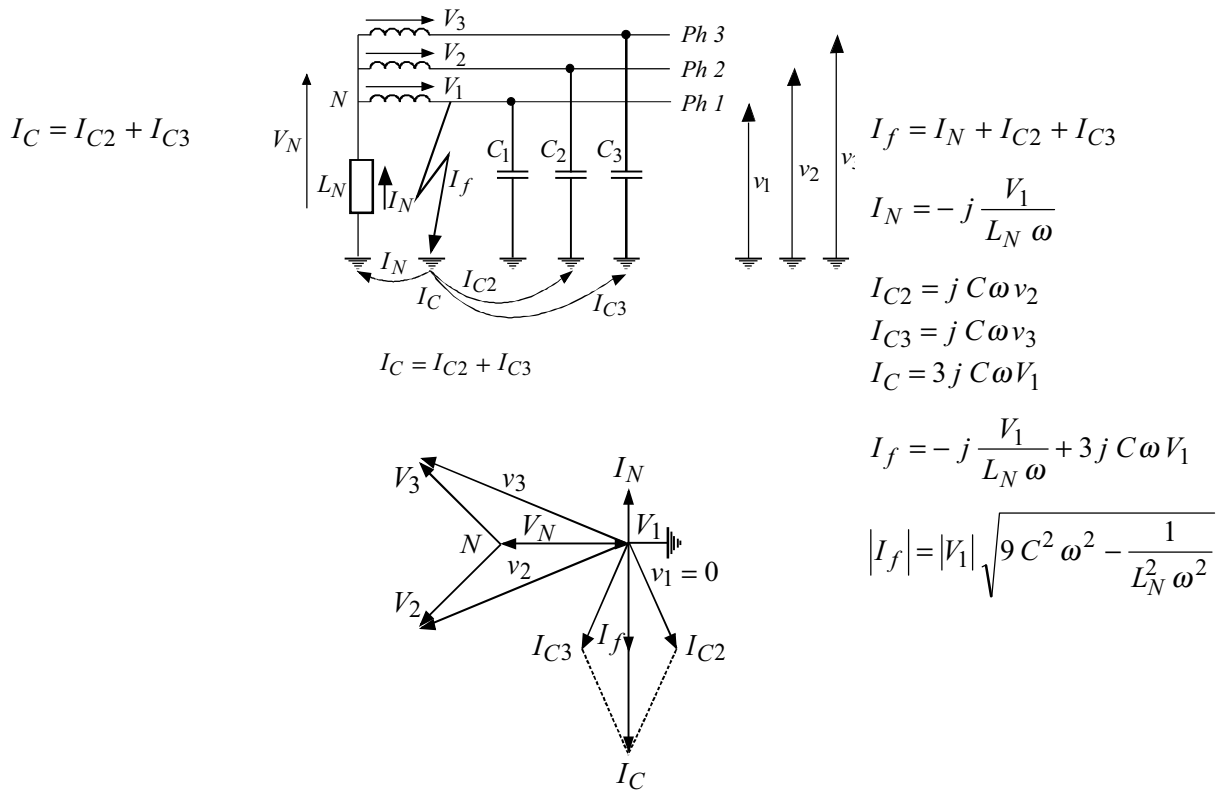
Unearthed neutral



Resistance earthing



Reactance earthing



Petersen coil earthing

This is the previous case, for which:

$$3 C \omega = \frac{1}{L_N \omega}$$

where: $3 L_N C \omega^2 = 1$

The current in the fault is zero, when tuning is perfect.

Table 2-2: vectorial diagrams in the case of a solid earth fault

2.3.3 Touch voltages

■ touch voltage - non-dangerous limit voltage

Any person entering into contact with a live part is subjected to a difference in potential: the person therefore risks being electrified (i.e. receiving a non-lethal electric shock). There are two types of contact: direct contact and indirect contact.

□ direct contact

This is the contact of a person with a live part of a piece of equipment that is energized. Contact may occur with a phase or with the neutral (see fig. 2-6-a).

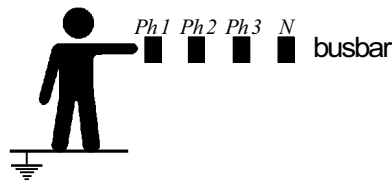
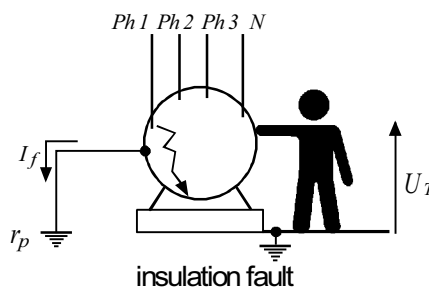


Figure 2-6-a: direct contact

□ indirect contact

This is the contact of a person with the exposed conductive part of a load which is accidentally live following an insulation fault (see fig. 2-6-b).



We have $U_T = r_p I_f$ as the impedance of the human body is very high compared with r_p .

U_T : touch voltage

I_f : fault current

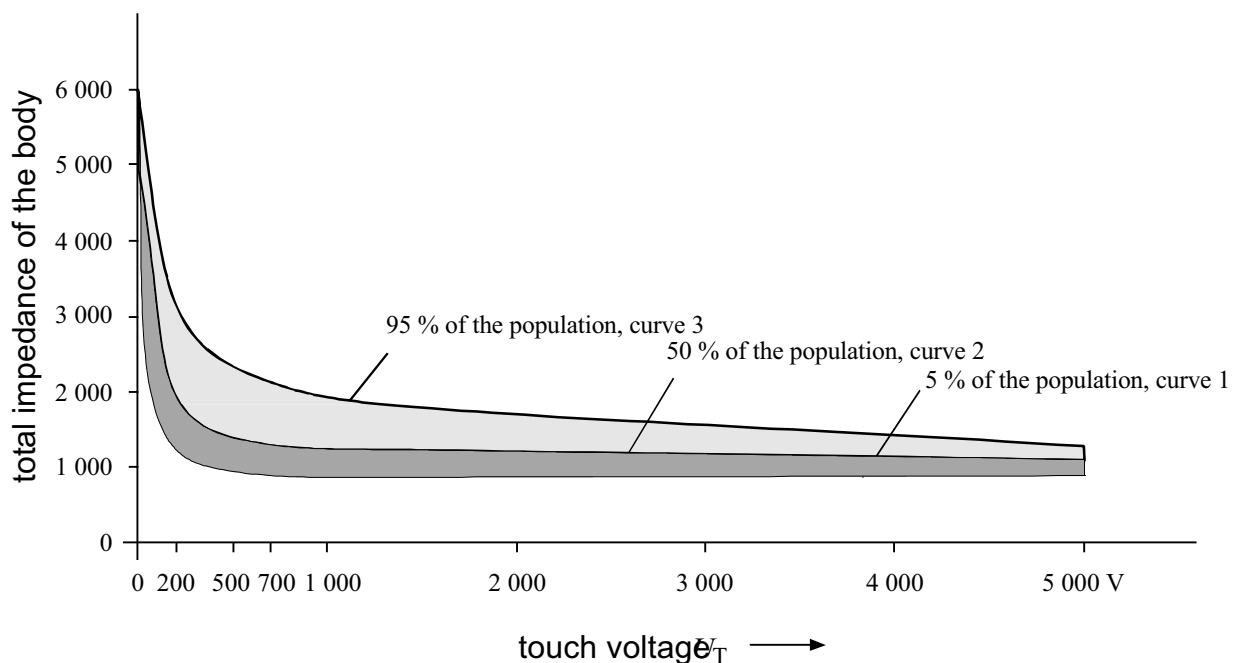
r_p : earth electrode resistance

Figure 2-6-b: indirect contact

Contrary to what is generally believed, the risk for persons is not only related to the value of the voltage applied to the human body, but also to that of the current likely to go through it and the contact time. The current and voltage are related by Ohm's law: $I = U / R$ where R is the impedance of the human body.

This impedance varies in relation to the touch voltage, the state and dampness of the skin, as well as the path that the current takes inside the human body.

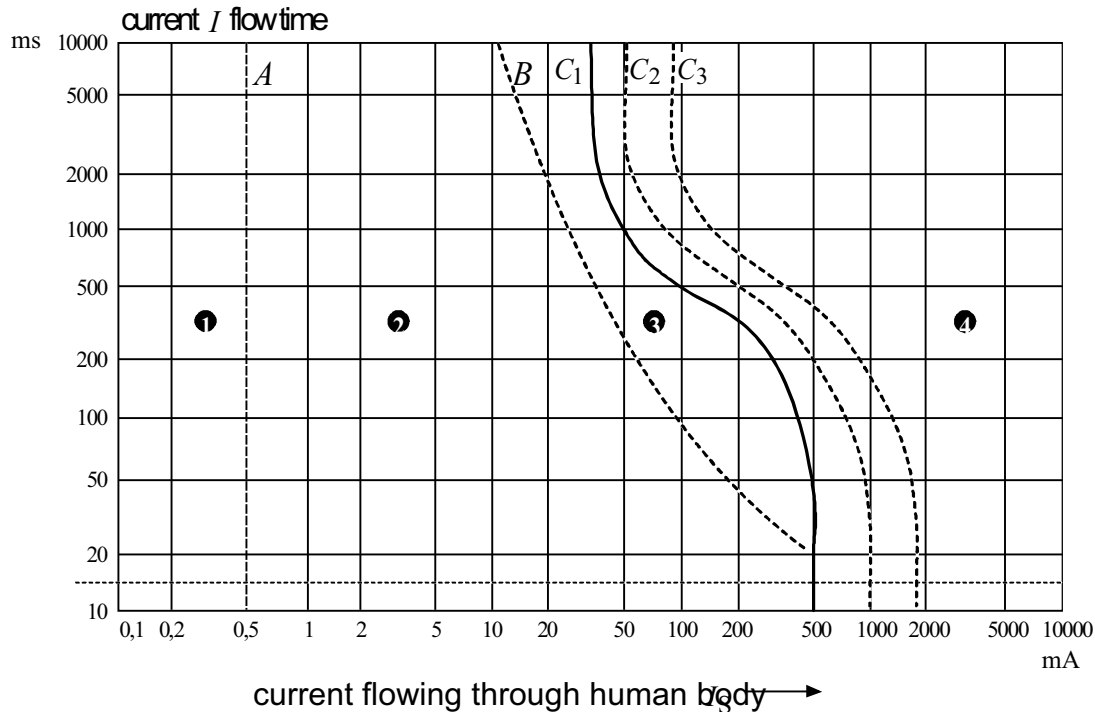
IEC publication 479 gives the human body impedance values in relation to the touch voltage to which it is subject (see fig. 2-7-a).



- 5 % of the population means that 5 % of people have an impedance below curve 1.
- 50 % of the population means that 50 % of people have an impedance below curve 2.
- 95 % of the population means that 95 % of people have an impedance below curve 3.

Figure 2-7-a: statistical values of the total impedances of the human body for a hand-to-hand or hand-to-foot current trajectory

This publication also gives the effects of electrical current on persons in relation to its value and duration. These effects are shown in figure 2-7-b for alternating current at 50 or 60 Hz.



- ❶ : not noticeable
- ❷ : noticeable
- ❸ : reversible effects - muscular contraction
- ❹ : possible irreversible effects, risk of death

Figure 2-7-b: effects of 50/60 Hz electrical current

Curve C1 defines the time-current limit of exposition to an electric shock, which must not be exceeded.

Tables 2-3-a and 2-3-b are based on these data and fix the maximum supply disconnection times in relation to the prospective touch voltage to which a person is subject. They have been drawn up using graphs 2-7-a and 2-7-b and taking into account an additional resistance created by shoes being worn and contact with the ground. They allow conventional limit voltages U_L , which can be held without this being dangerous for persons, to be defined in relation to the type of premises. In other words, a touch voltage below U_L does not require disconnection. On the other hand, any touch voltage above U_L requires the fault to be cleared in a time at the most equal to the time stipulated in tables 2-3-a and 2-3-b. The conventional limit voltages have been set at 50 V for dry premises and 25 V for damp premises.

The disconnection times to be used in practice and the protections to be implemented for disconnecting the power supply depend on the earthing systems (TT, TN, IT). They are specified in paragraphs 2-5-1 and 2-5-2.

Prospective touch voltage (V)	Maximum disconnecting time of the protective device(s)	
	alternating current	direct current
< 50	5	5
50	5	5
75	0.60	5
90	0.45	5
120	0.34	5
150	0.27	1
220	0.17	0.40
280	0.12	0.30
350	0.08	0.20
500	0.04	0.10

Table 2-3-a: maximum prospective touch voltage holding time in dry premises ($U_L = 50$ V)

Prospective touch voltage (V)	Maximum disconnecting time of the protective device(s)	
	alternating current	direct current
25	5	5
50	0.48	5
75	0.30	2
90	0.25	0.80
110	0.18	0.50
150	0.12	0.25
230	0.05	0.06
280	0.02	0.02

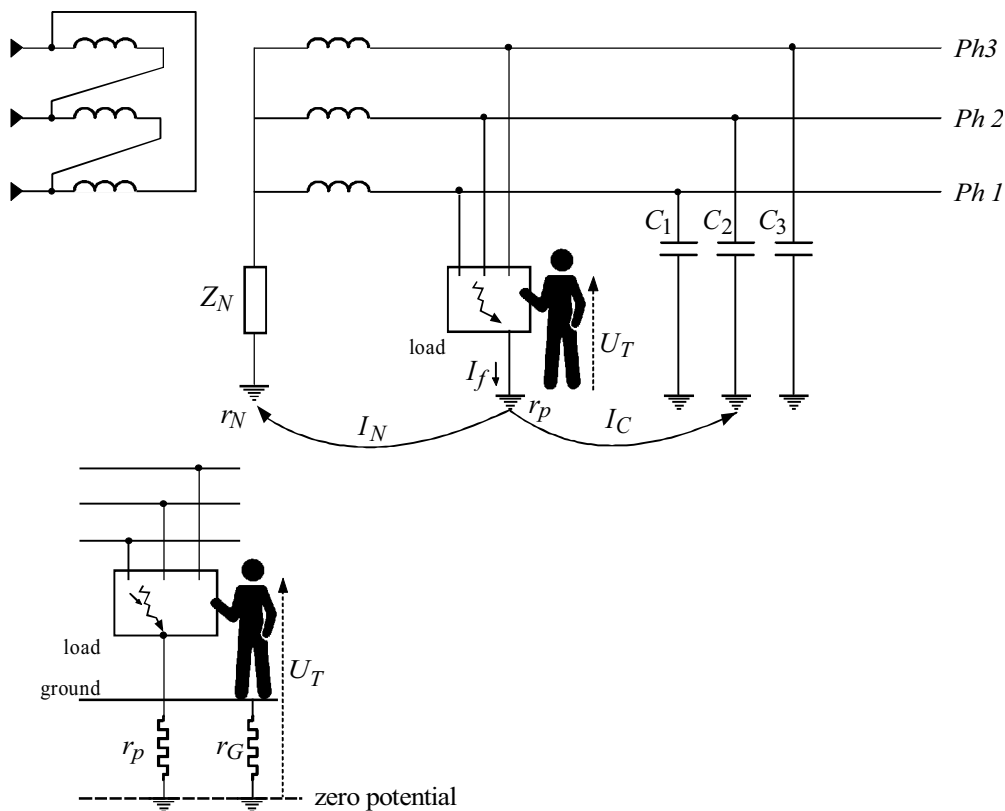
Table 2-3-b: maximum prospective touch voltage holding time in damp premises ($U_L = 25$ V)

■ touch voltage on occurrence of an insulation fault

Let us assume that owing to an insulation fault in a network a phase accidentally comes into contact with the exposed conductive part of a load (see fig. 2-8). A fault current I_f is then established between the load and earth and any person entering in contact with the exposed conductive part is subject to a difference of potential U_T referred to as the touch voltage:

$$U_T = r_p I_f$$

As for the fault current, the touch voltage is closely linked to the value of the impedance Z_N , and thus to the earthing system. If the neutral is unearthed, the values of the fault current I_f and touch voltage U_T are very low. It is therefore not necessary to disconnect the power supply. They are, on the other hand, high if the neutral is solidly earthed and, in this case, the power supply must be disconnected.



- r_N : neutral earth electrode resistance
- r_p : exposed conductive part earth electrode resistance
- r_G : ground resistance
- I_f : fault current
- U_T : touch voltage

Figure 2-8: diagram of touch voltage

2.3.4 Overvoltages

When there is no fault, all networks operate in steady-state conditions. The phase-to-phase and phase-to-earth voltages are perfectly controlled and equal to the duty voltages.

The occurrence of a fault, a phase-earth fault for example, leads to a modification of the initial steady state, there is a rise in potential of the healthy phases in relation to earth and transient voltages develop which may lead to equipment breakdown, if its insulation level has not been correctly chosen. The earthing system plays a determining role in the development of overvoltages due to a phase-earth fault. The mechanisms are multiple and complex. See paragraph 5.1.1.1. dealing with overvoltages for a more detailed analysis.

2.3.5 Damage caused to equipment

The damage that may be caused to the equipment of an electrical network having an insulation fault depends on the values of currents and overvoltages which are developed in the network the moment the fault occurs. These are thus limited as far as possible when there are sensitive loads.

It is advisable to find a compromise as the means which reduce fault currents tend to encourage the occurrence of overvoltages and vice versa.

■ MV rotating machines (see chapter 10.1.1. of the Protection guide)

The most frequent fault affecting a medium voltage generator or motor is flashover between a phase and the magnetic circuit. This type of fault is called a "stator frame" fault.

When a stator frame fault occurs in a machine, the entire phase-earth fault current circulates in the faulty phase and in the magnetic circuit earthed via the frame. An electric arc develops at the place where the faulty phase touches the magnetic circuit and a lot of energy is dissipated leading to deterioration of the magnetic circuit and insulation. The extent of the damage depends on the fault current value. Experience shows that not very high currents, present for a very short time, do not lead to deterioration deep in the iron core. It is generally admitted that a fault current below 20 or 30 A does not result in extensive damage and does not require the magnetic circuit to be remade. Tests have shown that a 7.5 A fault for 10 minutes does not cause extensive damage whereas a 200 A fault for 0.3 s does.

For fault times below one second, the empirical law:

$$I^4 t = cte$$

relates the fault current value to the time during which it can be applied without causing considerable damage.

To reduce the risks in a medium voltage network comprising motors and generators, the phase-earth fault current is as far as possible limited to a value of 20 A maximum by choosing the limiting resistor earthing system: $I_r \leq 20A$

However, in order to limit the amplitude of transient overvoltages which are created when a phase to earth fault is cleared by a circuit-breaker, the relation $I_r \geq 2 I_C$ should be respected as far as possible (see § 5.1.3.3).

I_r : current circulating in the neutral point earthing resistor

I_C : network capacitive current

For a very long network (high capacitive current), these two relations may be incompatible and a compromise must therefore be made.

■ effects of fault currents on MV cable screens

Medium voltage cables, whether they are the individually screened or collectively screened type (see fig. 2-2-a and 2-2-b), all have earthed metal screens. The earthing mode for these screens is described in paragraph 6.2.8.

When the insulating material of one phase breaks down, the conductor and screen are practically joined: all the fault current then flows via the screen which must be able to withstand it without being damaged. With the fault current being directly dependent on the earthing system, we can see how important the earthing system is in the choice and sizing of cable screens.

The screens can be made of copper or aluminium and take various forms, the most notable being:

- one or several copper or aluminium bands wrapped around the insulating material
- a thin copper or aluminium band installed lengthways
- a flat arrangement of copper or aluminium wires
- a braid of copper wires.

Lead is also used to make screens for very high currents, or when it is necessary to endow the insulating material with a particularly effective protection against damp or corrosive products.

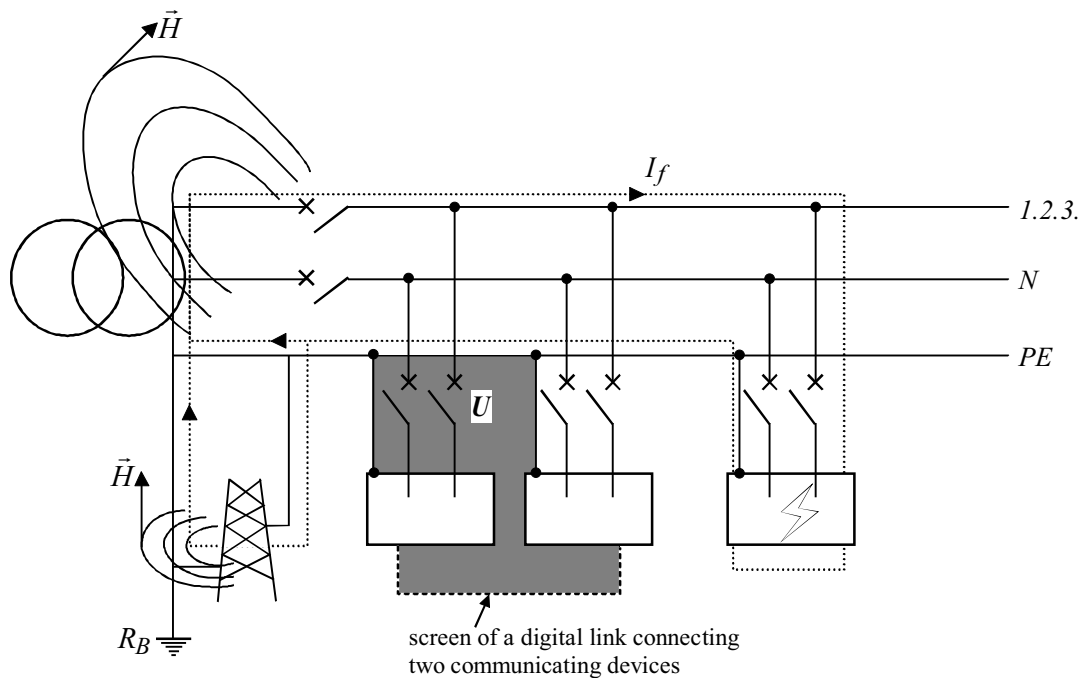
The permissible current in a screen depends on the material it is made of, its cross-sectional area, the type of insulating material with which it is in contact and the time during which the fault current will flow through it.

In all cases, it is important to check that the screen is suited to the operating conditions. Paragraph 6.2.5. gives the short-time currents allowed in cable screens with extruded synthetic insulation.

2.3.6 Electromagnetic disturbances

Earthing systems leading to the development of high fault currents and their circulation in the metallic structures of buildings, especially the *TNC* system in low voltage, encourage the appearance of considerable magnetic fields which, through induction in the loops created by the protective conductors, may disturb or damage certain pieces of sensitive equipment (see fig. 2-9). When confronted with this situation, earthing systems enabling the disturbing fields to be correctly dealt with should be chosen.

Care must also be taken to reduce the surface of the loops created by all the conductors contributing to the equipotential bonding of the exposed conductive parts.



