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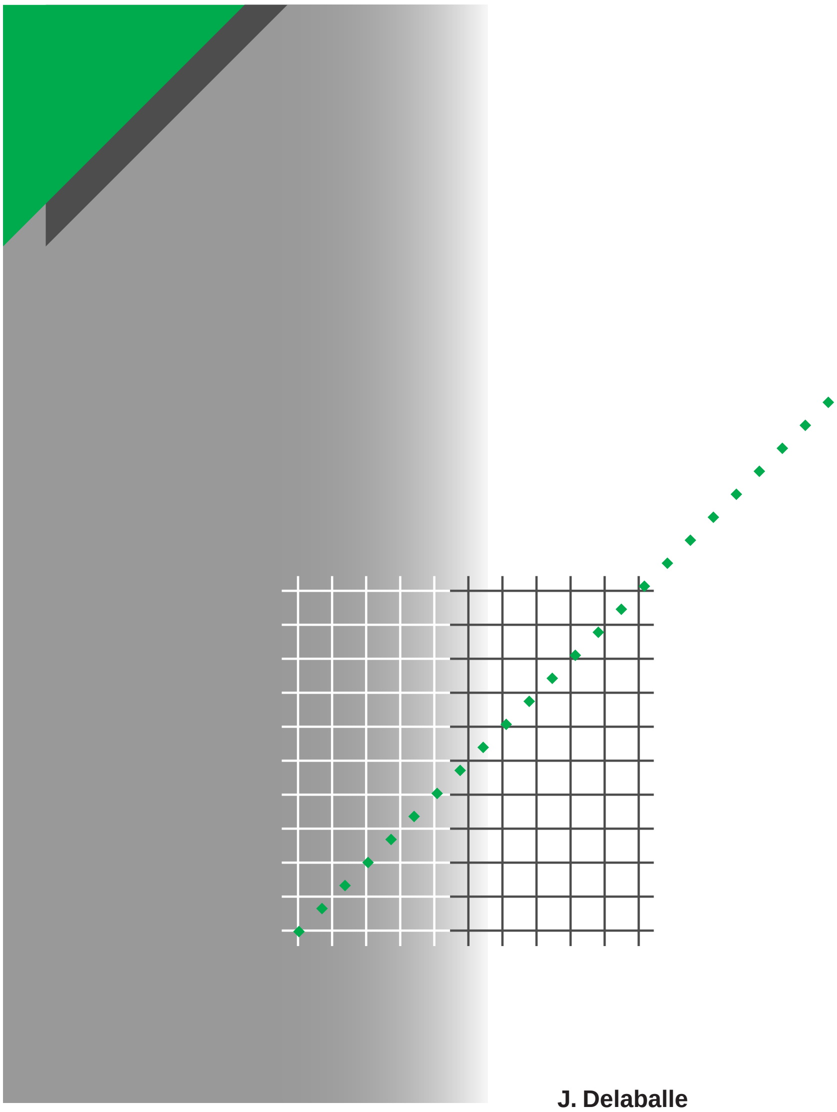
Cahier technique no. 177

Disturbances in electronic systems and earthing systems



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Foreword

no. 177

Disturbances in electronic systems and earthing systems

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Obtained his Ph.D from the University of Limoges in 1980, started at Merlin-Gerin in 1986 after seven years at Thomson.
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Lexicon

CES:
Communicating Electronic System.

EBS:
Equipotential Bonding System.

Electro shock:
Application of voltage between two parts of the body.

Electrocution:
Electro shock resulting in death.

EMC:
Electromagnetic Compatibility.

GFLD:
Ground Fault Location Device.

IEC:
International Electrotechnical Commission.

IΔn:
Value of operating threshold for an RCD.

LV:
Low Voltage.

MV:
Medium Voltage (1 to 35 kV according to CENELEC), in France HTA (1 to 50 kV).

PIM:
Permanent Insulation Monitor.

RCD/HS:
High Sensitivity Residual Current Devices (⩽ 30 mA).

RCD/LS:
Low Sensitivity Residual Current Devices.

RCD/MS:
Medium Sensitivity Residual Current Devices.

SCPD:
Short-Circuit Protection Device.

Disturbances in electronic systems and earthing systems

In today’s society, power and signal processing (analog, digital) electronics are omnipresent in all types of building.

Information technology, automation control, hierarchical control and monitoring systems, weave a web around the electrical networks that supply them.

Although non-linear loads (rectifiers, variable speed drives, power controllers, switch mode power supplies, etc) create disturbances, “low current” electronic systems are affected by all kinds of electrical and magnetic disturbances.

The choice of Earthing System is an important factor for electronic systems, especially when they use digital links (bus) to communicate.

This “Cahier Technique” first examines the disturbance found on LV installations and then looks at the advantages and disadvantages of earthing systems in terms of the cohabitation of “high” and “low” currents.

Contents

1. Introduction

An electrical wave is characterized by:

- its frequency,
- its voltage,
- its intensity.

In the large supply networks of industrialized countries, the frequency is perfectly stable.
It may vary when network splitting on a private installation involves the use of replacement sources, but this variation has little effect on the earthing systems and protective equipment required.

It makes no difference whether the frequency is 50 or 60 Hz. However, certain networks distribute power at 400 Hz, in which case the influence of the earth leakage capacities may need to be taken into account when selecting the earthing system.

During normal operation and in the event of an insulation fault, the currents and voltages present in electrical installations are essentially variable in terms of value and waveform, which may be completely different from the sine wave. This is particularly true for currents resulting from an insulation fault downstream of a static convertor (see “Cahier Technique” no. 114).

Phenomena that distort or disturb the “mains” sine wave have many different origins and, depending on the earthing system, may result in different types of disturbances in the LV distribution, and also in communicating electronic systems.

Three earthing systems are defined by publication IEC 60364. These are discussed in “Cahiers Techniques” no. 172 and no. 173 and a summary is included in appendix 1.

2 Disturbances originating outside LV networks

2.1 Telluric currents

These are currents with a frequency less than 50 Hz, caused by solar magnetic storms. They circulate deep in the earth. They can disturb transmission line protection devices, but cause few problems for small-scale LV networks and have no effect when these networks have only one earth connection.

2.2