\vec{H} : magnetic field generated by the circulation of fault currents

U : voltage induced in a loop made up of protective conductors and cable screens

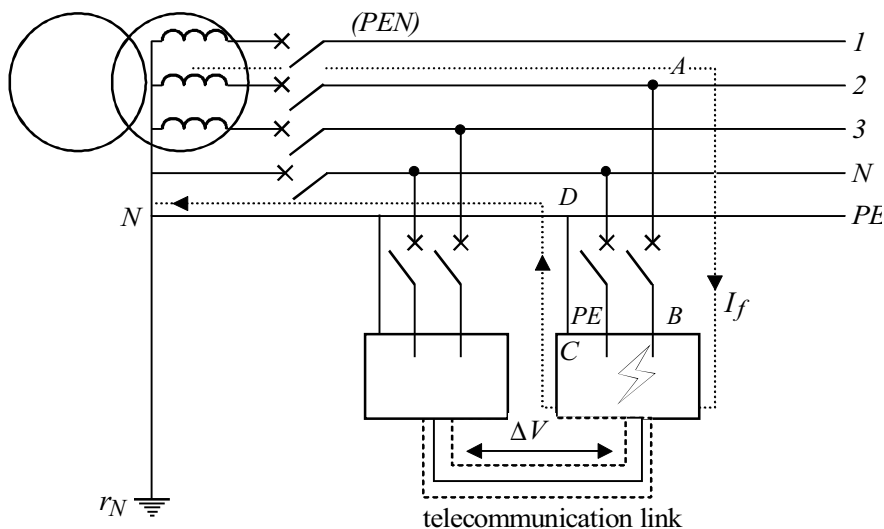
Figure 2-9: disturbance by a radiated magnetic field

2.3.7 Difference of potential along the protective conductor - Disturbance of communicating systems

In *TNC* and *TNS* earthing systems, on occurrence of an insulation fault, a high voltage may develop along the protective conductor connecting the exposed conductive part of the faulty load to the equipotential circuit which connects up all the exposed conductive parts of the installation.

The exposed conductive parts of the healthy loads do not necessarily undergo the same rise of potential as that of the faulty load. Thus, a considerable difference of potential may appear between the loads and any telecommunication link connecting these two loads may be disturbed (see fig. 2-10).

In the *TNC* earthing system, unbalance current due to single-phase loads and third harmonic and multiples of third harmonic currents circulate in the protective conductor (*PEN*) (see § 8) and create differences of potential. Equipotential bonding of the loads is then no longer ensured and telecommunication links connecting up the communicating devices may be disturbed; the risk of disturbance is permanent in this case (see fig. 2-11).



To simplify matters, let us assume that:

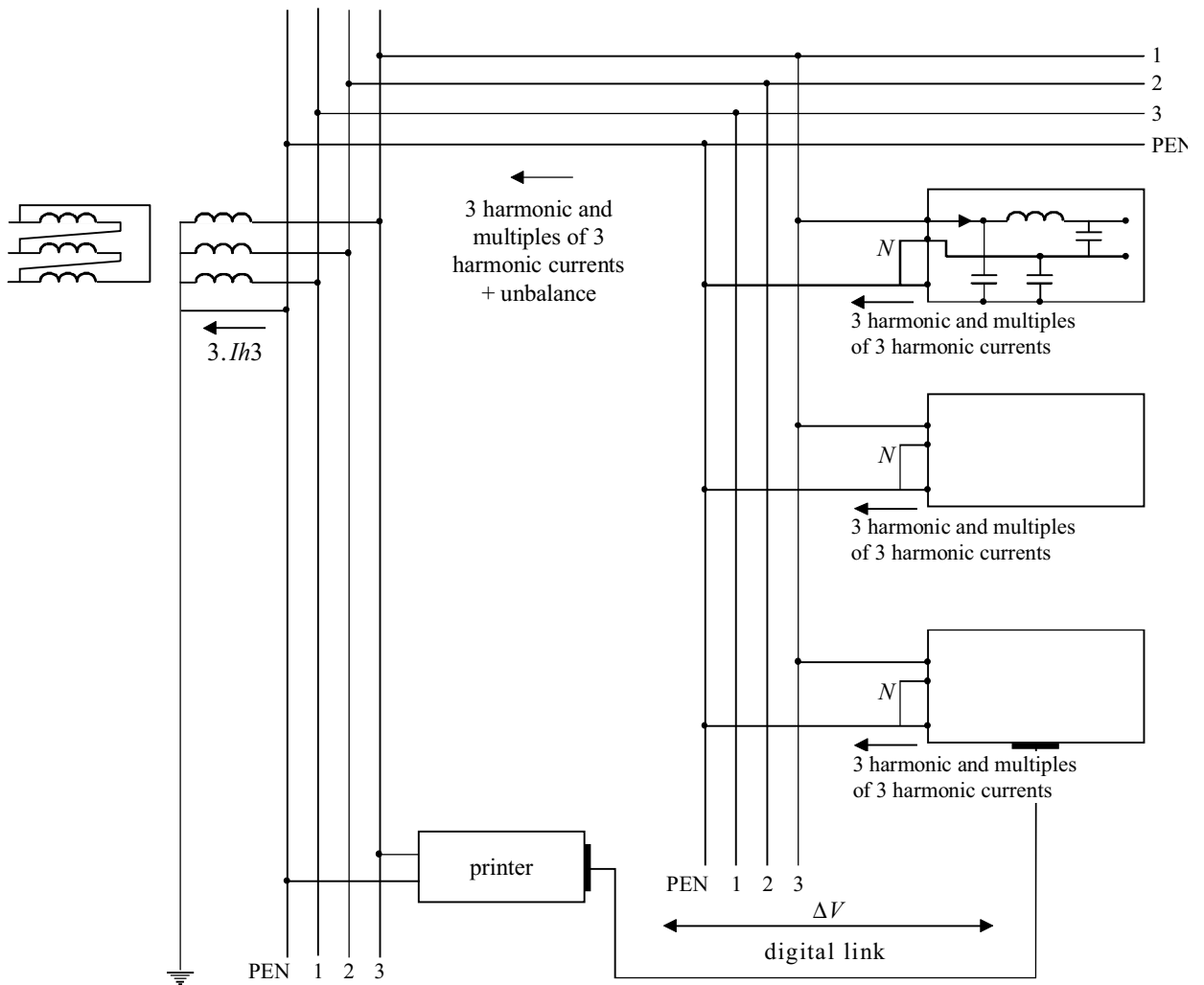
$$V_{AD} = 0.8 V_n$$

V_{DN} : negligible

PE : protective conductor has the same length and cross-sectional areas as the phase conductors.

$$\text{We thus have: } \Delta V \cong \frac{0.8 V_n}{2}$$

Figure 2-10: voltage drop along the protective conductor



ΔV : voltage drop due to the circulation of unbalance currents, third harmonic and multiples of third harmonic currents in the PEN conductor

Figure 2-11: effect of the circulation of unbalance currents and third harmonic and multiples of third harmonic currents

2.3.8 Risk of fire or explosion

Earthing systems generating high fault currents must be avoided in installations and premises where there is a risk of explosion or fire.

It has been established that a fault current of 500 mA can make conductors with a small cross-sectional area glow and thus cause a fire or explosion. This is why it is advisable to use residual current devices having a setting below or equal to 500 mA for premises and installations where there is a risk of fire or explosion (IEC 364-4-482) (see fig. 2-12).

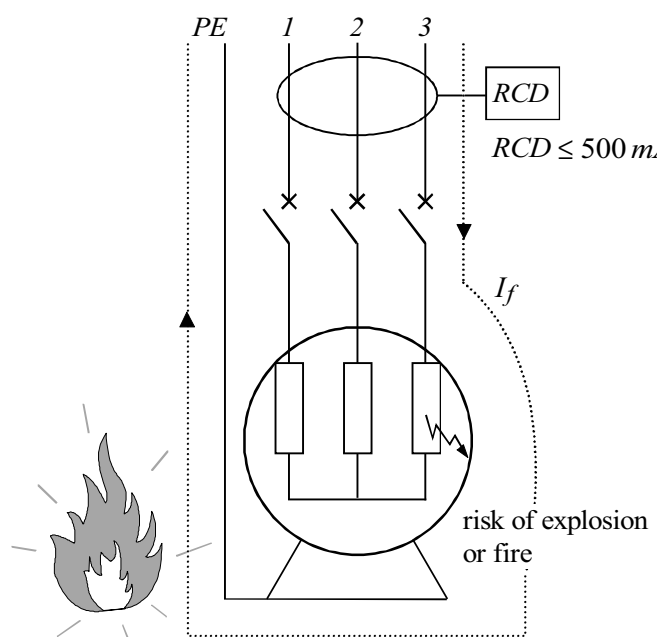


Figure 2-12: risk of fire or explosion

2.4. Earthing systems used in low voltage

In low voltage, earthing systems are governed by international IEC standard 364-3. Three systems are considered. Each one is defined by two letters.

The first letter defines the situation of the neutral point in relation to earth.

T : solidly earthed neutral

I : unearthed or high impedance earthed neutral.

The second letter defines the connection method of the electrical installation's exposed conductive parts:

T : the exposed conductive parts are interconnected and solidly earthed, regardless of whether the neutral point is earthed or not

N : the exposed conductive parts are directly connected to the neutral conductor.

2.4.1. Unearthed or impedance earthed neutral (*IT* system, figure 2-13)

The neutral is unearthed or earthed via a high impedance (first letter *I*). An impedance between 1000 and 2000 Ω is frequently used.

The exposed conductive parts of loads are interconnected, either altogether, or in groups. Each interconnected group is connected to an earth electrode (second letter *T*). It is possible for one or several exposed conductive parts to be separately earthed.

Where possible, it is advisable to interconnect all the exposed conductive parts of the same installation and connect them to the same earth electrode. It is nonetheless possible for exposed conductive parts which are far away from each other, or located in different buildings, not to be. In this case, each group of exposed conductive parts connected to the same electrode and each individually earthed exposed conductive part must be protected by a residual current device.

The earth electrodes of the exposed conductive parts and the neutral may or may not be interconnected or the same.

It is not advantageous to distribute the neutral which results in the maximum length of wiring systems being reduced (see table 2-4).

Installing an overvoltage limiter between the neutral point of the MV/LV transformer and earth is compulsory. If the neutral is not accessible, the overvoltage limiter is installed between one phase and earth. It protects the low voltage network against rises in voltage due to flashover between the transformer medium voltage and low voltage windings (see § 5.3.2. - overvoltages).

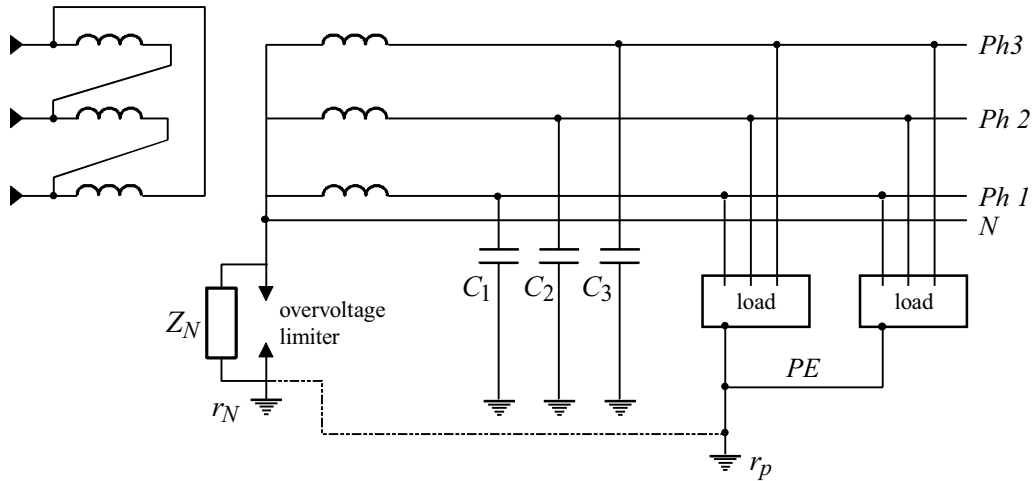


Figure 2-13: unearthed or impedance earthed neutral (IT earthing system) in low voltage

2.4.2. Solidly earthed neutral (TT earthing system, figure 2-14)

The neutral point is directly earthed (first letter *T*).

The exposed conductive parts of the loads are interconnected, either altogether, or in groups, or individually, and are earthed (second letter *T*). Protection is ensured by residual current devices. All the exposed conductive parts protected by the same protective device must be connected to the same earth electrode.

The neutral earth electrode and that of the exposed conductive parts may or may not be interconnected or the same. The neutral may or may not be distributed.

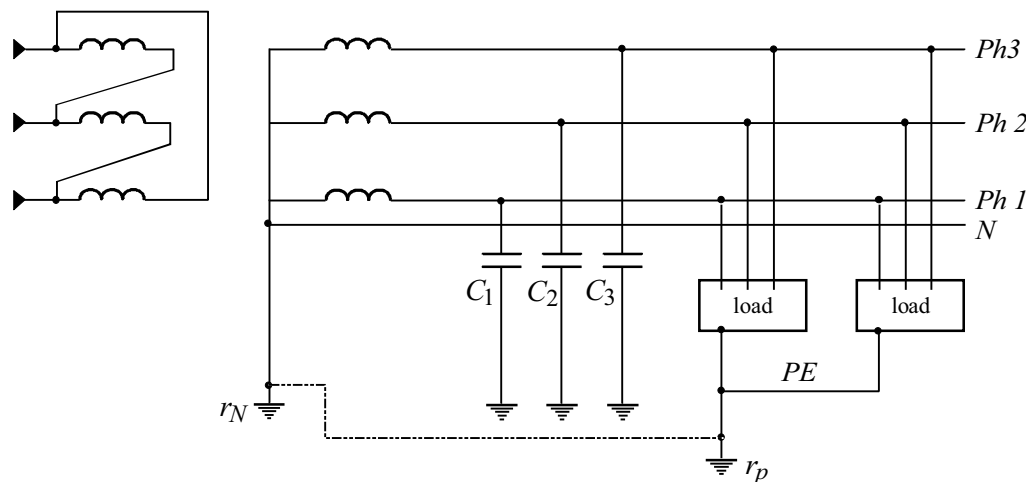


Figure 2-14: solidly earthed neutral (TT earthing system) in low voltage

2.4.3. Neutral earthing (*TN earthing system*)

The neutral point is directly earthed (first letter *T*).

The exposed conductive parts of the loads are connected to the neutral conductor (second letter *N*).

There are two possible systems depending on whether the neutral conductor (*N*) and protective conductor (*PE*) are one and the same or not.

■ case one

The neutral and protective conductors form a single conductor called the *PEN* . This system is identified by a third letter *C* and is called the *TNC* system (see fig. 2-15):

- it is advisable to regularly connect the *PEN* to earth
- this system must not to be used for cross-sectional areas below 10 mm² for copper or 16 mm² for aluminium, as well as for mobile wiring systems. It is also forbidden downstream of a *TNS* system.

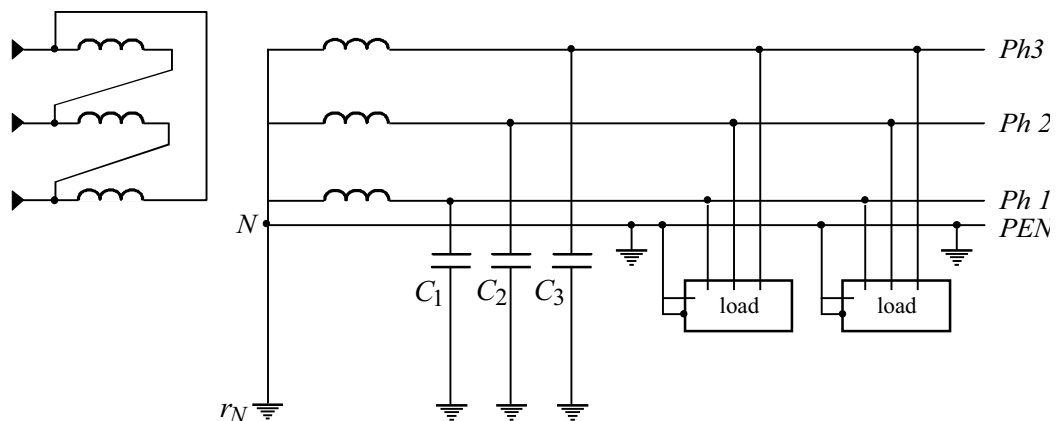


Figure 2-15: TNC earthing system

■ case two

The neutral conductor and protective conductor are separate. The system is then identified by the third letter S and is referred to as the *TNS* system (see fig. 2-16).

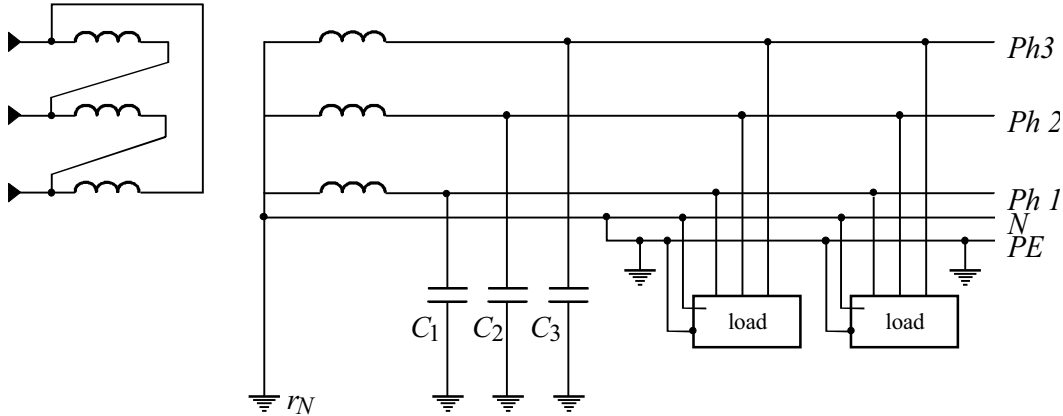


Figure 2-16: TNS earthing system

As for the TNC earthing system, it is advisable to regularly connect the protective conductor to earth.

This earthing system is compulsory for cross-sectional areas below 10 mm² for copper or 16 mm² for aluminium, as well as for mobile wiring systems. It must not be used upstream of a *TNC* earthing system.

Note: both *TNC* and *TNS* earthing systems can be used in the same installation. We then refer to a *TN-C-S* earthing system. But the *TNC* earthing system (4 wires) must never be downstream of the *TNS* earthing system (5 wires) (see fig. 2-17). As previously specified, neutral earthing requires the creation of an equipotential bonding system to avoid the rise in potential of the exposed and extraneous conductive parts during phase-earth faults. It is consequently necessary to connect the *PEN* conductor to numerous earth electrodes spread out over the installation.

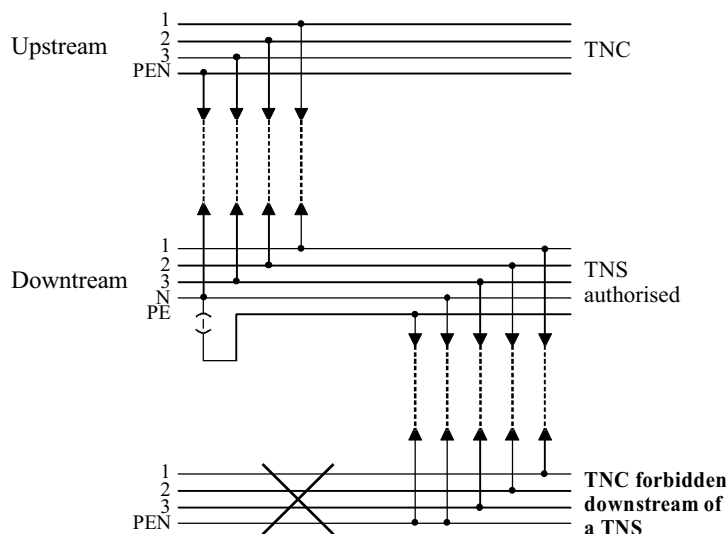


Figure 2-17: combination of TNC and TNS earthing systems

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2.5. Indirect contact in low voltage with respect to the earthing system

2.5.1. Unearthed neutral

■ touch voltage developing on occurrence of the first insulation fault (see fig. 2-18)

Let us take an initially well insulated network. When a first insulation fault occurs on a phase, the fault current I_f is equal to the capacitive current which returns via the healthy phases.

Let us take a very widespread network comprising 10 km of cable; the capacitance between each phase and earth is roughly 2.5 μF and the fault current then has the following value:

$$|I_f| = 3 C \omega V_n \cong 520 \text{ mA} , \text{ neglecting } r_p \text{ and } r_G \text{ in relation to } \frac{1}{C \omega}$$

If $r_p = 10 \Omega$, the interconnected exposed conductive parts are all raised to the same potential:

$$U_T = r_p I_f = 0.52 \times 10 = 5.2 \text{ V}$$

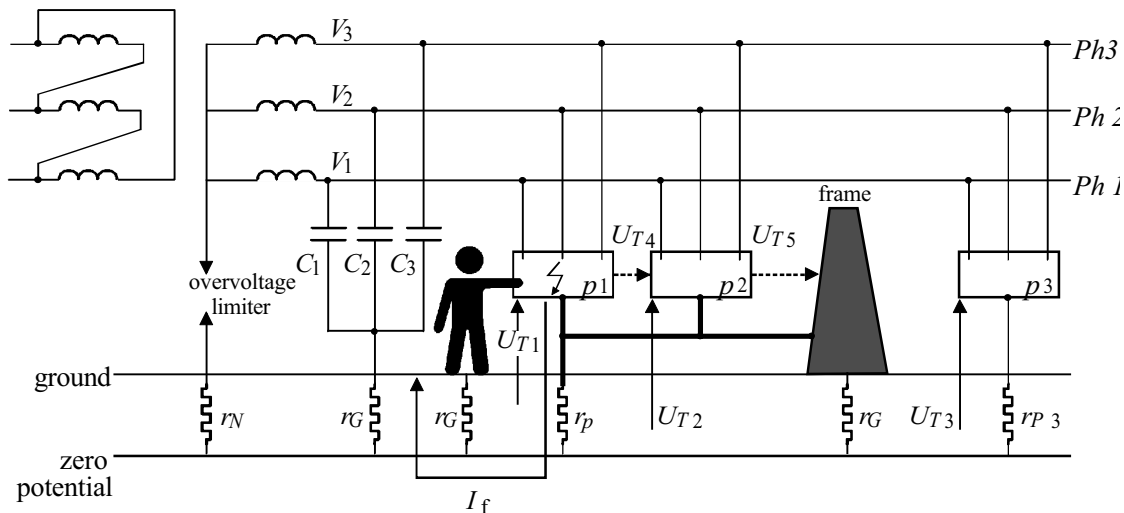
This potential is not dangerous. The voltage occurring between two simultaneously accessible neighbouring exposed conductive parts is negligible. The rise in potential of a non-interconnected remote exposed conductive part is zero.

An unearthed network, even very widespread, is not dangerous when a first insulation fault occurs; operation can continue but the fault must be signalled, located and cleared.

Nevertheless, in the case of a network feeding numerous loads having a high phase-earth capacitive current (e.g. computing equipment input capacitive filters), it is necessary to check that the touch voltage which develops on occurrence of the first insulation fault is lower than the safe limit voltage U_L :

$$U_T = r_p I_f < U_L$$

$U_L = 50 \text{ V}$ for dry premises, 25 V for damp premises.



- r_N : neutral earth electrode resistance
- r_P : exposed conductive part earth electrode resistance
- r_{P3} : resistance of the earth electrode of a non-interconnected remote exposed conductive part
- r_G : ground resistance
- C_1, C_2, C_3 : phase-earth capacitances
- I_f : fault current
- U_{T1}, U_{T2}, U_{T3} : touch voltages in relation to the ground
- U_{T4}, U_{T5} : touch voltage between two simultaneously accessible exposed conductive parts

Figure 2-18: touch voltages in an unearthed network on occurrence of a first insulation fault

■ touch voltage developing on occurrence of the second insulation fault (see fig. 2-19)

When a second insulation fault occurs, a fault current I_f is established between exposed conductive parts p_1 and p_2 .

This current circulates in the phase conductors and protective conductors which ensure interconnection of the exposed conductive parts. It is only limited by the impedance of the fault loop $ABCDEFGHIJ$.

Let us assume that:

- the first load is fed by a 50 mm² copper cable 50 m long and the second by a 25 mm² copper cable 30 m long
- the protective conductors have the same length and the same cross-sectional area as the phase conductors
- the impedance is zero for the FE section.

If we neglect the reactances, the impedance of the *ABCDEFGHJIJ* loop is then equal to:

$$\begin{aligned} Z_{loop} &= 2 \left[\rho \times \left(\frac{30}{25} + \frac{50}{50} \right) \right] \\ &= 2 \times 22.5 \times 10^{-3} \times 2.2 \\ &= 99 \text{ m}\Omega \end{aligned}$$

where:

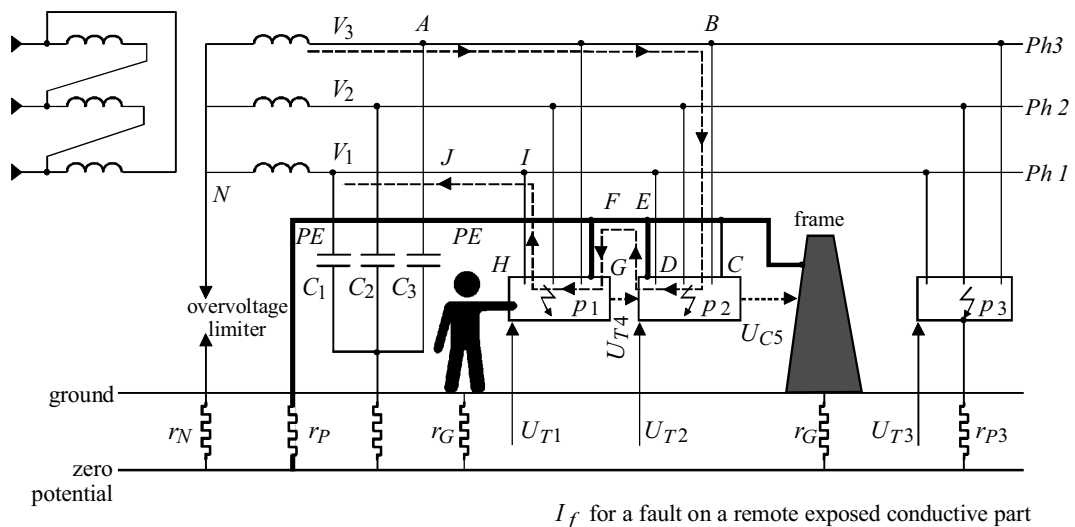
$$\rho = 22.5 \cdot 10^{-3} \Omega \cdot \text{mm}^2 / \text{m} \text{ (copper resistivity).}$$

By taking:

$$U_{BI} = 0.8 U_n = 400 \times 0.8 = 320 \text{ V}$$

to take into account connections *AB* and *IJ*, we have:

$$I_f = \frac{320}{99 \times 10^{-3}} = 3232 \text{ A}$$



I_f for a fault on a remote exposed conductive part

- r_N : neutral earth electrode resistance
- r_P : exposed conductive part earth electrode resistance
- r_{P3} : resistance of the earth electrode of a non-interconnected remote exposed conductive part
- r_G : ground resistance
- C_1, C_2, C_3 : phase-earth capacitances
- I_f : fault current
- U_{T1}, U_{T2}, U_{T3} : touch voltages in relation to the ground
- U_{T4}, U_{T5} : touch voltage between two simultaneously accessible exposed conductive parts
- ABCDEFGHJIJ* : fault loop

Figure 2-19: touch voltage in an unearthed network on occurrence of a second insulation fault

The voltage then occurring between exposed conductive parts p_1 and p_2 is equal to:

$$Z_{DG} I_f = Z_{loop} / 2 \times I_f = 159 \text{ V}$$

The exposed conductive part p_1 is raised to a potential of:

$$\begin{aligned} Z_{FG} I_f &= \left(\rho \frac{50}{50} \right) I_f = 22.5 \cdot 10^{-3} I_f \\ &= 22.5 \cdot 10^{-3} \times 3\,232 \\ &= 73 \text{ V} \end{aligned}$$

and the exposed conductive part p_2 to a potential of:

$$\begin{aligned} Z_{ED} I_f &= \left(\rho \frac{30}{25} \right) I_f \\ &= 22.5 \cdot 10^{-3} \times 1.2 \times 3\,232 \\ &= 87 \text{ V} \end{aligned}$$

The non-interconnected exposed conductive part p_3 does not undergo a rise in potential.

In the case where the second fault is generated on a non-interconnected remote exposed conductive part, the fault current I_f then returns via earth and is limited by the earth electrode resistances r_P and r_{P3} .

If $r_P = 10 \Omega$ and $r_{P3} = 15 \Omega$ for example, the interconnected exposed conductive parts are raised to a potential of:

$$\frac{U_n}{r_P + r_{P3}} r_P = 160 \text{ V}$$

and the remote exposed conductive part to:

$$\frac{U_n}{r_P + r_{P3}} r_{P3} = 240 \text{ V}$$

Whatever the case, the touch voltages are dangerous and it is necessary to disconnect the power supply.

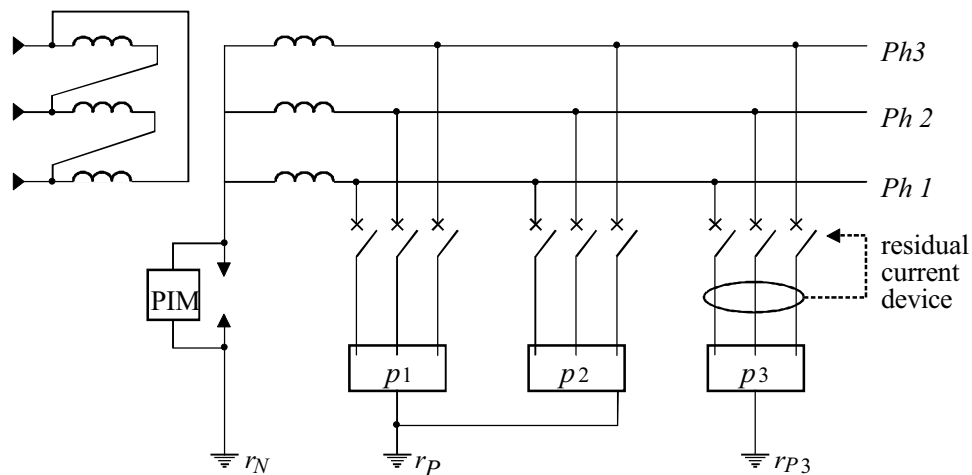
In an unearthed network, the touch voltages which develop on occurrence of a first insulation fault are not dangerous. They only become dangerous on occurrence of a second insulation fault which necessitates disconnection of the power supply.

The operating rules of an unearthed network are as follows:

- permanent monitoring of the insulation by an insulation monitor
- signalling of the first insulation fault, follow-up of its location and clearance by qualified personnel
- compulsory disconnection on occurrence of the second insulation fault.

Disconnection is normally performed by devices ensuring protection against phase-to-phase faults (circuit-breakers, fuses, etc.). It is necessary to check that the current that is generated on occurrence of a second insulation fault is high enough to make these devices operate. This is why it is necessary to interconnect up all the exposed conductive parts of the installation by protective conductors so that the impedances of the loops in which the fault currents develop are controlled.

As previously mentioned, the remote exposed conductive parts may not be interconnected with the others. In this case, the currents which develop on occurrence of two insulation faults are no longer capable of making the phase-to-phase fault protective devices operate. Tripping is then obtained by residual current protective devices. This type of device must be installed on each outgoing feeder supplying a load or group of loads whose exposed conductive parts are not interconnected with those of the other loads (see fig. 2-20).



PIM : permanent insulation monitor

b) We consider that the two faulty circuits have the same impedance

$$R_{AH} = 2 \rho L \left(\frac{1}{S_{ph}} + \frac{1}{S_{PE}} \right)$$

$$R_{AH} = 2 \rho L \frac{1}{S_{ph}} (1 + m)$$

where $m = S_{ph} / S_{PE}$

a) For the faulty circuit, we have:

$$I_f = \frac{U_{AH}}{R_{AH}}$$

$U_{AH} = 0.8 U_n$ by hypothesis

c) I_f must be above $I_{magn.}$ for the protection of persons to be ensured:

$$I_{magn.} < \frac{0.8 U_n S_{ph}}{2 \rho L (1 + m)}$$

$$L_{max} = \frac{0.8 U_n S_{ph}}{2 \rho (1 + m) I_{magn.}}$$

d) touch voltage

$$U_T = R_{CD} I_f = \frac{\rho L}{S_{PE}} I_f = \frac{0.4 U_n m}{1 + m}$$

Table 2-5-a: checks on tripping conditions in an IT earthing system in the case of a non-distributed neutral

a) We consider the first fault on a phase, and the second on the neutral

b) For circuit *A* which does not comprise the neutral, we write:

$$I_f = \frac{U_{AH}}{R_{AH}}$$

$$U_{AH} = 0.8 V_n \text{ by hypothesis}$$

$$R_{AH} = 2 \rho L \left(\frac{1}{S_{ph}} + \frac{1}{S_{PE}} \right)$$

$$= \frac{2 \rho L}{S_{ph}} (1 + m)$$

where $m = S_{ph} / S_{PE}$

c) For circuit *B* comprising the neutral, we write:

$$I_f = \frac{U_{AH}}{R_{AH}}$$

$$U_{AH} = 0.8 V_n \text{ by hypothesis}$$

$$R_{AH} = 2 \rho L \left(\frac{1}{S_N} + \frac{1}{S_{PE}} \right)$$

$$= \frac{2 \rho L}{S_N} (1 + m)$$

where $m = S_N / S_{PE}$

d) touch voltage

$$U_T = R_{CD} I_f = \frac{\rho L}{S_{PE}} I_f = 0.4 V_n \frac{m}{1 + m}$$

$$I_{magn.} < \frac{0.8 V_n S_{ph}}{2 \rho L (1 + m)}$$

$$L_{max} = \frac{0.8 V_n S_{ph}}{2 \rho (1 + m) I_{magn.}}$$

Table 2-5-b: checks on tripping conditions in an IT earthing system in the case of a distributed neutral

$ABCDEFGHI$: fault loop

I_f : fault current

L : length of cables

L_{\max} : in metres

V_n : single-phase voltage in volts (230 V for a 230/400 V network)

U_n : phase-to-phase voltage in volts (400 V for a 230/400 V network)

U_T : touch voltage

S_{ph} : cross-sectional area of phases in mm^2

$S_1 = S_{ph}$ if the circuit considered does not comprise the neutral,

$S_1 = S_N$ if the circuit does comprise the neutral

S_N : neutral conductor cross-sectional area

S_{PE} : protective conductor cross-sectional area

ρ : resistivity of the conductors

$\rho = 27 \cdot 10^{-3} \Omega \cdot \text{mm}^2 / \text{m}$ for copper = 1.5 times the resistivity at 20 °C

$\rho = 43 \cdot 10^{-3} \Omega \cdot \text{mm}^2 / \text{m}$ for aluminium = 1.5 times the resistivity at 20 °C

$$m = \frac{S_{ph} \text{ (or } S_1)}{S_{PE}}$$

$I_{\text{magn.}}, I_{\text{fus}}$: currents ensuring operation of the protective devices in a time less than the disconnection time

corresponding to the touch voltage developing on the faulty load.

Table 2-5-c: key to tables 2-4-a and 2-4-b

2.5.1.1. Implementing the *IT* earthing system and operation

■ general provisions

The *IT* earthing system does not require the power supply to be automatically disconnected on occurrence of an insulation fault, referred to as the "first fault".

Indeed, we have seen that for this system the touch voltages which develop on occurrence of a first insulation fault are not dangerous for persons.

Thus, operation can continue in spite of the "first fault" thus increasing service continuity. This system requires the following means to be implemented:

- installation of a permanent insulation monitor (*PIM*) which must signal the "first fault" (sound or visual signal or both).
- search for the first insulation fault by an efficient maintenance service so that all the advantages of this earthing system are exploited. Automatic fault location equipment may be used to facilitate the process.
- tripping on occurrence of any new fault, referred to as the "second fault".
- checking of phase-to-phase fault protective device tripping conditions with the setting up of specific means if these conditions cannot be guaranteed (see § specific provisions).
- installation at the transformer secondary terminals of an overvoltage limiting device connected between the neutral and earth or between one phase and earth.

■ monitoring of insulation and help with first fault location

Systems for insulation monitoring and help with first fault location have been developed and provide a significant reduction in the number of maintenance and repairs operations.

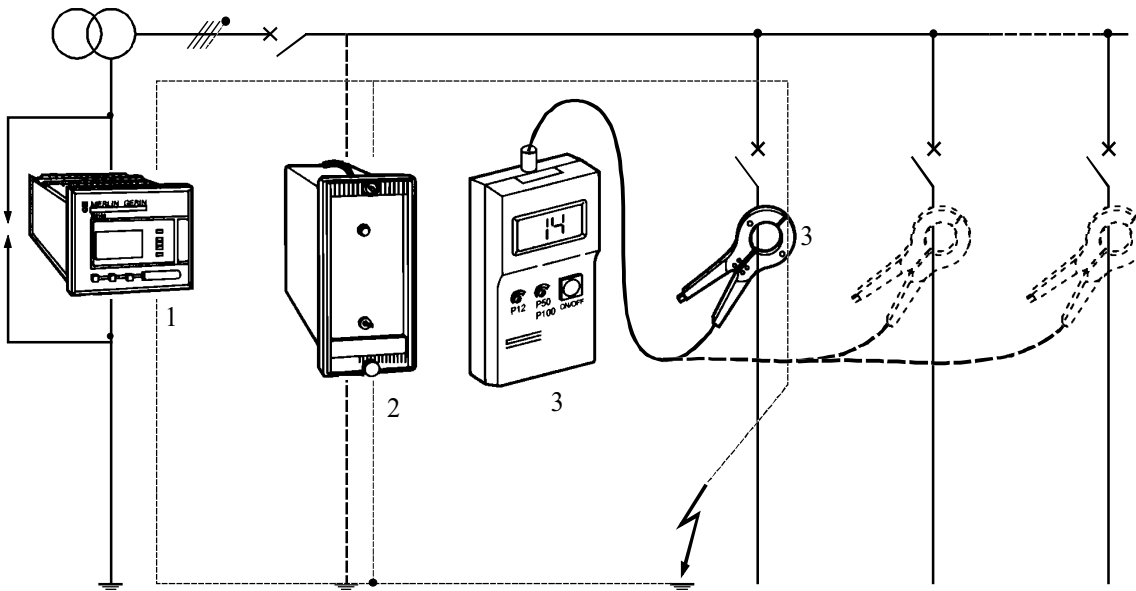
The principle implemented consists in applying a low frequency or d.c. low voltage between the network to be monitored and earth using a suitable generator. When the insulation decreases a leakage current is established. The measurement of this current helps to evaluate the level of network insulation and locate the position of an eventual fault.

Only systems injecting a low frequency signal allow faults to be located. These may be used both on direct current and alternating current installations and some are able to distinguish between the resistive part and the capacitive part of the earth current and thus carry out a true measurement of the network insulation resistance.

Modern systems allow the insulation resistance of each circuit to be continuously measured; prevention of the first fault thus becomes possible. The measurements carried out in an installation are transmitted by digital link to a central processing unit which supplies all the information necessary to the users.

□ example 1: hand-held mobile fault location (see fig. 2-21)

The generator can be stationary or mobile and both the detector and ammeter are mobile.

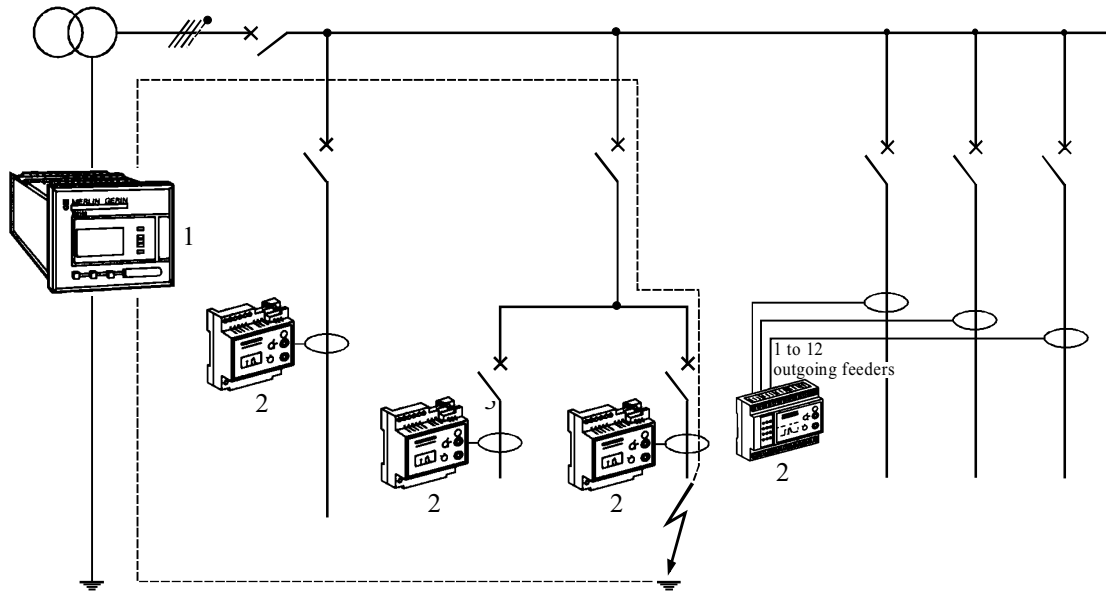


- 1 : LF fixed generator
- 2 : LF mobile generator
- 3 : mobile detector and ammeter

Figure 2-21: hand-held mobile fault location

□ example 2 : automatic fixed fault location

The permanent insulation monitor and the detectors associated with toroids installed on each outgoing feeder provide an energized automatic location system.



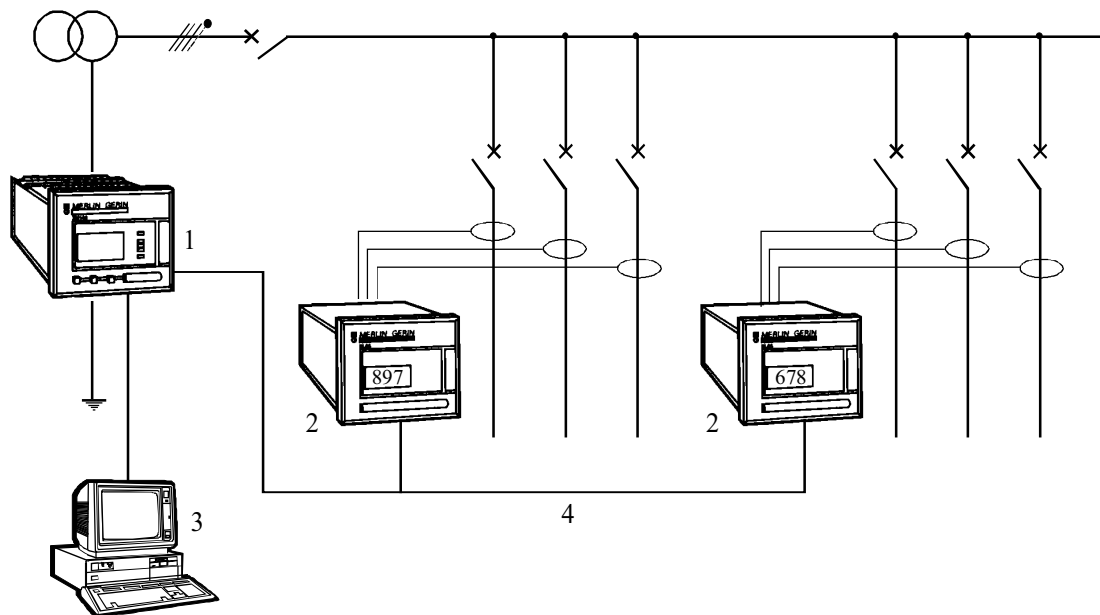
- 1 : *LF* fixed generator
- 2 : fixed detectors

Figure 2-22: automatic fixed fault location

□ **example 3: automatic operation and fault location** (see fig. 2-23)

The insulation monitor and detectors associated with toroids installed on each outgoing feeder enable the changes in insulation level of each circuit to be followed.

The central processing unit communicates with a PC which provides an overall view of the network, its insulation level and the changes in insulation of each circuit.



- 1 : LF fixed generator and central processing unit
- 2 : detectors
- 3 : PC
- 4 : digital link

Figure 2-23: automatic operation and fault location

■ **specific provisions**

□ **use of high-sensitivity residual current devices** (see fig. 2-24)

IEC 364-4-471 recommends the use of high-sensitivity ($\leq 30 \text{ mA}$) residual current devices in the following cases:

- $\leq 32 \text{ A}$ rated power outlet circuits, whatever the premises
- power outlet circuits in damp premises whatever their rated current
- power outlet circuits in temporary installations
- circuits feeding washrooms and swimming pools
- power supply of work site installations, caravans, pleasure boats, fun fairs.

This protection may be individual, by circuit or by group of circuits connected to the same earth electrode.

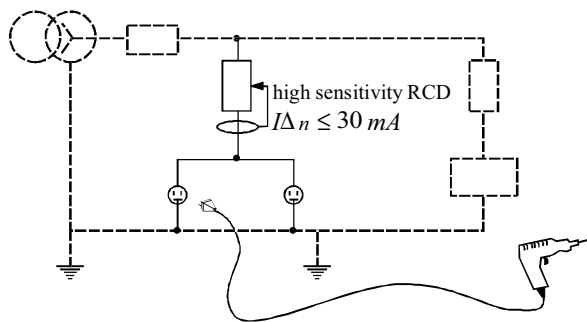


Figure 2-24: power outlet circuit

□ **prevention in premises where there is a risk of fire** (see fig. 2-25)

Using residual current devices having a $\leq 500 \text{ mA}$ sensitivity is recommended for the protection of circuits (IEC 364-4-482).

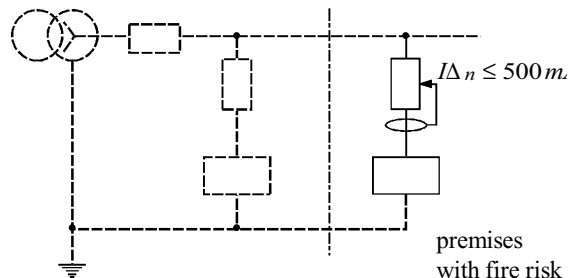


Figure 2-25: premises where there is a risk of fire

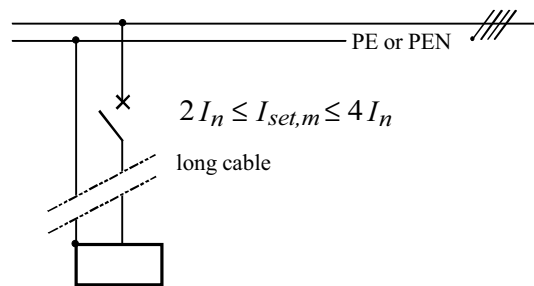
□ **case where the loop impedance is particularly high**

When the conditions to ensure tripping of protective devices against phase-to-phase faults cannot be fulfilled, the following solutions may be used.

- **suggestion 1** (see fig. 2-26)

Install a device with a sufficiently low magnetic setting to guarantee the relation $I_{sc\ min} > I_{magn}$.

This solution allows the protection of persons to be ensured for a long circuit. However, it is necessary to check that the device will not be tripped by high currents which are generated when loads (motors and other devices having a high inrush current) are energized.



$I_{set,m}$: magnetic operating threshold

Figure 2-26: device with low magnetic threshold

- **suggestion 2** (see fig. 2-27)

Install a residual current device. The high value of the fault currents authorises the use of weak-sensitivity devices (several amps to several dozen amps).

This solution does not require any checks to be carried out.

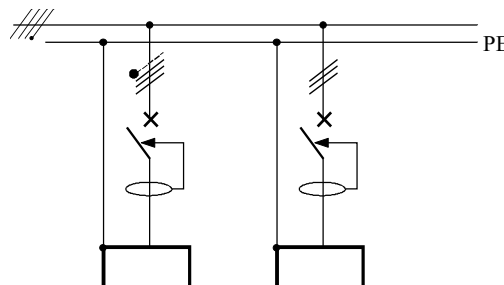


Figure 2-27: residual current protection

- **suggestion 3**

Increase the cross-sectional area of the protective conductors or phases or both simultaneously until the requirements for the protection of persons have been met. A protective conductor cross-sectional area equal to the cross-sectional area of the phases is generally chosen.

- **suggestion 4** (see fig. 2-28-a)

Make additional equipotential bonding which will help to reduce the fault loop impedances. Measurements must be carried out to check its effectiveness.

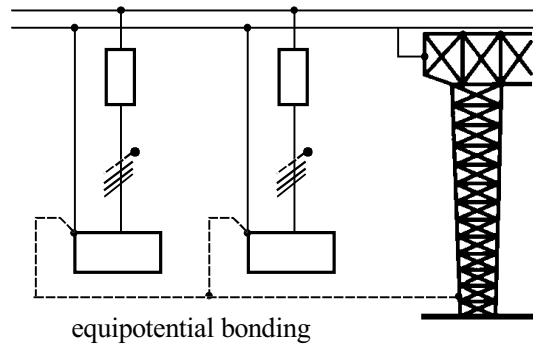


Figure 2-28-a: additional equipotential bonding

- **specific case where an exposed conductive part or group of exposed conductive parts is connected to a separate earth electrode** (see fig. 2-28-b)

Protection against indirect contact performed by a residual current device (RCD) must be installed at the head of each group of exposed conductive parts connected to a separate earth electrode. The sensitivity must match the earth electrode resistance r_{p2} :

$$I \Delta n \leq \frac{U_L}{r_{p2}}$$

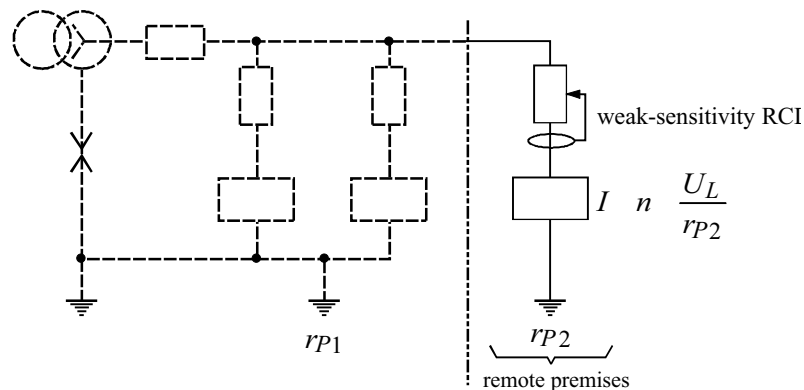


Figure 2-28-b: separate earth electrode

□ **protection when an exposed conductive part is not earthed** (see fig. 2-28-c)

Only tolerated for dry premises or places when it is not possible to construct an earth electrode.

It is compulsory to use a high-sensitivity (≤ 30 mA) residual current device on the outgoing feeder concerned.

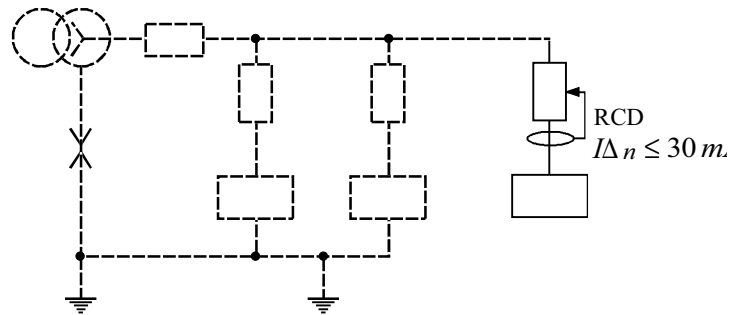
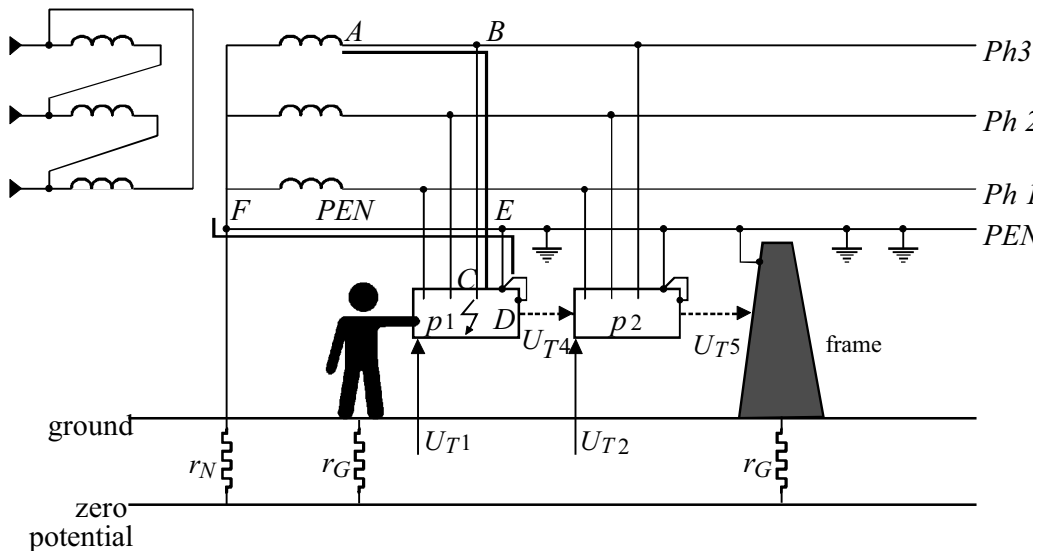


Figure 2-28-c: unearthed exposed conductive part

2.5.2. Neutral earthing (TN system) (see fig. 2-29)



- r_N : neutral earth electrode resistance
- r_G : ground resistance
- U_{T1}, U_{T2} : touch voltages between exposed conductive part and earth
- U_{T4}, U_{T5} : touch voltages between simultaneously accessible exposed conductive parts
- $ABCDEF$: fault loop

Figure 2-29: touch voltage on occurrence of a fault (TN earthing system)

The principle of neutral earthing is to transform any insulation fault into a phase-neutral single-phase short circuit. The fault current is no longer limited by the fault loop impedance $Z_{loop} = ABCDEF$.

In the case of a load fed by a 50 mm² copper cable 50 m long, for example, if the protective conductor has the same cross-sectional area as the phase conductors and if we neglect AB and EF , then we have:

$$Z_{loop} = Z_{BCDE} = 2 \times 22.5 \cdot 10^{-3} \times \frac{50}{50} = 45 \text{ m}\Omega$$

Taking a coefficient of 0.8 to take account of the upstream connections AB and EF :

$$V_{BE} = 0.8 \times 230 = 184 \text{ V}$$

we have:
$$I_f = \frac{184}{45 \cdot 10^{-3}} = 4\,089 \text{ A}$$

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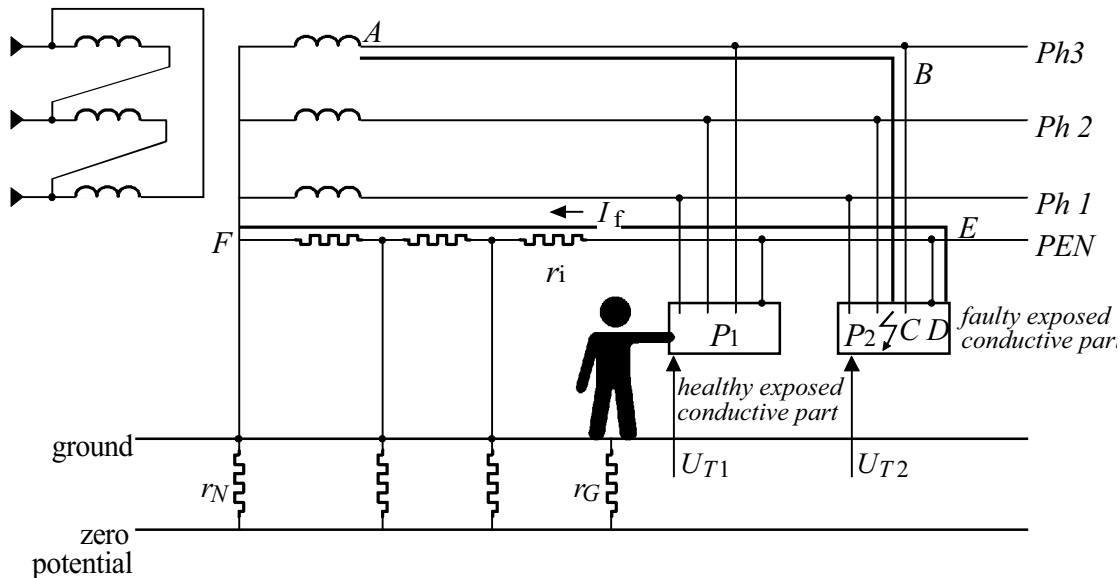
If we neglect the impedance of section EF , the exposed conductive part is then increased to a potential of $U_{T1} = Z_{DE} I_f$ in relation to earth,

$$Z_{DE} = \frac{Z_{BE}}{2}$$

and
$$U_{T1} = \frac{V_{BE}}{2} = \frac{184}{2} = 92 \text{ V}$$

The touch voltage U_{T4} between two neighbouring exposed conductive parts is also equal to $Z_{DE} I_f = 92 \text{ V}$.

If the protective conductor is earthed at regular intervals so that equipotential zones are created, the healthy exposed conductive parts are subject to a negligible rise in potential (see fig. 2-30).



r_N : neutral earth electrode resistance

r_G : ground resistance

r_i : resistance of the protective conductor portion connecting a healthy exposed conductive part to earth

I_f : fault current

$U_T = r_i I_f$: touch voltages on a healthy exposed conductive part

$ABCDEF$: fault loop

Figure 2-30: touch voltage on a healthy exposed conductive part

Indeed, in these conditions, the touch voltage that is generated on an exposed conductive part is equal to the voltage drop occurring along the portion of the protective conductor which connects this exposed conductive part to earth. If there are earth electrodes all along the protective conductor, the length of this portion is small compared with the length of the **fault loop**, such that the touch voltage which appears on the healthy exposed conductive part is low.

A network with neutral earthing (*TN* system) is dangerous on occurrence of the first insulation fault; the power supply must therefore be disconnected on occurrence of this fault.

With the fault currents being high, disconnection may be carried out by phase-to-phase fault protective devices (circuit-breakers, fuses) as in the *IT* earthing system for a double fault. It is essential that the tripping conditions of these devices are checked. The previously described simplified method for the *IT* earthing system can be applied (see table 2-6).

In the case where operation of these devices cannot be obtained due to the high values of the fault loop impedances, other protective devices should be used (residual current devices, for example) or specific means should be implemented (see § 2.5.2.1).

$$I_f = \frac{U_{AD}}{R_{AD}}$$

$$U_{AD} = 0.8 V_n \text{ by definition}$$

$$R_{AD} = \rho L \left(\frac{1}{S_{PE}} + \frac{1}{S_{ph}} \right) = \rho \frac{L}{S_{ph}} (1 + m)$$

where $m = \frac{S_{ph}}{S_{PE}}$

The current I_f must be higher than $I_{magn.}$ for the protection of persons to be ensured, whence:

$$I_{magn.} < \frac{0.8 V_n S_{ph}}{\rho L (1 + m)}$$

$$L_{max} = \frac{0.8 V_n S_{ph}}{\rho (1 + m) I_{magn.}}$$

The touch voltage is:

$$U_T = R_{CD} I_f$$

$$= \frac{0.8 V_n S_{ph}}{S_{PE} (1 + m)} = 0.8 V_n \frac{m}{1 + m}$$

Table 2-6: checking tripping conditions in a *TN* earthing system

To check tripping conditions, Ohm's law is applied to the only outgoing feeder concerned by the fault, with the following hypotheses being taken:

- 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 single-phase voltage
- for cross-sectional areas < 150 mm², the conductor reactances are neglected compared with their resistances (see § 2.5.1.)
- the protective conductor runs alongside the phase conductors.

The calculation shows that the circuit length must not be greater than the value given by the relation:

$$L_{\max} = \frac{0.8 V_n S_{ph}}{\rho (1 + m) I_{\text{magn.}} \text{ (or } I_{\text{fus}} \text{)}}$$

where:

- L_{\max} : maximum length in metres
- V_n : single-phase voltage ($V_n = 230$ V for a 230/400 V network)
- S_{ph} : phase cross-sectional area in mm²
- ρ : resistivity of conductors
- $\rho = 27 \cdot 10^{-3} \Omega \cdot \text{mm}^2 / \text{m}$ for copper = 1.5 times the resistivity at 20 °C
- $\rho = 43 \cdot 10^{-3} \Omega \cdot \text{mm}^2 / \text{m}$ for aluminium = 1.5 times the resistivity at 20 °C
- m : $m = S_{ph} / S_{PE}$
- S_{PE} : protective conductor cross-sectional area
- $I_{\text{magn.}}, I_{\text{fus}}$: currents ensuring operation of the protective devices (circuit-breaker or fuse) in times shorter than the times specified in tables 2-3-a and 2-3-b.

$I_{\text{magn.}}$ and I_{fus} are currents ensuring operation of the protective devices in times shorter than the times corresponding to the touch voltage which appears on the faulty load. As for the *IT* earthing system, IEC 364-4-41 authorises the prospective touch voltage which appears on occurrence of the fault to be neglected and stipulates constant disconnecting times depending on the network nominal voltage (see table 2-7).

Nominal voltage V_n	Disconnecting time (s)
120 - 127	0.8
220 - 230	0.4
380 - 400	0.2
> 400	0.1

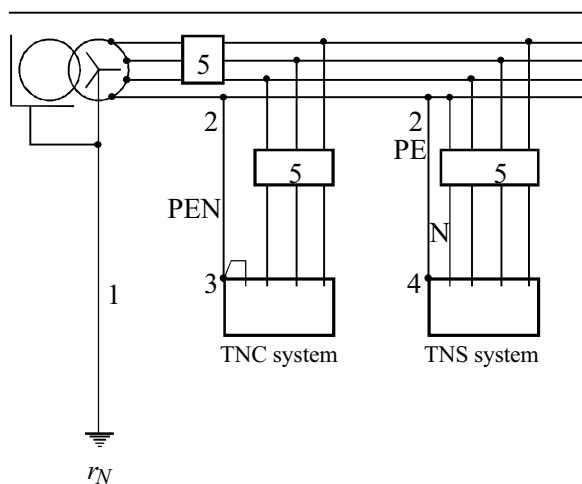
Table 2-7: TN earthing system - maximum disconnecting time (IEC 364-4-41)

2.5.2.1. Implementing the TN earthing system

■ general provisions

These are listed below and shown in figure 2-31:

- earth the *PE* protective conductor at regular intervals
- make the *PE* or *PEN* protective conductors run alongside the phase conductors without inserting any ferromagnetic device or using cables comprising phase conductors and the protective conductor
- connect the *PEN* conductor to the load "exposed conductive part"
- separation of the neutral conductor and protective conductor when the cross-sectional area is $\leq 6 \text{ mm}^2$ for copper or 10 mm^2 for aluminium or in the presence of mobile wiring systems
- tripping on occurrence of the first insulation fault via conventional protective devices (circuit-breaker or fuse)
- checking of protective device tripping conditions. This check must be made by means of calculation when the installation is being designed and by measurements when it is being started up .



- 1 : direct neutral point earthing
- 2 : *PE* or *PEN* protective conductor
- 3–4 : connection of exposed conductive parts to protective conductor
- 5 : phase-to-phase fault protective device

Figure 2-31: implementing the TN earthing system

Note: the *PEN* conductor must neither be disconnected, nor comprise switchgear. The protective devices are therefore:

- three-pole when the circuit comprises a *PEN* conductor (*TNC* earthing system)
- four-pole ($3P + N$) when the circuit comprises a neutral conductor and a *PE* conductor (*TNS* earthing system).

■ specific provisions**□ high-sensitivity residual current device** (see fig. 2-32)

Using high-sensitivity (≤ 30 mA) residual current devices (RCD) is compulsory in the following cases:

- ≤ 32 A rated power outlet circuits, whatever the type of premises
- power outlet circuits in damp premises whatever the rated currents
- power outlet circuits in temporary installations
- circuits feeding washrooms and swimming pools
- power supply of work site installations, caravans, pleasure boats, fun fairs.

This protection may be individual, by circuit or by group of circuits

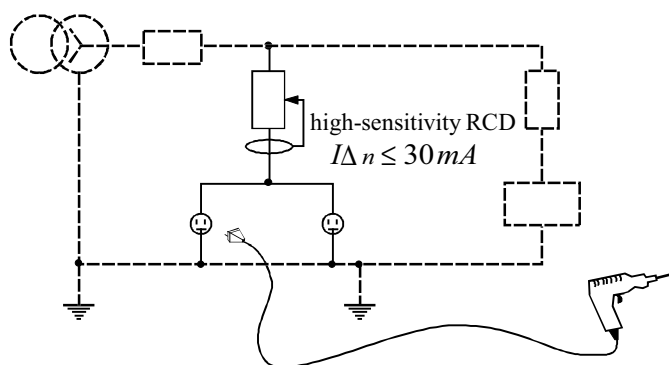


Figure 2-32: power outlet circuit

- **specific case where an exposed conductive part or a group of exposed conductive parts is connected to a separate earth electrode** (see fig. 2-33)

Protection against indirect contact performed by residual current devices (RCD) must be installed at the head of each group of exposed conductive parts connected to a separate earth electrode. The sensitivity must match the resistance r_{p2} of the earth electrode: $I \Delta n \leq \frac{U_L}{r_{p2}}$

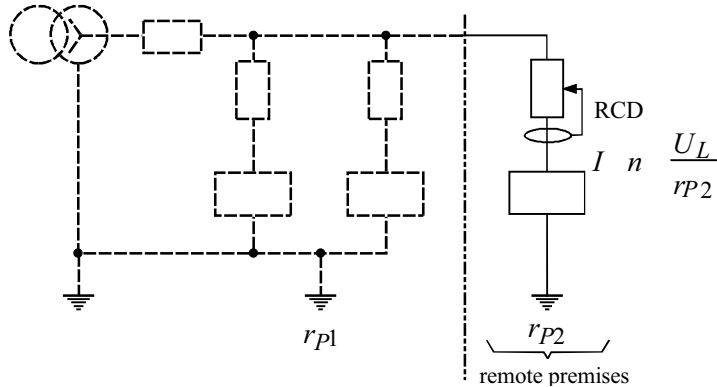


Figure 2-33: separate earth electrode

- **prevention in premises where there is a risk of fire** (see fig. 2-34)

In premises where there is a risk of fire, the $TN - C$ earthing system is forbidden and the $TN - S$ earthing system is therefore compulsory; the use of residual current devices with a sensitivity of $\leq 500 \text{ mA}$ is recommended for the protection of circuits (IEC 364-4-482).

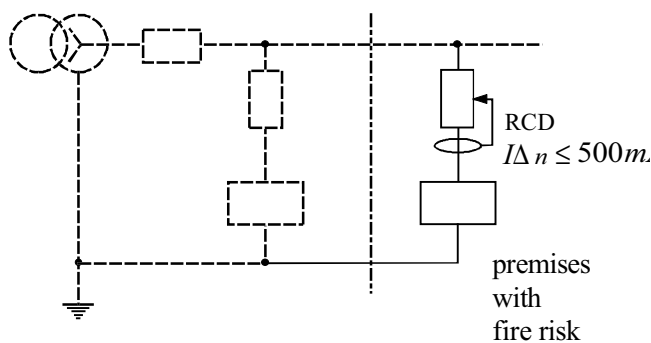


Figure 2-34: premises where there is a risk of fire

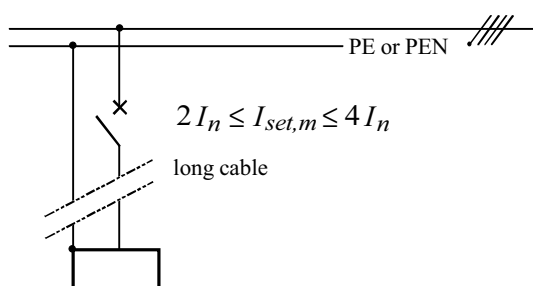
□ case where the loop impedance is particularly high

When tripping of the overcurrent protective devices cannot be carried out, the following solutions may be applied.

- **suggestion 1** (see fig. 2-35)

Install a device with a low magnetic setting.

This solution allows the protection of persons to be ensured for a circuit having a high fault loop impedance. However, it is necessary to check that the device will not be tripped by high currents when a load or loads are energized.



$I_{set,m}$: magnetic operating threshold

Figure 2-35: device with low magnetic threshold

- **suggestion 2** (see fig. 2-36)

Install a residual current device. The high value of the fault currents authorises the use of weak-sensitivity devices (several amps to several dozen amps).

This solution does not require any checks to be carried out.

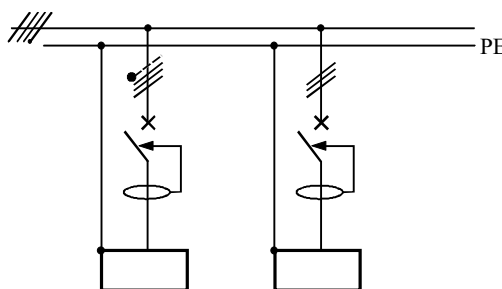


Figure 2-36: residual current protection

- **suggestion 3**

Increase the cross-sectional areas of the protective conductors (*PE* or *PEN*) or phase conductors or both simultaneously until the requirements for the protection of persons have been met.

- **suggestion 4** (see fig. 2-37-a)

Make additional equipotential bonding which will help to reduce the fault loop impedances. Measurements must be carried out to check their effectiveness.

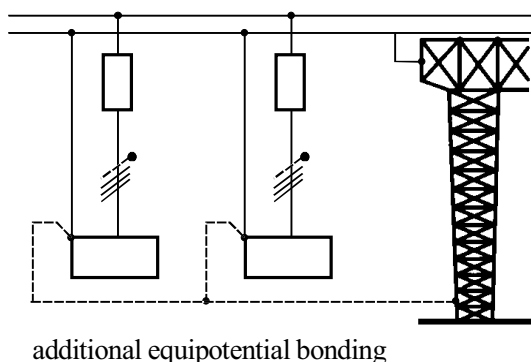


Figure 2-37-a: additional equipotential bonding

- **protection when an exposed conductive part is not earthed** (see fig. 2-37-b)

Only tolerated for dry premises or places when it is not possible to construct an earth electrode.

It is compulsory to use a high-sensitivity (≤ 30 mA) residual current device on the outgoing feeder concerned.

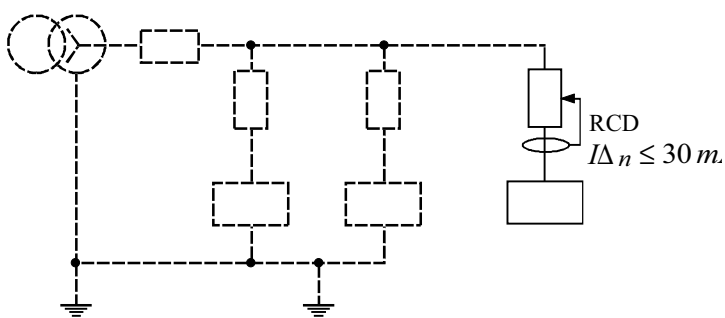
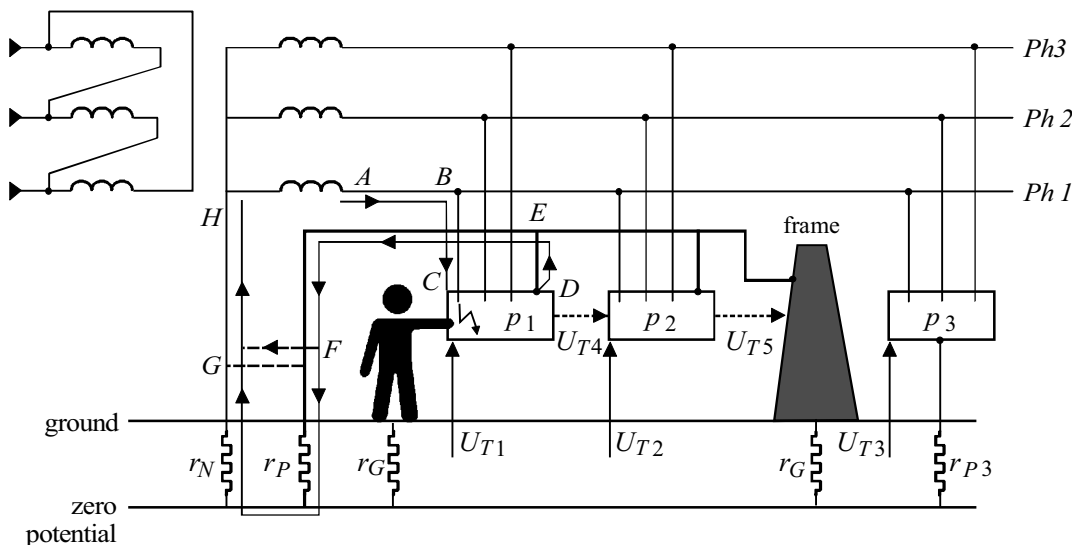


Figure 2-37-b: unearthed exposed conductive part

2.5.3. Neutral earthing (TT system) (see fig. 2-38)



- r_N : neutral earth electrode resistance
- r_P : resistance of the earth electrode of the exposed conductive parts
- r_G : ground resistance
- r_{P3} : resistance of the earth electrode of one non-interconnected remote exposed conductive part
- I_f : fault current
- U_{T1}, U_{T2}, U_{T3} : touch voltages between exposed conductive part and ground
- U_{T4}, U_{T5} : touch voltage between two simultaneously accessible exposed conductive parts
- $ABCDEFGH$: fault loop

Figure 2-38: touch voltage on occurrence of an insulation fault (TT earthing system)

In the presence of an insulation fault, a fault current I_f is generated which, if the earth electrode of the exposed conductive parts and that of the neutral are not interconnected, is essentially limited by the resistances of these earth electrodes:

$$I_f = \frac{V_n}{r_N + r_P}$$

V_n being the network single-phase voltage.

If $r_N = 10 \Omega$ and $r_P = 15 \Omega$ for example, we have:

$$I_f = \frac{230}{25} = 9.2 A$$

The interconnected exposed conductive parts are thus increased to a potential of U_{T1} :

$$U_{T1} = r_P I_f = 15 \times 9.2 = 138 \text{ V}$$

a potential which is dangerous and requires the power supply to be disconnected.

The voltage occurring between two neighbouring exposed conductive parts p_1 and p_2 is equal to:

$$U_{T4} \cong Z_{DE} I_f$$

Z_{DE} being the impedance of portion DE ; if this portion is made up of a 50 mm² copper cable 50 m long, we have:

$$Z_{DE} = 22.5 \times 10^{-3} \Omega$$

and $U_{T4} = 22.5 \times 9.2 \times 10^{-3}$, i.e. 0.21 V , which is an inoffensive potential.

An exposed conductive part p_3 which is not interconnected with the others is not subject to a rise in potential.

For example, if the neutral and exposed conductive part earth electrodes are connected by entrenched conductors, the fault current no longer returns via earth, and is only limited in practice by the $ABCDEFGH$ fault loop impedance .

Its value may be high and the exposed conductive parts increased to a dangerous potential. For a loop impedance Z_{loop} of 100 m Ω , we have a fault current of 2 200 A.

And if $Z_{DF} \cong Z_{loop} / 2$, for example, the exposed conductive part p_1 is increased to a potential of 110 volts. If $Z_{DE} \cong Z_{DF} / 2$, the voltage occurring between exposed conductive parts p_1 and p_2 is equal to 55 volts.

The touch voltages appearing on occurrence of an insulation fault in a network with a solidly earthed neutral (TT system) are dangerous. Tripping on occurrence of a fault is thus obligatory. Furthermore, if the neutral earth electrode and that of the exposed conductive parts are not interconnected, the fault currents are low and are not detected by the phase-to-phase fault protective devices (circuit-breaker or fuse). Disconnection must therefore be obtained by residual current devices (RCD). When the neutral and exposed conductive part earth electrodes are interconnected or the same, the fault currents are much higher.

Nevertheless, since no provision is required in this system in order to reduce, calculate and measure fault loop impedances, it is impossible to be sure that the phase-to-phase fault protective devices can operate, the installation remains a *TT* type and installing residual current devices is still obligatory (see fig. 2-39).

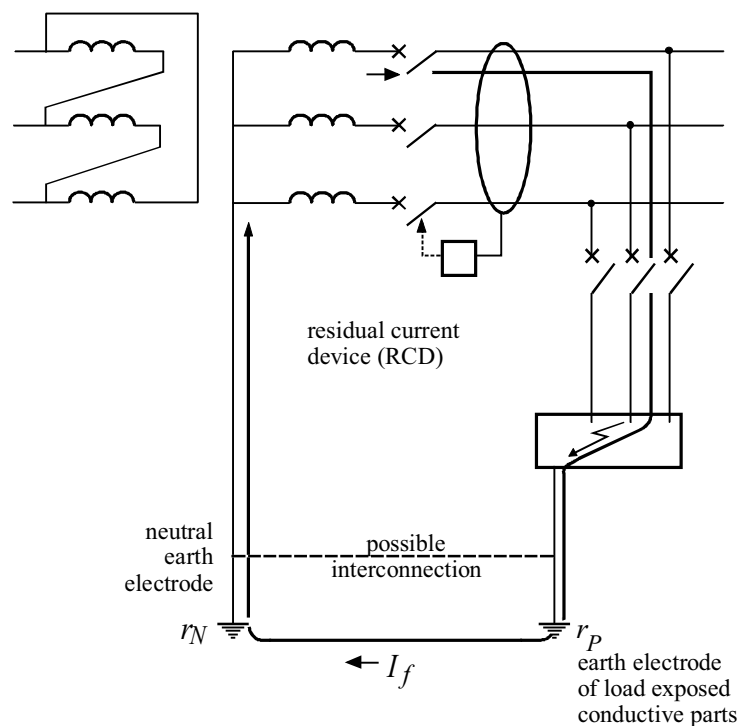


Figure 2-39: protection by a residual current device (*TT* earthing system)

2.5.3.1. Implementing the *TT* earthing system

■ general provisions

The exposed conductive parts are interconnected and earthed either altogether or in groups, or individually.

Protection against indirect contact is ensured by *RCD* having a sensitivity $I \Delta n$ to meet the condition:

$$I \Delta n \leq \frac{50 V}{r_p} \quad (1)$$

(1) 25 V in damp premises, work site installations and farm buildings.

The choice of RCD sensitivity, which depends on the earth electrode resistance, is given in table 2-8.

$I \Delta n$	Maximum earth electrode resistance	
	$U_L = 50 V$	$U_L = 25 V$
3 A	16 Ω	8 Ω
1 A	50 Ω	25 Ω
500 mA	100 Ω	50 Ω
300 mA	166 Ω	83 Ω
30 mA	1 660 Ω	833 Ω

Table 2-8: upper limit of the exposed conductive part earth electrode resistance which must not be exceeded in relation to the sensitivity of the RCD and the limit voltage U_L

■ specific provisions

□ provisions to ensure selectivity

To allow selectivity, IEC 364-4-41 authorises operation of the residual current device placed at the head of the installation to be delayed by a time at the most equal to 1 sec. It is thus possible to carry out total selectivity for earth faults and on several levels as shown in figure 2-40.

Total selectivity with 4 levels

Protection :

- at A: RCD delayed
- at B: RCD delayed
- at C: RCD delayed
- at D: RCD instantaneous

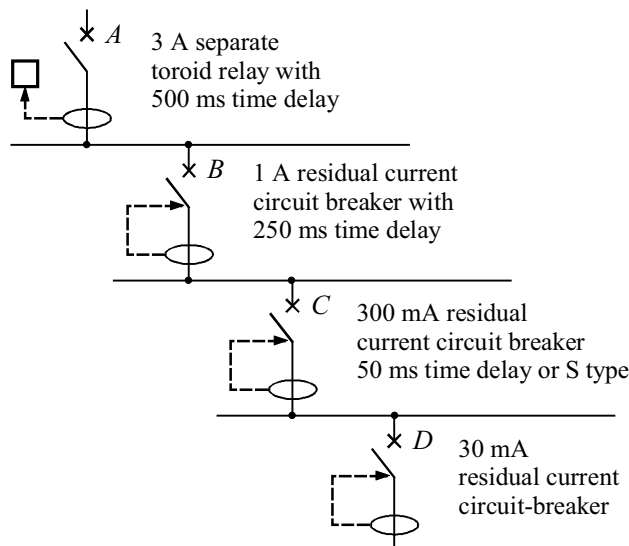


Figure 2-40: total selectivity with 4 levels

□ case where an exposed conductive part or a group of exposed conductive parts is connected to a separate earth electrode (see fig. 2-41)

Protection against indirect contact performed by an RCD must be installed at the head of each group of exposed conductive parts connected to a separate earth electrode. The sensitivity must match the earth electrode resistance r_{p2} .

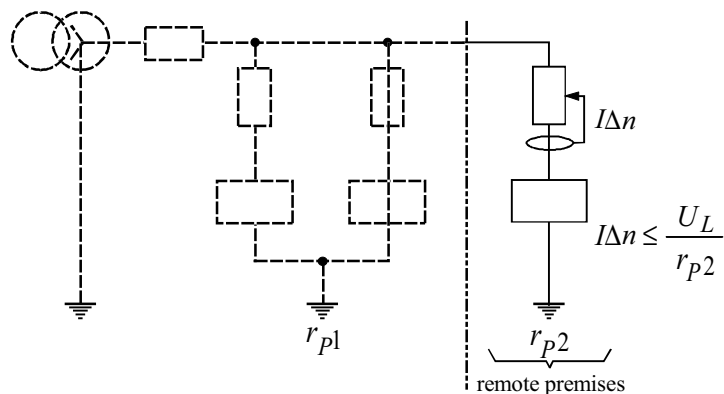


Figure 2-41: separate earth electrode

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□ **high-sensitivity residual current device** (see fig. 2-42)

IEC 364-4-41 recommends the use of high-sensitivity (≤ 30 mA) residual current devices in the following cases:

- ≤ 32 A rated power outlet circuits, whatever the type of premises
- power outlet circuits in damp premises whatever their rated current
- power outlet circuits in temporary installations
- circuits feeding washrooms and swimming pools
- power supply of work site installations, caravans, pleasure boats, fun fairs.

This protection may be individual, by circuit or by group of circuits.

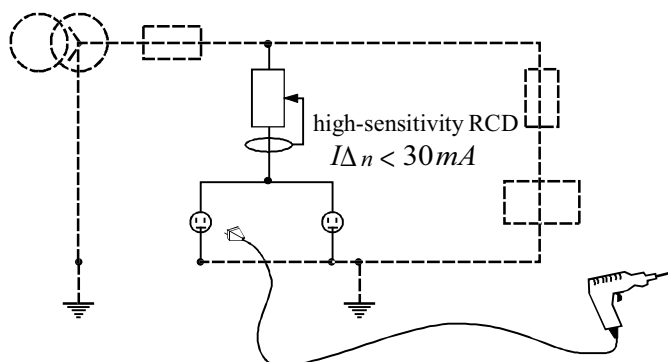


Figure 2-42 : power outlet circuit

□ **prevention in premises where there is a risk of fire** (see fig. 2-43)

The use of ≤ 500 mA sensitive residual current devices is recommended for the protection of circuits (IEC 364-4-482).

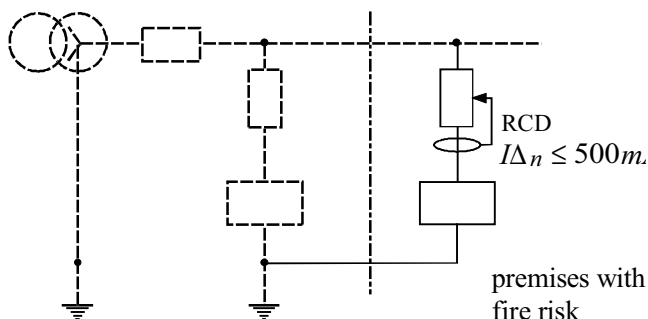


Figure 2-43: premises where there is a risk of fire

□ **protection when an exposed conductive part is not earthed** (see fig. 2-44)

Only tolerated for dry premises or places when it is not possible to construct an earth electrode.

It is compulsory to use a high-sensitivity (≤ 30 mA) residual current device on the outgoing feeder concerned.

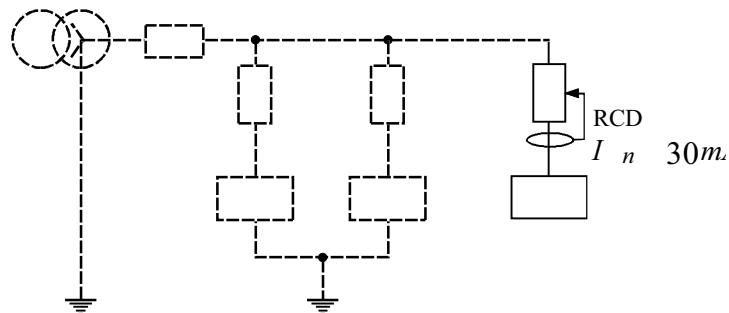


Figure 2-44: unearthed exposed conductive part

2.6. Specific features of residual current devices

2.6.1. Description, general principle

The operating principle of a residual current device is shown in figure 2-45.

A coil wound around a magnetic circuit arranged around the conductors of the circuit to be protected makes up the sum of the currents flowing through this circuit. In normal circumstances, this sum and the current i_3 are zero. On occurrence of the insulation fault, a differential current I_d appears which returns via the outside (protective conductor, earth electrodes, etc.) and a current i_3 which causes the device to operate.

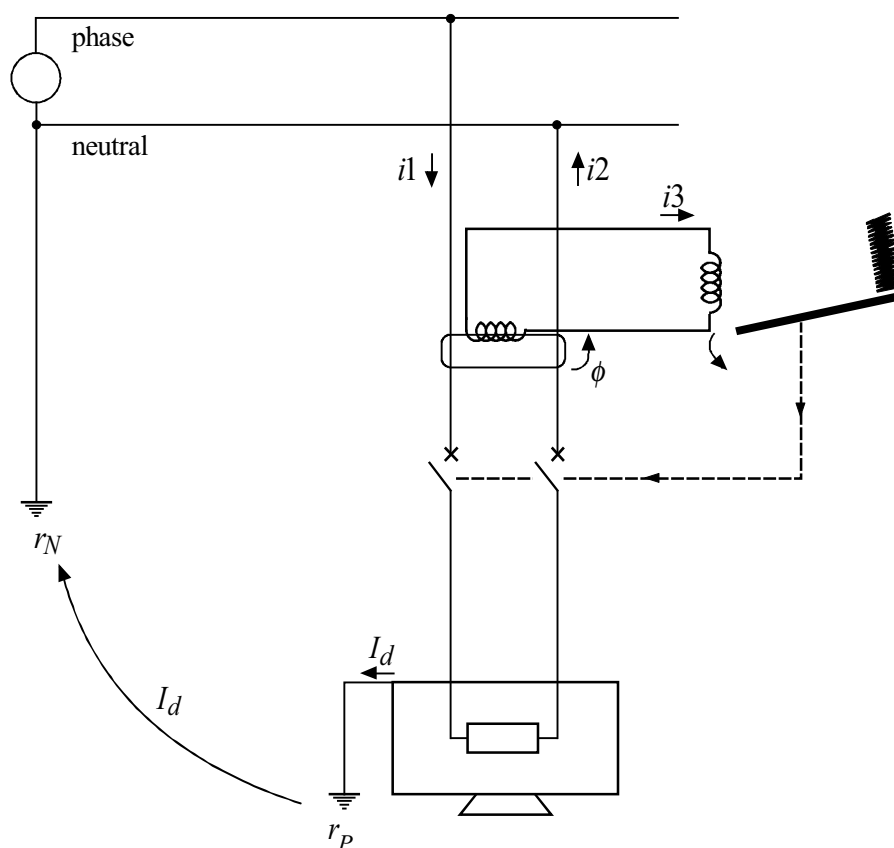


Figure 2-45: illustration of the principle of residual current devices

2.6.2. Characteristics of implementing RCD

Various phenomena can disturb the operation of residual current devices and thus cause spurious tripping. These phenomena are described below.

2.6.2.1. Continuous leakage currents

All *LV* electrical installations have an earth leakage current due mainly to the phase-to-earth capacitance of the conductors. The more widespread the network the higher it is. It is increased by the capacitances incorporated in the filters of certain electronic loads (office automation, computers, etc.). The continuous leakage current may be evaluated on the following basis:

- single or three-phase wiring systems: 1.5 mA/100 m
- single or three-phase filters: roughly 3 mA/load
- heated floors: 1 mA/kW.

These currents may cause spurious operation of residual current devices having high sensitivity.

2.6.2.2. Transient leakage currents

Energization of the previously mentioned capacitances generates very short transient inrush currents which can be mathematically shown by a $0.5 \mu\text{s} / 100 \text{ kHz}$ oscillating current wave (see fig. 2-46). Amplitudes above 10 A with a rise front of $1 \mu\text{s}$ may be observed on energization.

The appearance of a first insulation fault is the cause of transient currents which correspond to a sudden change in the voltage applied to the installation's capacitances. The capacitance of the faulty phase is discharged and the capacitances of the healthy phases are charged.

These currents, which are by nature unbalanced, can lead to the spurious operation of the residual current devices.

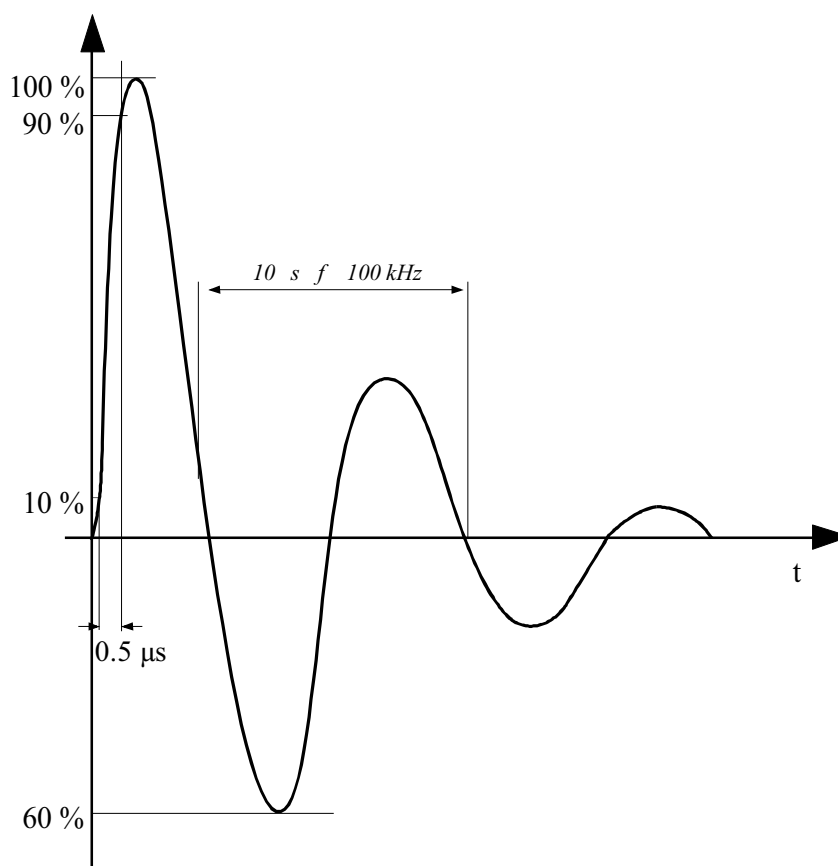


Figure 2-46: $0.5 \mu\text{s} / 100 \text{ kHz}$ standard current wave

2.6.2.3. Influence of overvoltages

Atmospheric overvoltages or overvoltages due to the operation of protective devices (disconnection of inductive loads for example) occur in electrical networks.

Observing them has shown that their level in low voltage generally remains below 6 kV and that they may be represented by the conventional $1.2 / 50 \mu s$ wave (see fig. 2-47).

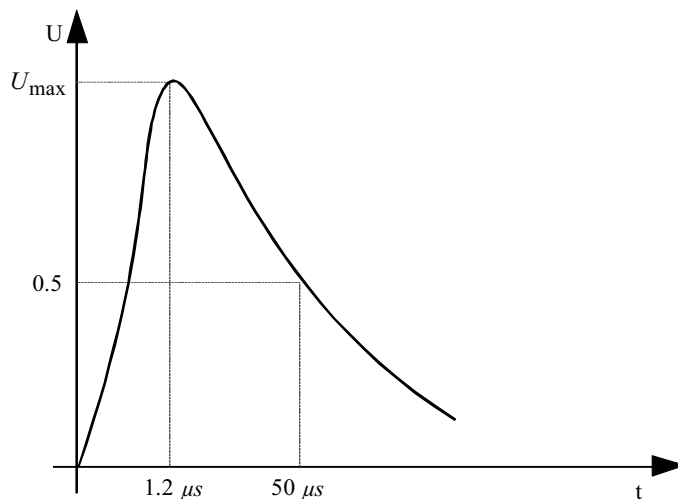


Figure 2-47: standard $1.2/50 \mu s$ overvoltage

These overvoltages are at the origin of currents shown by the conventional $8/20 \mu s$ wave having a peak value of several dozen amps (see fig. 2-48).

They flow to earth via the installation's capacitances, the surge arresters or through weak points in the installation breaking down and may cause the residual current devices to operate.

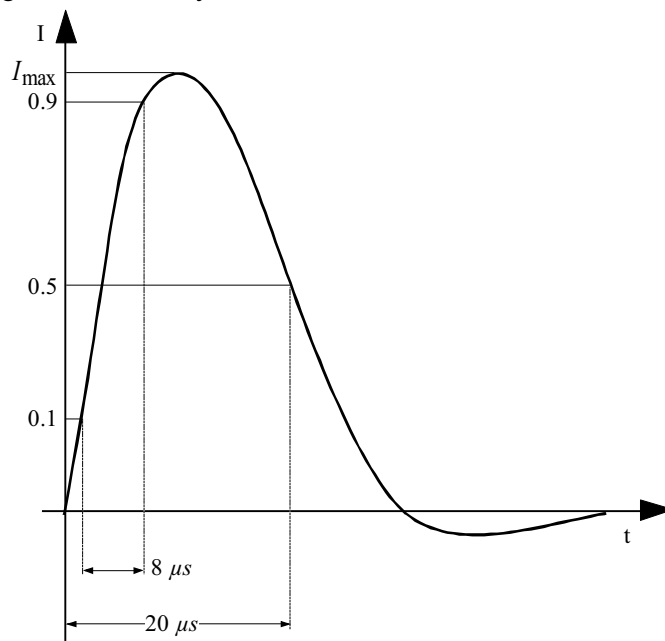


Figure 2-48: standard $8/20 \mu s$ current wave

2.6.2.4. Solutions

The capacitive leaks and transient currents mentioned previously as well as switching (contactor coils, relays, etc.), electrostatic discharges and radiated electromagnetic waves, generate differential currents which may cause sensitive residual current devices to operate.

These must have a sufficient level of immunity with respect to this (see fig. 2-49).

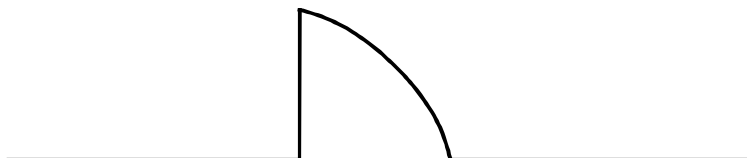


Figure 2-49: standard symbol used by some countries to indicate the immunity of RCD to electromagnetic disturbances

Any installed *RCD* must have a minimum level of immunity and the symbol shown in figure 2-49 guarantees the correct behaviour of the device in the presence of the disturbances defined in table 2-9.

Continuous leakage currents downstream of an *RCD* must be evaluated, especially in the case of widespread networks or in the presence of equipment with filters.

It is recommended that the level of leakage currents downstream of an *RCD* should not exceed $0.5 I_{\Delta n}$.

In practice, limiting the continuous leakage current to $0.25 I_{\Delta n}$ by subdividing the circuits eliminates the influence of all corresponding transient currents.

Disturbance	Type of test	Required withstand
Overvoltage	1.2 / 50 μ s voltage wave	6 kV
Transient current	0.5 μ s / 100 kHz current wave 8 / 20 μ s current wave	200 A 200 A 60 A for 10 mA devices 5 kA for S or intentional delay types
Switching	rapid transients in successive bursts IEC 801-4	4 kV
Electrostatic discharges	electrostatic discharges IEC 801-2	8 kV
Radio electric waves	radiated electromagnetic waves IEC 801-3	3 V/m

Table 2-9: levels of withstand to electromagnetic compatibility tests required for RCD

2.6.2.5 Direct components

The power supply to certain types of equipment has rectifying devices (diodes, thyristors, triacs, etc.).

In the event of an insulation fault downstream of these devices, the earth leakage current, measured upstream of this equipment, comprises in certain cases a direct component which can cause the magnetic circuits of the RCD to saturate and their operation to be disturbed. It is advisable in this case to use RCD suited to the situation.

To resolve this problem, the International Electrotechnical Commission (IEC) has classed residual current devices according to three types depending on their ability to operate when the fault current has a direct component:

- class AC RCD : device sensitive to a pure alternating residual current
- class A RCD : device sensitive to a pulsating residual current
- class B RCD : device sensitive to a pure residual direct current.

2.6.2.6. Recommendations for installing RCD with separate toroid

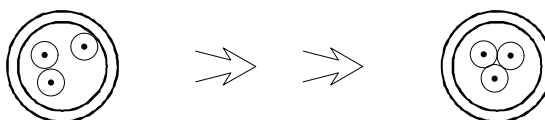
Since the sensor is a magnetic toroid, a high inrush current such as the starting current of a motor can saturate it locally and be at the origin of unwanted tripping.

If a separate toroid device is installed without taking any specific precautions, the setting of $I \Delta n$ cannot be below 1/1 000th of the maximum phase current:

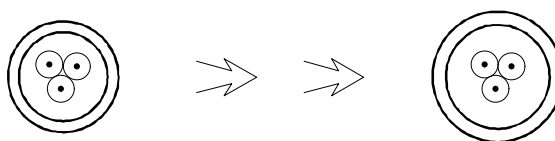
$$I \Delta n \geq \frac{I_{phase \ max.}}{1\ 000} \quad \text{whence} \quad \frac{I \Delta n}{I_{phase \ max.}} \geq \frac{1}{1\ 000}$$

This limit can be considerably lowered if the means illustrated in fig. 2-50-a and described in table 2-10 are taken:

- centre the cables in the toroid



- take 1 toroid that is bigger than necessary



- install a magnetic sleeve to channel the flux

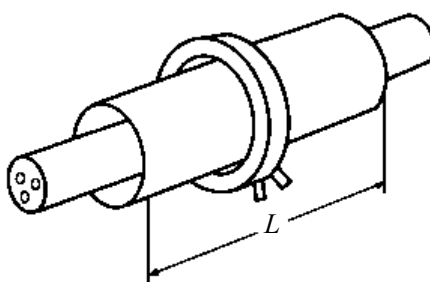


Figure 2-50-a: means of improving the performance of an RCD used with separate toroid

Means		Gain factor	
Carefully centring cables in the toroid		3	
Oversizing the toroid	ϕ 50 ⁽¹⁾ \rightarrow ϕ 100 ⁽²⁾	2	
	ϕ 80 \rightarrow ϕ 200	2	
	ϕ 120 \rightarrow ϕ 200	6	
Using a steel or soft iron sleeve	ϕ 50	4	
	. 0.5 mm thick	ϕ 80	3
	. having the same length as the toroid diameter	ϕ 120	3
	. completely surrounding the cable with an overlap at the ends	ϕ 200	2
(1) sufficient diameter for the cable considered (2) diameter used			

Table 2-10: means of reducing the ratio $I_{\Delta n} / I_{phase\ max}$.

2.6.2.7. Recommendations for using high-sensitivity residual current devices (RCD)

■ capacitive current unbalance (see fig. 2-50-b)

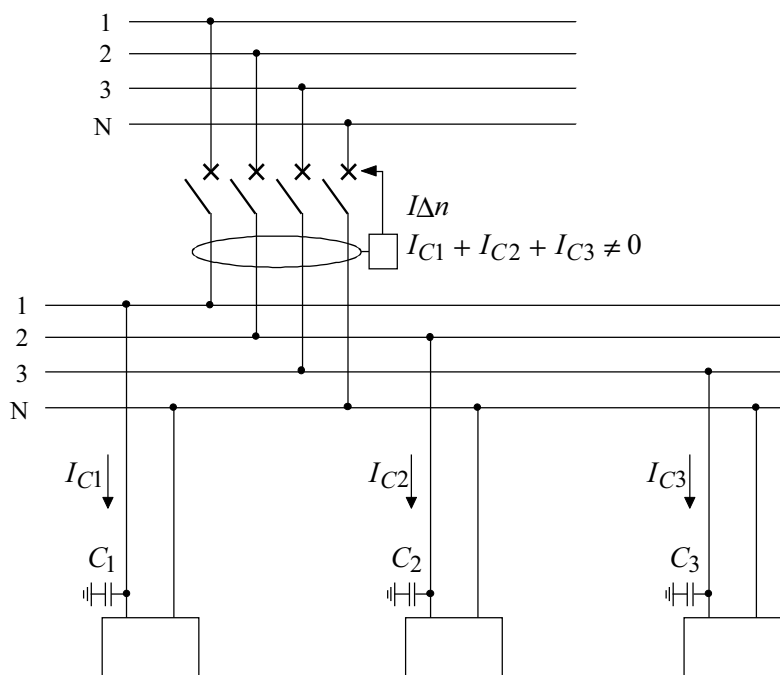
The single-phase loads and wiring systems naturally lead to capacitive current unbalance which can cause high-sensitivity ($I_{\Delta n} \leq 30 \text{ mA}$) residual current devices to operate .

This problem can be solved by subdividing the circuits placed downstream of a high-sensitivity RCD so that the unbalance is reduced and thus spurious tripping avoided.

It should be noted that the unbalance of the capacitive currents of the circuits placed downstream of an RCD must not exceed half of the RCD setting current.

For example:

$$I_{unbalance} \leq 15 \text{ mA for } I_{\Delta n} = 30 \text{ mA}$$



$$C_1 \neq C_2 \neq C_3$$

$$I_{C1} \neq I_{C2} \neq I_{C3}$$

$$I_{rsd} = I_{C1} + I_{C2} + I_{C3} \neq 0$$

$$I_{rsd} \leq \frac{I_{\Delta n}}{2}$$

Figure 2-50-b: capacitive current unbalance

■ **spurious tripping** (see fig. 2-50-c and 2-50-d)

On occurrence of an insulation fault the capacitive current spreads out in the healthy outgoing feeders and can thus cause the residual current devices installed on these outgoing feeders to trip.

The solution consists in limiting the length of the wiring systems and the number of loads placed downstream of a high-sensitivity residual current device.

It should be noted that the capacitive current of an outgoing feeder must not exceed a quarter of the setting threshold of the RCD which ensures its protection.

$$I_C \leq \frac{I\Delta n}{4}, \quad \text{whence} \quad I\Delta n \geq 4 I_C$$

This rule allows transient currents which are generated when the loads are energized and on occurrence of an insulation fault to be taken into account and the problem posed by the capacitive current unbalance to be solved.

The values of the capacitive currents that return via a healthy outgoing feeder can be evaluated using the following expressions:

- three-phase <i>IT</i> earthing system without neutral	$I_C = 3 C \omega V_n$
- three-phase <i>IT</i> earthing system + neutral	$I_C = 4 C \omega V_n$
- single-phase <i>IT</i> earthing system	$I_C = 2.7 C \omega V_n$ (for a load fed by a healthy phase)
- three-phase <i>TT</i> earthing system without neutral	$I_C = 3 C \omega V_n$
- three-phase <i>TT</i> earthing system + neutral	$I_C = 4 C \omega V_n$
- single-phase <i>TT</i> earthing system	$I_C = 2.7 C \omega V_n$ (for a load fed by a healthy phase)
- three-phase <i>TN</i> earthing system without neutral	$I_C = C \omega V_n$
- three-phase <i>TN</i> earthing system + neutral	$I_C = C \omega V_n$
- single-phase <i>TN</i> earthing system	$I_C = C \omega V_n$

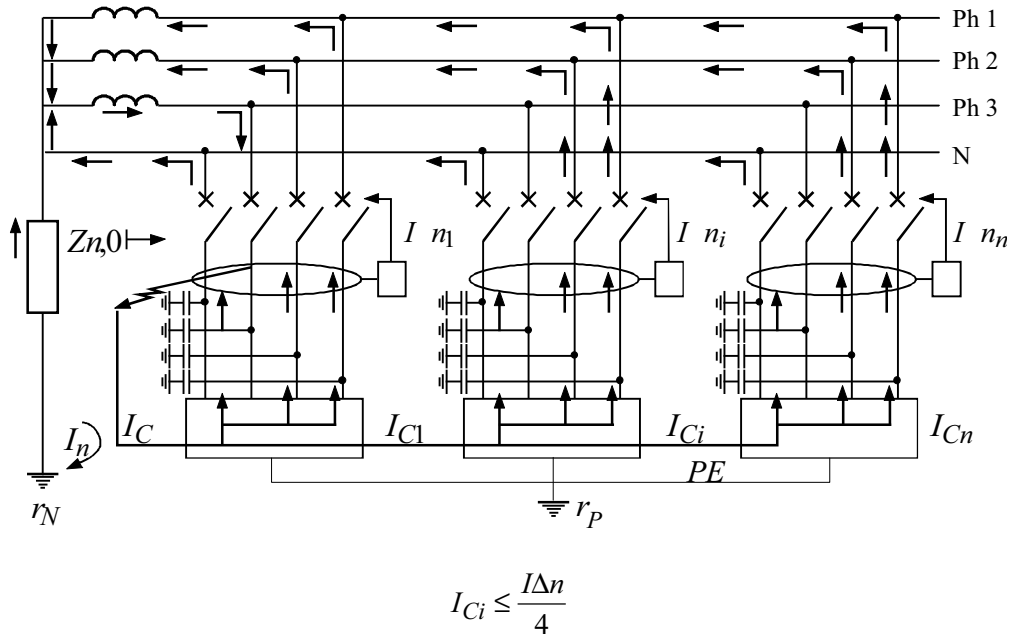


Figure 2-50-c: three-phase network - spurious tripping

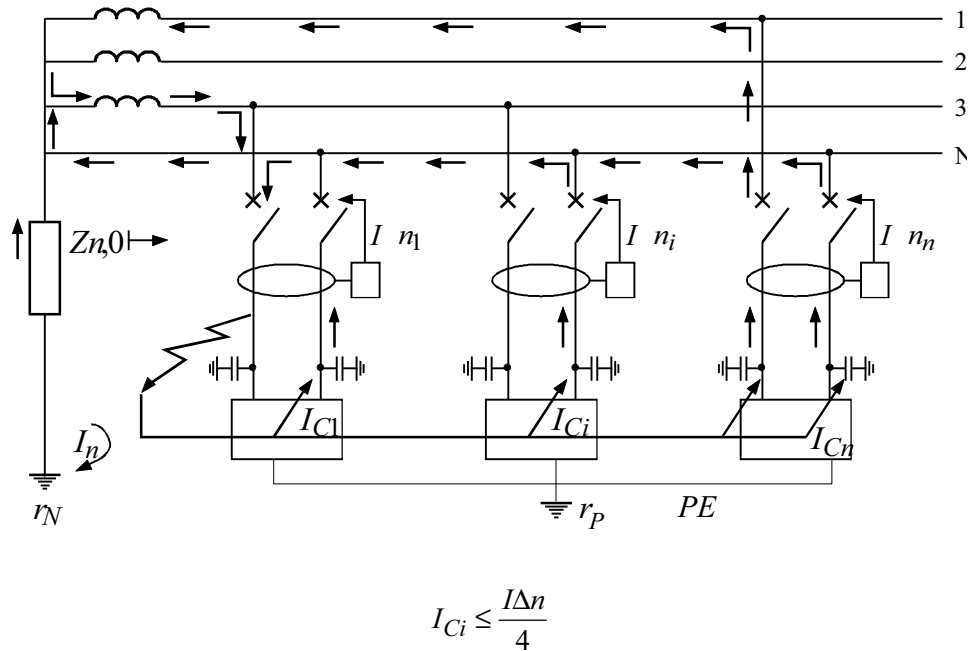


Figure 2-50-d: single-phase network - spurious tripping

2.7. Protection, sizing and disconnection of neutral conductor

It is advisable to apply the following rules

2.7.1. Neutral conductor sizing

2.7.1.1. *TT and TN-S earthing systems*

- **three-phase circuit with a cross-sectional area $\leq 16 \text{ mm}^2$ for copper or 25 mm^2 for aluminium and single-phase circuit whatever the cross-sectional area**

The neutral cross-sectional area must be equal to that of the phase conductors.

- **three-phase circuits with a cross-sectional area $> 16 \text{ mm}^2$ for copper or 25 mm^2 for aluminium**

The neutral cross-sectional area can be chosen to be:

- equal to that of the phase conductors
- smaller on condition that:
 - . the current likely to flow through the neutral conductor during normal service is lower than its current-carrying capacity (the influence of third harmonics and multiples of third harmonics must especially be taken into account, in this case the neutral cross-sectional area can be greater than that of the phases, see § 8.2. - neutral conductor heating)
 - . the power carried by the circuit is mainly absorbed by devices with a phase-to-phase supply (single-phase power $< 10\%$ of the total power carried)
 - . the neutral conductor is protected against overcurrents.

2.7.1.2. *TN-C earthing system*

The same conditions as those above are applied in theory but their advantage is lessened since it is forbidden to insert any protective device on the neutral which has taken priority as a protective conductor.

2.7.1.3. *IT earthing system*

It is generally not recommended to distribute the neutral.

When it is necessary to distribute it, the conditions described above for *TT* and *TNS* earthing systems are applicable.

2.7.2. Isolation

- it must be possible to isolate any circuit on each of its live conductors
- the *PEN* must never be disconnected or isolated
- with the neutral being a live conductor just like the phase conductors, the application of these provisions leads to the following rules:
 - . in the *TNC* earthing system the *PEN* must neither be disconnected nor isolated
 - . in the *TNS*, *TT* and *IT* earthing systems, it must be possible to isolate or disconnect the neutral.

2.7.3. Neutral conductor protection

■ installations having a solidly earthed neutral (*TT* or *TN* earthing systems)

- When the neutral conductor cross-sectional area is at least equal to that of the phase conductors, it is not necessary to provide overcurrent detection on the neutral conductor.
- When the neutral conductor cross-sectional area is smaller than that of the phase conductors it is necessary to provide overcurrent detection on the neutral conductor which matches its cross-sectional area. Nevertheless, in this case it is not necessary to provide overcurrent detection on the neutral conductor if both of the following conditions are met:
 - . the neutral conductor is protected against short circuits by the phase conductor protective device
 - . during normal service, the maximum current which may flow through the neutral conductor is clearly smaller than the value of its current-carrying capacity.

■ installations having a neutral that is not solidly earthed (*IT* earthing system)

- When it is necessary to distribute the neutral conductor, overcurrent detection must be provided on the neutral conductor of any circuit and this detection must lead to all the live conductors being disconnected from the corresponding circuit, including the neutral conductor.

This provision is not necessary if:

- the neutral conductor considered is effectively protected against short circuits by a protective device placed upstream, for example, at the origin of the installation
- or if the circuit considered is protected by a residual current device having a rated differential-residual current at the most equal to 0.15 times the current-carrying capacity of the corresponding neutral conductor: this device must disconnect all the live conductors of the corresponding circuit, including the neutral conductor.

2.8. Protection and disconnection of phase conductors

It is recommended to apply for the following rules.

2.8.1. Disconnection of phase conductors

Each phase conductor must be able to be disconnected and isolated.

2.8.2. Protection of phase conductors

Overcurrent detection must be provided on all the phase conductors, it must cause disconnection of the conductor in which the overcurrent is detected, but must not necessarily cause other live conductors to be disconnected.

Nevertheless, in *TT* and *TN* earthing systems, on circuits with a phase-to-phase power supply and in which the neutral conductor is not distributed, overcurrent detection may not have to be provided on one of the phase conductors, subject to the following conditions being simultaneously met:

- there is a residual current device, either upstream or at the same point, which will cause disconnection of all the phase conductors
- there must be no distributed neutral conductor from an earthing transformer on the circuits located downstream of the residual current device referred to above.

2.9. Influence on switchgear of rules pertaining to disconnection and protection of neutral conductor and phase conductors

The application to circuit-breakers of all the rules described above has been summarised in table 2-11.

		Earthing systems			
		<i>TT</i>	<i>TN - C</i>	<i>TN - S</i>	<i>IT</i>
Reminder: protection against indirect contact		by <i>RCD</i>	by circuit-breaker or fuse	by circuit-breaker or fuses (1)	by circuit-breaker or fuses (1)
Circuit to be protected					
single-phase	$P - N$				
two-phase	$2P$				
three-phase	$3P$				
three-phase + neutral	$3P - N$ $S_n = S_{ph}$				
three-phase + neutral	$3P - N$ $S_n < S_{ph}$				

Table 2-11: disconnection rules and choice of switchgear

: this symbol represents the circuit-breaker short circuit and overload tripping relays

(1) : if the length of the wiring system exceeds the limit ensuring protection against indirect contact, an RCD must be installed.

- (A) authorised in *TT* and *TN* earthing systems when an *RCD* is installed at the origin of the circuit or upstream and if there is no earthing transformer downstream of it.
- (B) authorised in *TT* and *TN* earthing systems if the neutral conductor is protected against short circuits by protective devices against phase-to-phase faults and if the normal duty current is notably lower than its current-carrying capacity.
- (C) authorised in the *IT* earthing system in certain conditions: if the circuit is part of a set of homogenous terminal outgoing feeders the highest and lowest ratings of which do not exceed the ratio of 2 and on condition that an *RCD* having a sensitivity lower than or equal to 15 % of the rating of the smallest outgoing feeder is installed upstream of these outgoing feeders.

2.10. Interaction between medium voltage and low voltage (see fig. 2-50-e)

Any insulation fault occurring on the medium voltage part of an MV / LV substation has repercussions on the low voltage network that it supplies; this leads especially to the development of overvoltages and rises in the potential of the exposed conductive parts which may cause breakdown of equipment and be dangerous for people, if the provisions for limiting them are not taken when the network is being designed.

The description of these phenomena and the provisions to be taken for protection against them are described in paragraph 5.3.2.1. - overvoltages. Their development depends on the configuration of the earth electrodes of the neutral and exposed conductive parts as well as the way the substation and installation exposed conductive parts are earthed. In order to study them, IEC 364-4-442 takes the seven earthing systems grouped together in table 2-12. Their behaviour on occurrence of an insulation fault on the medium voltage part of the substation is analysed in paragraph 5.3.2.1. - overvoltages.

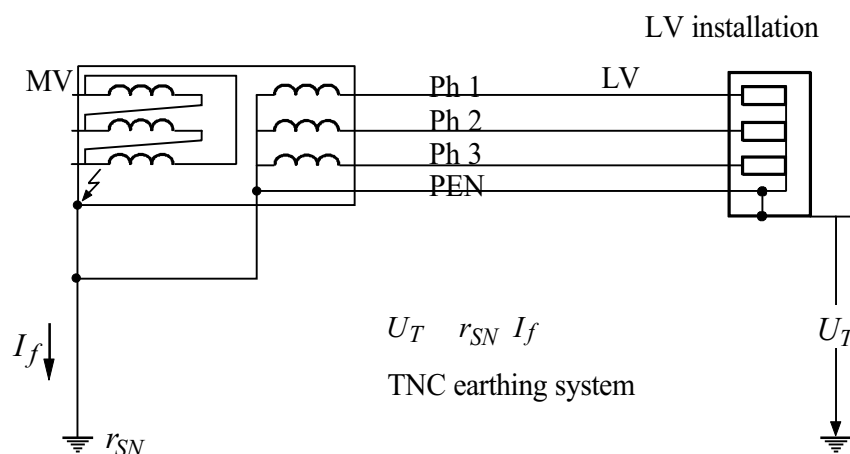


Figure 2-50-e: example of a rise in potential of the LV exposed conductive parts for a fault on the medium voltage part of the substation

- (A) authorised in *TT* and *TN* earthing systems when an *RCD* is installed at the origin of the circuit or upstream and if there is no earthing transformer downstream of it.
- (B) authorised in *TT* and *TN* earthing systems if the neutral conductor is protected against short circuits by protective devices against phase-to-phase faults and if the normal duty current is notably lower than its current-carrying capacity.
- (C) authorised in the *IT* earthing system in certain conditions: if the circuit is part of a set of homogenous terminal outgoing feeders the highest and lowest ratings of which do not exceed the ratio of 2 and on condition that an *RCD* having a sensitivity lower than or equal to 15 % of the rating of the smallest outgoing feeder is installed upstream of these outgoing feeders.

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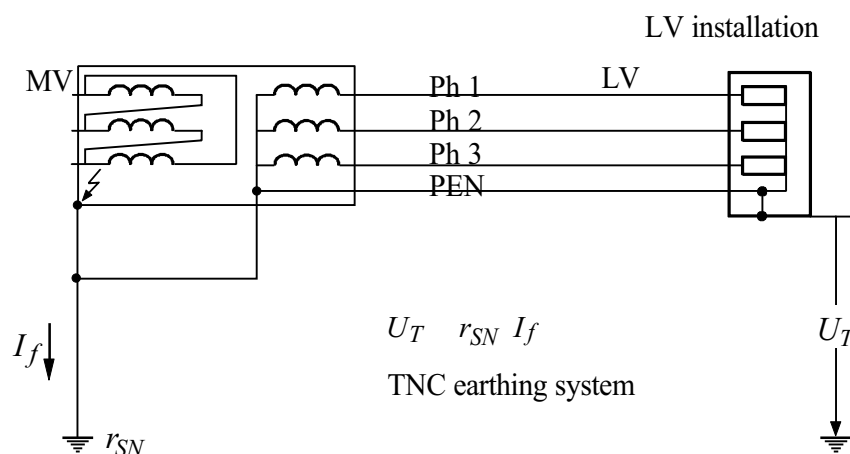


Figure 2-50-e: example of a rise in potential of the LV exposed conductive parts for a fault on the medium voltage part of the substation

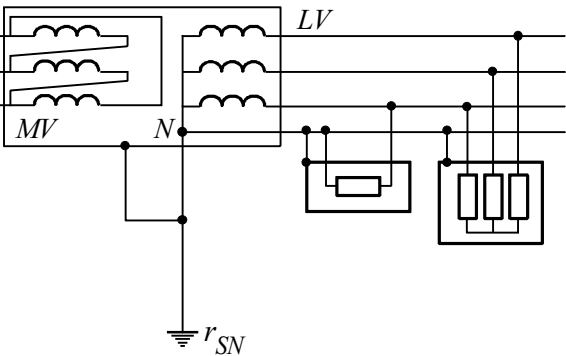
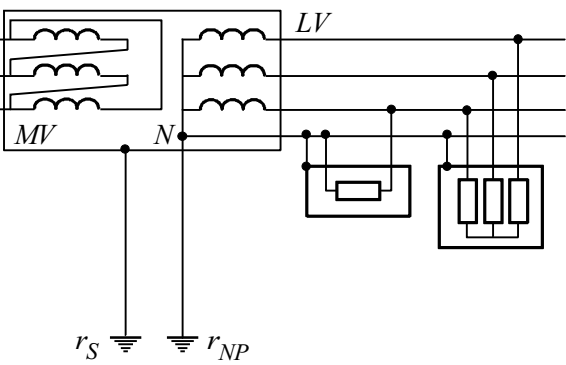
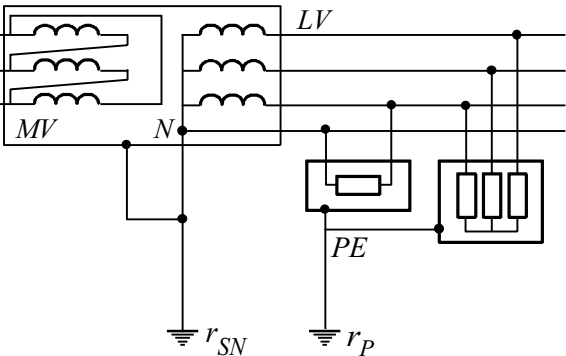
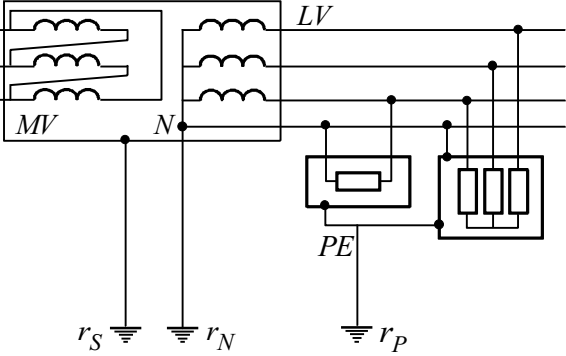
<p><i>TN – a</i> system</p> <ul style="list-style-type: none"> - the MV/LV transformer neutral is solidly earthed - the exposed conductive parts of the LV installation are connected to the neutral conductor - the exposed conductive parts of the substation are connected to the neutral earth electrode. 	
<p><i>TN – b</i> system</p> <ul style="list-style-type: none"> - the MV/LV transformer neutral is solidly earthed - the exposed conductive parts of the LV installation are connected to the neutral conductor - the exposed conductive parts of the substation are connected to a separate earth electrode from that of the neutral. 	
<p><i>TT – a</i> system</p> <ul style="list-style-type: none"> - the MV/LV transformer neutral point is solidly earthed - the exposed conductive parts of the LV installation are interconnected and connected to a different earth electrode from that of the neutral - the exposed conductive parts of the substation are connected to the neutral earth electrode 	
<p><i>TT – b</i> system</p> <ul style="list-style-type: none"> - the MV/LV transformer neutral is solidly earthed - the exposed conductive parts of the LV installation are interconnected and connected to a different earth electrode from that of the neutral - the exposed conductive parts of the substation are connected to a different earth electrode from that of the neutral and that of the exposed conductive parts of the installation. 	

Table 2-12: interactions between medium and low voltage

<p>IT – a system</p> <ul style="list-style-type: none"> - the MV/LV transformer neutral is unearthed or earthed via an impedance - the exposed conductive parts of the LV installation are interconnected and connected to the neutral earth electrode - the exposed conductive parts of the substation are connected to the neutral earth electrode. 	
<p>IT – b system</p> <ul style="list-style-type: none"> - the MV/LV transformer neutral is unearthed or earthed via an impedance - the exposed conductive parts of the LV installation are interconnected and connected to a separate earth electrode from that of the neutral - the exposed conductive parts of the substation are connected to the neutral earth electrode. 	
<p>IT – c system</p> <ul style="list-style-type: none"> - the MV/LV transformer neutral is unearthed or earthed via an impedance - the earth electrodes of the substation, neutral and exposed conductive parts of the installation are separate. 	

Table 2-12 (cont.): interactions between medium and low voltage

2.11. Comparison of different low voltage earthing systems - choice

2.11.1. Comparison of different earthing systems

2.11.1.1. TT earthing system

- this is the simplest solution to implement. In France, it can be used for installations directly supplied by the low voltage public distribution network
- it does not require any specific monitoring although a regular inspection of the residual current devices may be necessary
- protection is ensured by residual current devices (*RCD*) which also make it possible for fire risks to be prevented when the device sensitivity is ≤ 500 mA
- each insulation fault leads to disconnection. This disconnection can be limited to the only faulty circuit by setting up an appropriate selectivity
- loads or installation parts, which generate high earth leakage currents, must be fitted with suitable *RCD* in order to avoid spurious tripping.

2.11.1.2. TN earthing system

- in France, it can only be used in installations fed by a private MV/LV or LV/LV transformer
- it requires earthing of the protective conductor at regular intervals
- it requires the operation of the protective devices against phase-to-phase faults to be checked for an insulation fault
- it requires any modification or extension to be carried out by qualified personnel fully conversant with implementation rules
- on occurrence of an insulation fault, it may lead to considerable deterioration of the windings of rotating machines and sensitive equipment,
- in premises where there is a risk of fire, it may be dangerous due to the high value of the fault currents.

The $TN - C$ earthing system:

- installation savings may be made since one pole and one conductor are removed
- it involves the use of fixed and rigid wiring systems
- it is forbidden in premises where there is a risk of fire
- during insulation faults it generates a high level of electromagnetic disturbances which may damage sensitive electronic equipment or disturb their operation
- unbalance currents, third harmonics and multiples of third harmonics circulate in the PEN protective conductor and may be the cause of multiple disturbances.

The $TN - S$ earthing system:

- this can be used even in the presence of flexible conductors or wiring systems with a small cross-sectional area
- through the separation of the neutral and protective conductor it allows good equipotential bonding of the exposed conductive parts to be maintained and the level of electromagnetic disturbances to be reduced. It is thus recommended for computing premises
- it is compulsory in premises where there is a risk of fire, if the installation has a TN earthing system.

2.11.1.3. IT earthing system

- in France it can only be used in installations supplied by a private MV/LV or LV/LV transformer
- it is the solution that ensures the best continuity of service
- signalling of the first insulation fault followed by its location and clearance allows any interruptions in power supply to be systematically prevented
- it requires maintenance personnel for monitoring and operation
- it requires network insulation to be maintained in good condition
- any modification or extension must be carried out by qualified personnel fully conversant with implementation rules
- it involves dividing up the network if it is very widespread and loads with a high earth leakage current being fed by an insulating transformer
- it requires the operation of protective devices against phase-to-phase faults to be checked for a double insulation fault.

2.11.2. Choice of earthing system

2.11.2.1. Earthing system performances

The performances of earthing systems can be assessed according to the following six criteria:

- protection against electric shocks
- protection against fires of electrical origin
- supply continuity
- protection against overvoltages
- protection against electromagnetic disturbances
- implementation requirements.

■ protection against electric shocks

All earthing systems ensure equal protection against electric shocks as long as they are implemented and used in compliance with standards.

■ protection against fires

□ *TT* and *IT* earthing system

On occurrence of an insulation fault in a *TT* and *IT* earthing system the value of the current generated by the fault is respectively low or very low, and the risk of fire is smaller than in a *TN* earthing system.

□ *TN-C* earthing system

The risk of fire in a *TN-C* earthing system is high. Indeed, the load unbalance current permanently flows not only through the *PEN* conductor, but also through the elements which are connected to it: metallic structures, exposed conductive parts, shielding, etc., and may cause a fire. In the event of a solid fault, the value of the current generated by the insulation fault is high and there is therefore a considerable risk. In the event of an impedant fault, the *TN-C* earthing system, which does not allow the use of a residual current device, does not guarantee sufficient protection since tripping is not ensured. This is why it is forbidden in premises where there is a high risk of explosion or fire. It is necessary to change to a *TN-S* earthing system combined with the use of residual current devices.

■ supply continuity

Choosing the IT earthing system allows all the harmful consequences of an insulation fault to be avoided:

- voltage dip
- disturbances caused by the fault current
- damage to equipment
- opening of the faulty outgoing feeder.

If it is correctly used the likelihood of a second fault occurring is eliminated and supply continuity is also guaranteed.

■ protection against overvoltages

In all earthing systems, protection against overvoltages may be necessary. For further details concerning the installation of such means, refer to chapter 5.

■ protection against electromagnetic disturbances

It does not matter which system is chosen:

- for all differential mode disturbances
- for all common mode or differential mode disturbances having a frequency above the MHz.

The TT , $TN-S$ and IT earthing systems are able to meet all electromagnetic compatibility criteria if they are correctly implemented. Note simply that the $TN-S$ earthing system causes more disturbances throughout the duration of the fault since the fault current is higher.

On the other hand, the $TN-C$ or $TN-C-S$ ⁽¹⁾ earthing systems are not recommended. Indeed, in these earthing systems, a continuous fault current owing to the load unbalance and the presence of third and multiples of third harmonics flows through the PEN conductor, the exposed conductive parts of equipment and the cable shielding.

(1) $TN-C-S$ means that a $TN-S$ earthing system is used downstream of a $TN-C$ earthing system.

■ implementation requirements

The TT earthing system, as well as the $TN-S$ earthing system when it is installed with residual current devices, are the simplest to implement.

The $TN-S$ earthing system without residual current devices and the $TN-C$ and IT earthing systems require operation of the protective devices against phase-to-phase faults to be checked. This leads to the maximum lengths of wiring systems being limited and requires the intervention of qualified personnel to carry out extensions and modifications to the installation.

2.11.2.2. Choice and recommendations for use (see table 2-13)

When it is possible to choose the earthing system, the choice is carried out cases by case, based on the requirements relating to the electrical installation, the loads, the user's needs and regulations.

It is often advantageous not to choose one system for the entire installation.

■ the TT earthing system is recommended for installations with little monitoring and future extensions

Indeed, this is the simplest earthing system to implement and use.

■ the IT earthing system is recommended if there is a service continuity requirement

Indeed, the IT earthing system guarantees better energy availability.

On the other hand, it requires:

- implementation rules to be respected
- problems generated by earth leakage currents to be taken into account
- a qualified maintenance service for the location and clearance of the first insulation fault as well as for installation extensions and modifications.

■ **the $TN-S$ earthing system is recommended for installations with few future changes**

It is generally set up without any residual current device.

The currents generated by an insulation fault are high and may cause:

- temporary disturbances
- risks of extensive damage
- fires.

Like the IT earthing system it requires the implementation rules to be respected.

If medium-sensitivity residual current devices are installed, they provide this earthing system with better protection against fires and flexibility in design and use.

■ **with respect to withstand to overvoltages and electromagnetic disturbances, the IT, TT and $TN-S$ earthing systems which have been built in compliance with the rules of the art are generally satisfactory; the TNC or $TNC-C-S$ ⁽¹⁾ earthing system, on the other hand, is not recommended as it continuously constitutes a number of risks and notably:**

- voltage drops along the PEN
- circulation of current in the metallic structures, shielding and exposed conductive parts
- radiated magnetic field
- absence of protection against impedant insulation faults
- in the event of a solid fault, the current value is high, hence the risk of considerable damage.

(1) $TNC-C-S$ means that a $TN-S$ earthing system is used downstream of a $TN-C$ earthing system.

	<i>TNC</i>	<i>TNS</i>	<i>TT</i>	<i>IT</i>
Loads sensitive to fault currents	<i>NR</i>	<i>NR</i>	<i>P</i>	<i>R</i>
Loads sensitive to electromagnetic disturbance	<i>NR</i>	<i>R</i>	<i>P</i>	<i>P</i>
Premises where there is a risk of fire	<i>F</i>	<i>NR(1)</i>	<i>P(1)</i>	<i>R(1)</i>
Installation with frequent modifications	<i>NR</i>	<i>NR</i>	<i>R</i>	<i>NR</i>
Installation where the continuity of earth circuits is uncertain (work sites)	<i>NR</i>	<i>P</i>	<i>R</i>	<i>NR</i>
Need for service continuity	<i>NR</i>	<i>NR</i>	<i>NR</i>	<i>R</i>
Network, loads with high leakage currents	<i>R</i>	<i>R</i>	<i>P</i>	<i>NR</i>

(1) the use of a < 500 mA sensitive *RCD* is compulsory

R : Recommended

P : Possible

NR : Not Recommended

F : Forbidden

Table 2-13: choice of earthing system

2.11.2.3. Economic analysis

Any economic analysis must take into account all the costs:

- design studies
- equipment costs
- maintenance
- modifications and extensions
- production losses.

It must be underlined that only a complete economic analysis really reflects the advantage for the final user.

2.12. Earthing systems used in medium voltage installations

This paragraph deals with the type of earthing for the HV/MV or MV/MV substation exposed conductive parts, the MV neutral and the MV installation exposed conductive parts.

2.12.1. Principles and earthing systems used in medium voltage

If we consider public distribution networks and industrial or tertiary private networks without making any distinction between them, we can see that the same earthing system principles are used in each. In other words :

- solidly earthed neutral
- unearthed neutral
- resistance earthing
- reactance earthing
- partially or totally tuned Petersen coil earthing.

These principles are summarised in table 2-15. The advantages and drawbacks of each system are described in table 2-16.

As far as standards are concerned, only French standard NF C 13-200 (article 312) gives a precise definition of earthing systems and draws up implementation rules. The systems are defined by a code with three letters.

■ the first letter specifies the situation of the MV neutral point in relation to earth

We can distinguish between:

- installations having a solidly earthed neutral point, installations designated by the letter *T*
- installations having an unearthed or impedance earthed neutral point, installations designated by the first letter *I* .

■ the second letter specifies the situation of the exposed conductive parts of the MV installation

We can distinguish between:

- installations with exposed conductive parts being directly connected to the earthed neutral point, installations designated by a second letter *N*
- installations with exposed conductive parts being directly earthed, regardless of any possible neutral earthing, installations designated by a second letter *T* .

- the third letter specifies any possible connections between the exposed conductive parts of the HV/MV or MV/MV substation, the MV neutral point and the exposed conductive parts of the MV installation

We can distinguish between:

- installations whose supply substation exposed conductive parts are connected to the same earth electrode as that of the neutral and of the installation's exposed conductive parts, installations designated by a third letter *R*
- installations whose supply substation exposed conductive parts are connected to the neutral earth electrode, with the exposed conductive parts of the installation being connected to a separate earth electrode, installations designated by a third letter *N*
- installations whose supply substation exposed conductive parts, neutral and installation exposed conductive parts are connected to separate earth electrodes, installations designated by a third letter *S*.

In practice, French standard C13-200 only takes the six systems shown in table 2-14.

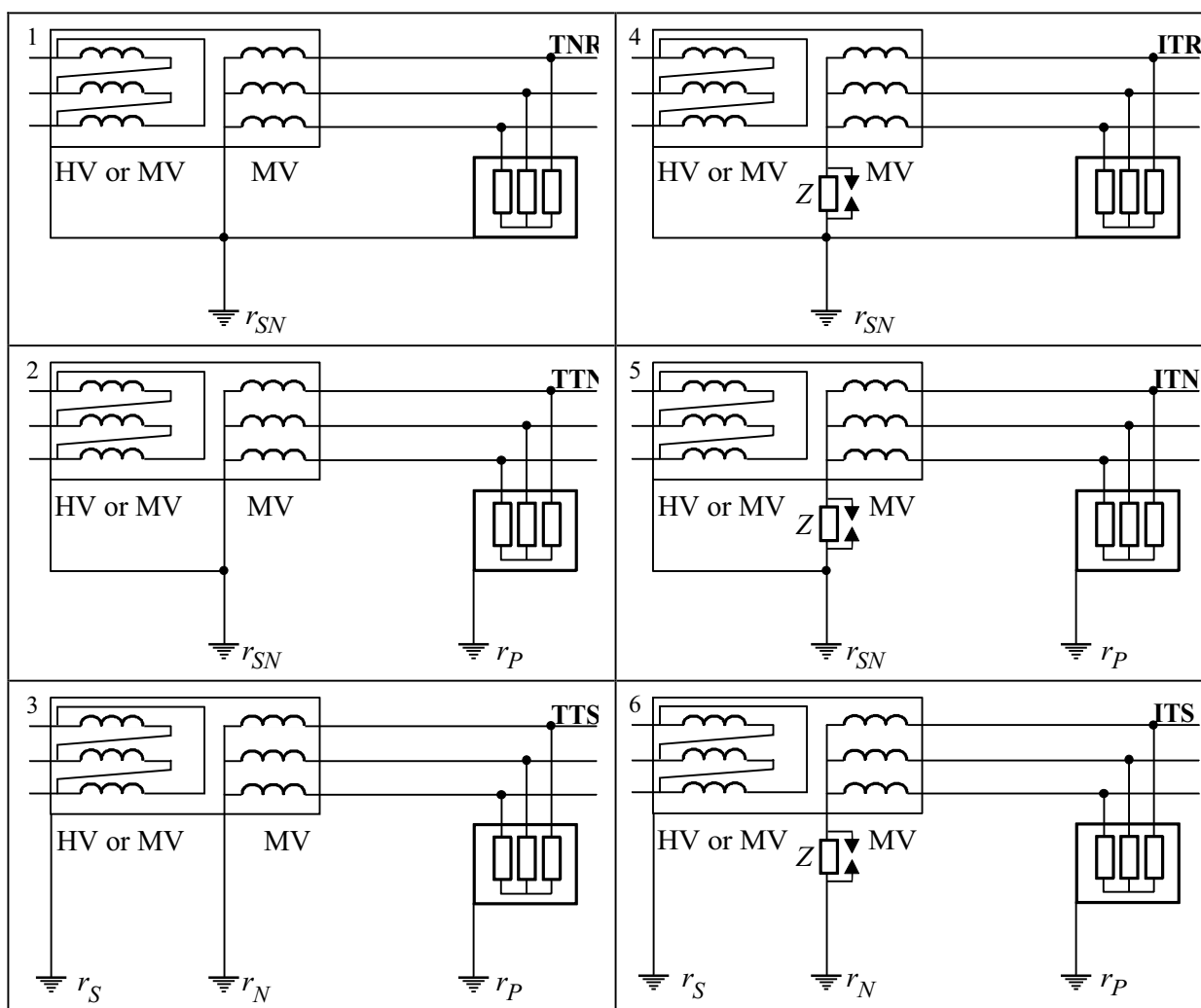


Table 2-14: definition of neutral earthing systems in medium voltage

2.12.2. Recommended earthing systems in industrial or tertiary installations

In public distribution, all the types of earthing system mentioned in table 2-15 can be found. Choices vary according to the country, from the solidly earthed neutral to the Petersen coil earthed neutral, and have been in use for several decades and are in some cases not entirely adapted to the present situation of networks and environmental conditions. Thus, the initial choices are currently being called into question and there is a general movement towards partially tuned Petersen coil earthing. A choice which has been thought through is always a compromise as it implements multiple and complex phenomena as well as economic considerations. We shall not deal with this topic in this guide as it only concerns private networks and installations.

For networks and private installations, limiting resistor earthing or unearthed neutral systems are recommended when service continuity is imperative. Indeed, the latter enables the power supply not to be disconnected on occurrence of a first insulation fault.

Solid neutral earthing or earthing via a tuned coil are not recommended. The solidly earthed neutral generates very high fault currents which are always damaging for the load and lead to the occurrence of touch voltages able to exceed a thousand volts. The implementation of neutral earthing via a tuned coil is both delicate and costly. It should only really be used for very widespread networks where the power supply must not be interrupted on occurrence of a first insulation fault. In practice this case is fairly rare.

The operating techniques, advantages and drawbacks of each earthing system are given in table 2-16.

<p>Solidly earthed neutral</p> <p>An electrical connection is intentionally made between the neutral point and earth.</p>	
<p>Unearthed neutral</p> <p>There is no electrical connection between the neutral point and earth, except for measuring and protective devices.</p> <p>High impedance earthing</p> <p>A high impedance is inserted between the neutral point and earth.</p>	
<p>Resistance earthing</p> <p>A resistor is inserted between the neutral point and earth</p>	
<p>Reactance earthing</p> <p>A reactor is inserted between the neutral point and earth</p>	
<p>Petersen coil earthing</p> <p>A reactor L tuned to the network capacitances is inserted between the neutral point and earth so that if an earth fault occurs, the fault current is zero.</p>	<p> $\vec{I}_f = \vec{I}_L + \vec{I}_C$ I_f : fault current I_L : current in the neutral earthing reactor I_C : current in the phase-earth capacitances </p>

Table 2-15: neutral point connection methods

■ unearthed neutral		
Operating technique	Advantages	Drawbacks
<ul style="list-style-type: none"> - no supply disconnection on occurrence of first insulation fault; it is thus compulsory to: <ul style="list-style-type: none"> . carry out permanent insulation monitoring . signal the first insulation fault . locate and clear the first insulation fault . carry out disconnection on occurrence of the second insulation fault. 	<ul style="list-style-type: none"> - authorises service continuity by only tripping on occurrence of the second fault as long as: <ul style="list-style-type: none"> . the network insulation is permanently monitored . the network capacitance does not lead to a high first earth fault current which would be dangerous for personnel and loads. 	<p>The unearthed neutral leads to:</p> <ul style="list-style-type: none"> - the use of equipment having a phase-to-earth insulation level which is at least equal to the phase-to-phase voltage; indeed, when there is a continuous phase-to-earth fault, the voltage of the two healthy phases in relation to earth can take the value of the phase-to-phase voltage - risks of high overvoltages of internal origin - compulsory insulation monitoring with visual and sound indication of the first fault if tripping only takes place on occurrence of the second - the presence of maintenance personnel to monitor and locate the first fault during operation - difficulties with the implementation of selective protections on occurrence of the first fault - risks of ferro-resonance.
■ neutral earthed via limiting resistor		
Operating technique	Advantages	Drawbacks
<ul style="list-style-type: none"> - disconnection on occurrence of the first insulation fault. 	<ul style="list-style-type: none"> - limits fault currents (less damage and disturbances) - damps internal overvoltages - does not require the use of equipment and especially cables having a special phase-earth insulation level - allows simple selective protections to be used. 	<ul style="list-style-type: none"> - tripping on occurrence of the first fault - large sized resistor to take the fault current into account.
■ solidly earthed neutral		
Operating technique	Advantages	Drawbacks
<ul style="list-style-type: none"> - disconnection on occurrence of the first insulation fault. 	<ul style="list-style-type: none"> - reduces the risk of overvoltages occurring - authorises the use of equipment having a phase-earth insulation level - enables simple and selective protections to be installed. 	<ul style="list-style-type: none"> - obligatory tripping on occurrence of the first insulation fault - very high fault current leading to maximum damage and disturbance - the danger for personnel is considerable throughout the duration of the fault, with the touch voltages being high.

Table 2-16: comparison of different earthing systems in medium voltage

■ neutral earthed via limiting reactor
Operating technique

- disconnection on occurrence of first insulation fault.

Advantages

- limits fault currents (less damage and disturbance)
- allows simple selective protections to be implemented if:

$$I_L \gg I_C$$

Drawbacks

- can cause high overvoltages during clearance of earth faults
- compulsory tripping on occurrence of the first fault.

■ neutral earthed via tuned limiting reactor (Petersen coil)
Operating technique

- no supply disconnection on occurrence of first insulation fault; it is thus compulsory to:

- . carry out permanent insulation monitoring
- . signal the first insulation fault
- . locate and clear the first insulation fault
- . carry out disconnection on occurrence of the second insulation fault.

Advantages

- if the reactance is such that :

$$3 L C \omega^2 = 1$$

the phase-earth fault current is zero. This allows:

- . the spontaneous extinction of non-continuous phase-earth faults
- . the installation being kept in service in spite of a continuous fault, with tripping necessarily taking place on occurrence of the second fault
- . the first fault is indicated by the detection of the flow of current in the coil. The coil is sized for continuous operation.

Drawbacks

- difficulties meeting the condition :

$$3 L C \omega^2 = 1$$

- due to uncertain knowledge of the network capacitance; this leads to a residual current circulating in the fault throughout its duration; it is essential to make sure that this current is not dangerous for personnel and equipment
- owing to the differences in value of the capacitances of each phase, a current circulates in the coil, even during normal operation
- the risks of overvoltages occurring are high
- requires the presence of monitoring personnel
- impossible to carry out selective protection on occurrence of the first fault if tuning is equal to:

$$3 L C \omega^2 = 1$$

in the case of a systematic absence of tuning $(3 L C \omega^2 \neq 1)$ selective protection on occurrence of the first fault is complex and costly.

Table 2-16 (cont.): comparison of different earthing systems in medium voltage

2.12.3. Indirect contact in medium voltage depending on the earthing system

The occurrence of a touch voltage may result:

- either from an insulation fault in the equipment of the installation considered
- or from an insulation fault coming from the supply network at the point where the transformer substation is located.

As in low voltage, the value taken by the touch voltage is closely related to the network earthing system in which it occurs, as well as whether or not there is an interconnection between the exposed conductive parts of the installation and the neutral earth electrode.

2.12.3.1. Case of *TNR-TTN* and *TTS* earthing systems (see table 2.14)

The neutral is solidly earthed, the exposed conductive parts of the installation are interconnected and connected either to a separate earth electrode (*TTN* and *TTS* earthing systems) or to the neutral earth electrode (*TNR* earthing systems).

■ case of *TTN* and *TTS* earthing systems (see fig. 2-51)

On occurrence of an insulation fault in the installation, the fault current returns via the earth electrode of the exposed conductive parts r_P and the neutral earth electrode r_N or r_{SN} . The faulty exposed conductive part is then approximately raised to the potential:

$$U_T = \frac{V \cdot r_P}{r_P + r_N}$$

for:

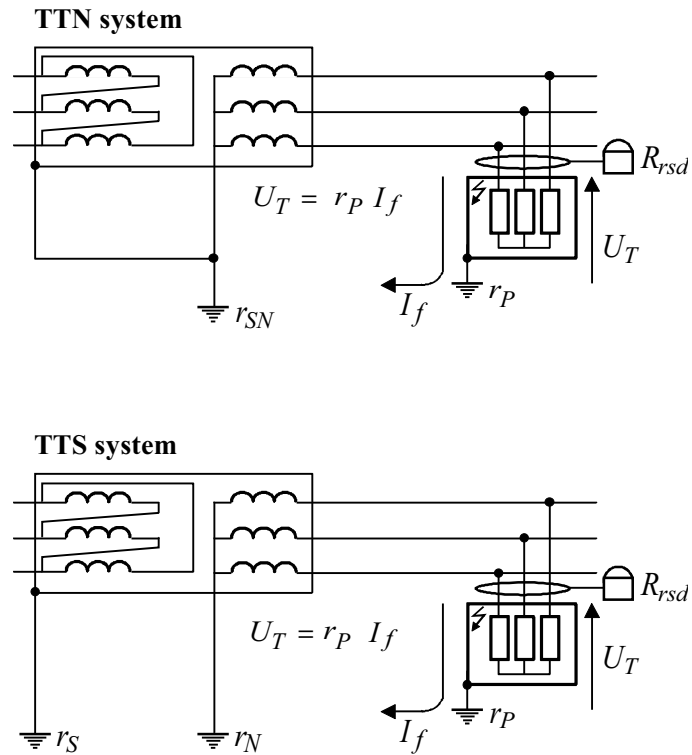
$$V_n = 6\,000 / \sqrt{3} \text{ V}$$

$$r_P = 2 \Omega$$

$$r_N = r_{SN} = 1 \Omega$$

we have:

$$U_T = \frac{6\,000 \times 2}{\sqrt{3} (2 + 1)} = 2\,309 \text{ V}$$



- r_{SN} : resistance of the earth electrode common to the substation exposed conductive parts and the neutral
- r_N : resistance of the neutral earth electrode
- r_S : resistance of the earth electrode of the substation exposed conductive parts
- r_P : resistance of the earth electrode of the installation exposed conductive parts
- I_f : fault current for a fault occurring in the installation
- U_T : touch voltages
- R_{rsd} : protective device sensitive to residual current

Figure 2-51: indirect contact in the case of TTN and TTS earthing systems

■ **case of TNR earthing system** (see fig. 2-52)

All the exposed conductive parts of the installation are interconnected and connected to the neutral earth electrode. On occurrence of a fault, the current returns via the protective conductor; it is only limited by the impedance of the fault loop comprising the transformer, the faulty phase conductors and the protective conductor. The touch voltage, which appears on a faulty exposed conductive part is equal to the voltage drop which occurs along the protective conductor connecting this exposed conductive part to the common earth electrode, may be very high.

For example, for an installation with the following characteristics:

- 20 kV / 6 kV transformer with a power of 5 MVA and $U_{sc} = 7.5\%$, whence
- a load is fed by a 50 mm^2 copper cable 300 m long; the protective conductor is the same as the feeder cable, and , whence

When an insulation fault occurs on the load, the touch voltage which appears is:

- : resistance of the earth electrode common to the substation exposed conductive parts, the neutral and the installation exposed conductive parts
- : fault current for a fault occurring on the installation
- : protective device sensitive to residual current

Figure 2-52: indirect contact in the case of earthing systems

The touch voltages occurring in a medium voltage network with a solidly earthed neutral may be very high and the corresponding disconnection times which must be respected to ensure the safety of persons cannot technically be guaranteed by the protective and switching devices used in medium voltage (see tables 2-3-a and 2-3-b). Indeed, for a touch voltage of 500 V, the disconnecting time must be much lower than 40 ms (see table 2-3-a), which is incompatible with the protective devices and switching devices used in medium voltage. The solution consists in equipotentially bonding the entire installation according to the rules given in chapter 2.12.3.3.

2.12.3.2. Case of ITR, ITN and ITS earthing systems

The neutral is unearthed or earthed via an impedance.

The exposed conductive parts of the installation are interconnected and connected either to a separate earth electrode (and earthing systems) or to the neutral earth electrode (system).

■ case of and earthing systems (see fig. 2-53)

On occurrence of an insulation fault in the installation, the fault current returns via the earth electrode of the exposed conductive parts, the neutral earth electrode and the neutral earthing impedance which may be infinite if the neutral is unearthed. The faulty exposed conductive part is then approximately raised to the potential:

for:

$$\frac{U_{f1}}{U_{f2}} = \frac{Z_{n1}}{Z_{n2}} \quad \text{(fault current limited to 100 A)}$$

we have:

$$\frac{U_{f1}}{U_{f2}} = \frac{Z_{n1}}{Z_{n2}} \quad \text{(fault current limited to 50 A)}$$

we have:

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- : neutral earth electrode impedance
- : resistance of the earth electrode common to the substation exposed conductive parts and neutral
- : resistance of the earth electrode of the installation exposed conductive parts
- : resistance of the neutral earth electrode
- : resistance of the substation earth electrode
- : fault current for a fault occurring in the installation

Figure 2-53: indirect contact in the case of and earthing systems

For (unearthed neutral), the fault current is essentially due to the capacitive current which returns via the healthy phases; for a capacitive current of 10 A corresponding to roughly 10 km of cable, a touch voltage of roughly 20 volts is obtained on a faulty exposed conductive part connected to an earth electrode of .

■ **case of the earthing system** (see fig. 2-54)

- : neutral earthing impedance
- : resistance of the earth electrode common to the substation exposed conductive parts, neutral and installation exposed conductive parts
- : fault current for a fault occurring in the installation
- : touch voltage

Figure 2-54: indirect contact in the case of the earthing system

All the exposed conductive parts of the installation are interconnected and connected to the neutral earth electrode. The fault current returns via the protective conductor and the neutral earthing impedance which may be infinite, if the neutral is unearthed. The touch voltage that occurs on one faulty exposed conductive part is then, as in the case of the earthing system, equal to the voltage that develops along the protective conductor connecting this exposed conductive part to the common earth electrode. For example, for a fault current limited to 100 A and a 50 mm² copper protective conductor 300 m long (, see case of TNR), we obtain a touch voltage of 15 volts. The touch voltages are thus weak when the current limited is low or when the neutral is unearthed.

2.12.3.3. Conclusion concerning touch voltages in medium voltage

To conclude, it appears that:

- solid neutral earthing may lead to the development of very high touch voltages that cannot be cleared in a time compatible with the safety of persons (see tables 2-3-a and 2-3-b)
- limiting fault currents using an impedance inserted between the neutral point and earth reduces touch voltages to values similar to those encountered in low voltage networks
- the creation of an equipotential bonding zone according to the principles described in figure 2-55 allows touch voltage values to be reduced yet further.

On the basis of these remarks, French standard C13-200 (articles 413-1-2 and 413-1-3) imposes the following rule:

"In the event of an insulation fault between a live part and an exposed conductive part, the touch voltage at any point of the installation must not be able to exceed the conventional limit voltage equal to:

- 50 V in alternating current in indoor and sheltered installations
- 25 V in alternating current in outdoor installations."

In practice, protection against indirect contact is ensured by equipotentially bonding all exposed conductive parts and all extraneous conductive parts, including the ground.

This bonding must be such that the resistance between two simultaneously accessible extraneous conductive parts must not be above:

being the maximum earth fault current of the installation.

Applying these rule leads to earthing being carried out in accordance with the principles described in fig. 2-55.

In addition to this, it should be noted that the only two principles recommended for medium voltage industrial or tertiary installations are:

- neutral earthing via limiting resistor, which is simple to implement
- unearthed neutral, which authorises the installation to continue to operate in the presence of the first insulation fault.

Figure 2-55: earthing principle in a medium voltage installation

2.12.4. Implementing neutral earthing via limiting resistor

2.12.4.1. Choice of limited current value

In order to limit transient overvoltages able to develop in networks on occurrence of an insulation fault, the current limited by the resistor should not be lower than double the total capacitive current of the network, see § 5.1.3.3. and fig. 2-56 :

Figure 2-56: choice of current limited by earthing resistor

2.12.4.2. Carrying out neutral earthing

■ earthing when the neutral is accessible

A resistor is inserted between the neutral output terminal and the earth electrode, either directly (see fig. 2-57-a), or via a single-phase transformer charged on the secondary via an equivalent resistor (see fig. 2-57-b). This solution is applicable whenever the network is fed by a transformer having a star-connected secondary with accessible neutral, or by a generator with accessible neutral.

(a) direct connection

(b) connection via a single-phase transformer

Figure 2-57: earthing when the neutral is accessible

■ earthing through the creation of an artificial neutral

When the source neutral is not accessible (delta-connected winding), earthing is established via an earthing transformer connected to the main busbar.

There are several ways of making this earthing transformer:

- using a star-delta transformer, the limiting resistor is connected between the primary neutral point and earth, with the delta being closed on itself (see fig. 2-58-a)
- using a star-delta transformer having a primary neutral point which is solidly earthed, a fault current limiting resistor is inserted in the secondary delta (see fig. 2-58-b). This solution is economically preferable to case (a) since the resistor is in LV instead of MV
- using a zigzag coil, with the limiting resistor being connected between the coil neutral point and earth (see fig. 2-58-c)
- using a three-winding transformer (see fig. 2-58-d) :
 - . the neutral of the star-connected primary is solidly earthed
 - . the star-connected secondary feeds loads
 - . the open-delta-connected tertiary is closed on a limiting resistor.

The most common solutions are arrangements (b) and (c).

Figure 2-58: main arrangements for creating an earthing transformer in medium voltage

■ **problem of resistance earthing when several sources operate in parallel on a busbar**

- case 1** : each source has a non-disconnectable earthing resistor.
The earth fault current varies according to the number of sources in service (see fig. 2-59-a), it is necessary to use directional overcurrent protections to locate faults occurring on connections between sources and busbars (see § 7.4. and 10.1.5.2. of the *Industrial network protection guide*).
- case 2** : each source has a disconnectable earthing resistor. A switching device enables there to be only one earthed neutral point whatever the number of sources in service (see fig. 2-59-b).
The protection system is complex as logic selectivity taking into account the position of the switching devices and the state of the different earth fault protections must be used.
This solution is rarely used.

Direct earthing of each neutral point

In the event of a phase-to-earth fault, we have:

- : fault current
- : number of sources in service
- : current limited by each resistor

(a)

Earthing of each neutral point via a switching device

- a switching device is necessary on each neutral point
- a control logic taking into account the network configuration is necessary

(b)

Figure 2-59: neutral point earthing where there are several sources able to operate in parallel

case 3 : no source has an earthing resistor.

An artificial neutral point is created on the busbar of the main switchboard (see fig. 2-60). This method overcomes the problems of the first and second cases. Indeed, the fault current is constant whatever the number of sources in service; the protections to be implemented are simple as they no longer require the use of directional overcurrent protections or a complex logic (see § 10.1.5.2. of the *Industrial network protection guide*). We can see that as long as a source is not connected to the busbar, the network section including this source and the feeder connecting it to the busbar operates with an unearthed neutral. When this type of operation is frequent, specific provisions must be taken to monitor the insulation of this network section. Monitoring may be carried out by a residual overvoltage protection connected to the terminals of the source.

Figure 2-60: earthing transformer on the main busbar

2.12.4.3. Protection systems

Protection against insulation faults is ensured by devices measuring the residual currents and voltage. The way to implement these devices is described in detail in paragraph 10-1-5-2 of the *Industrial network protection guide*. As an example, figure 2-61 gives a detailed outline of the protections to be installed on a network fitted with two transformers operating in parallel and an earthing transformer connected to the main busbar.

- : capacitive current returning via outgoing feeder
- : limited current returning via the neutral point earthing resistor
- : set point of the protective device installed on outgoing feeder ,
- : set point of the protective device installed on the neutral point earthing resistor,
- and
- : time delay associated with the protective devices installed on the outgoing feeders. The value of is chosen so as to ensure selectivity with the downstream protective devices
- : time delay associated with the protective devices installed on the incoming feeders, is independent of
- : time delay associated with the protective devices installed on the neutral point earthing resistor, where is roughly 300 ms;
- : set point of the protective devices installed on incoming feeders

Figure 2-61: protection against earth faults - case of two transformers operating in parallel

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2.12.5. Implementing the unearthed neutral

2.12.5.1. No disconnection on 1st fault

With an unearthed neutral, it is possible not to disconnect on occurrence of a first insulation fault. This possibility requires the following conditions to be met:

- in T_N and T_N earthing systems, the resistance of the earth electrode of the installation exposed conductive parts must at the most be equal to:

I_{sc} is the current which circulates in the earth electrode of the exposed conductive parts on occurrence of a first insulation fault. It is equal to the capacitive current which returns via the network's healthy phases.

- in the T_N earthing system, any touch voltage which develops on occurrence of a first insulation fault must be lower than U_{TE}
- a permanent insulation monitoring system must signal the appearance of a first insulation fault in the installation.
This device must activate a sound or visual signal or both so that the fault can be quickly located and cleared.
- disconnection is obligatory as soon as a second insulation fault appears. Residual overcurrent devices are recommended for the detection and clearance of the second fault. It is not advisable to apply the principle chosen for the T_N system in low voltage which consists in checking operation of the protective devices against phase-to-phase faults in double fault configurations. Indeed, it is difficult to apply in medium voltage. The use of residual overcurrent protections enables simple implementation in all cases.

2.12.5.2. Disconnection on occurrence of the first fault

Disconnection on occurrence of the first fault may be activated by the insulation monitoring device. There is then an overall disconnection of the installation. Setting up a selective protection system is complex and requires the use of directional protections whose implementation in a network with an unearthed neutral is often tricky (see § 10.1.4.2., 10.1.5.2. and 10.1.6.2. of the *Industrial network protection guide*).

When disconnection on occurrence of the first insulation fault is required, it is not advisable to use the unearthed neutral. Neutral resistance earthing with current limiting to less than 20 A enabling the use of simple protections is recommended.

2.12.5.3. Insulation monitoring

This can be carried out by a residual overvoltage protection or an insulation monitor.

■ monitoring insulation using a residual overvoltage protection (see § 7.16. of the *Industrial network protection guide*)

This detects a rise in potential of the neutral point which characterises an earth fault.

■ monitoring insulation using an insulation monitor

The insulation monitor applies a direct voltage between the neutral and earth, or between a phase and earth if the neutral is not accessible. In the event of an insulation fault, a direct current goes through the monitor causing an alarm to go off.

The monitor is connected to the network via voltage transformers.

Where there is an accessible neutral, it is connected to the primary of the voltage transformer connected between the neutral point and earth (see fig. 2-62).

Where there is a non accessible neutral, it is connected to the primary on the neutral point of three voltage transformers (see fig. 2-63).

A standard mounting plate is connected in parallel and it comprises:

- a capacitor enabling the potential of the voltage transformers' neutral to be fixed to earth without shunting the direct current injected by the monitor
- an overvoltage limiter for overvoltages to be run off to earth
- a resistor enabling the voltage withstood by the monitor to be reduced.

Note: All the voltage transformers must be charged to avoid ferro-resonant phenomena which may appear on the network with unearthed neutral. This is the purpose of the resistors connected to the secondary (see fig. 2-62 and 2-63 and § 5.1.2.2.).

Where there are other star-connected voltage transformers in the same network, it is necessary to install (see fig. 2-63) :

- a capacitor between the neutral of the voltage transformers and earth, so that the insulation monitor does not supply a continuous direct current via these transformers (if this was the case, it would continuously detect a fault). The recommended value of the capacitor is with a voltage withstand of .
- an overvoltage limiter enabling overvoltages to be run off to earth (a 250 V model cardew is recommended).

When two networks having an insulation monitor can be coupled, it is necessary to set up a logic system so that the two monitors do not operate in parallel.

Figure 2-62: installation of an insulation monitor where there is an accessible neutral

Figure 2-63: installation of an insulation monitor where there is a non accessible neutral

2.12.5.4. Location of the first insulation fault

This can be carried out:

- either by a high performing selectivity system (see § 10.1.4.2., 10.1.5.2. and 10.1.6.2. of the *Industrial network protection guide*). As specified previously, in most cases this requires the use of directional residual overcurrent protections which are tricky to implement
- or by successive tripping of each outgoing feeder until the fault disappears. This latter solution is not recommended as it leads to disconnections on healthy outgoing feeders and may be prejudicial to the operating conditions.

2.13. Principles of setting up an earthing arrangement (see fig. 2-64)

The three main functions ensured by an earthing arrangement are:

- the protection of persons
- the reduction of the effects of electromagnetic disturbances
- the reduction of overvoltages in relation to earth (common mode overvoltages)

The protection of persons is notably ensured by the interconnection and connection to earth of the exposed conductive parts of the loads in compliance with the principles outlined for *TT*, *IT* and *TN* earthing systems.

Reducing the effects of electromagnetic disturbances and limiting common mode overvoltages leads to obtaining, as far as possible, the equipotential bonding of all the exposed conductive parts of the installation.

The following are considered as exposed conductive parts in an installation:

- frame enclosures and structures of electrical equipment and loads
- cable screens and armouring
- cable supports
- piping
- metallic structures of buildings.

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The following are considered as exposed conductive parts in an installation:

- frame enclosures and structures of electrical equipment and loads
- cable screens and armouring
- cable supports
- piping
- metallic structures of buildings.

As regards reducing the effects of electromagnetic disturbances, the following implementation principles must be respected:

- to reduce the effects of electromagnetic disturbances at low frequency (below 1 000 Hz):
 - . separation of the telecommunication cables and power cables by spacing them or using different paths (see § 5-7 of the *Protection guide*).
 - . installation of telecommunication cables inside regularly earthed metal troughs.
 - . installation of power cables in trefloid formation (avoid flat arrangements).
 - . avoid running telecommunication cables in parallel with power cables.
 - . any loop formed by circuits must be avoided.
 - . use a radial configuration for the distribution of auxiliary supplies (the loop configuration system must be avoided).
 - . protection of two different circuits by the same protective device must be avoided.
 - . all the conductors of the same control or monitoring circuit must be located in the same cable. When it is necessary to use different cables, they must follow the same path.
 - . twisted cables are recommended for low level signals.

- To reduce the effects of high frequency disturbances :
 - . try to equipotentially bond the installation area.
 - . eliminate loops which may be created by protective conductors and cable screens.
 - . install a protective system against lightning.
 - . use shielded telecommunication cables:
 - the screens must be continuous.
 - the screens must have a low resistance and a low screen-conductor coupling impedance.
 - all screens must be earthed at both ends.
 - screen earthing must be as short as possible.
 - screens must be earthed at the inlet of equipment to which they are connected. The connections must be preferably circular using suitable cable stuffing boxes.

- . in order to reduce differential mode voltages between different conductors, the telecommunication cables must be grouped together. The conductors of the same control and monitoring circuit must be grouped inside the same cable.

Figure 2-64: earthing arrangement principle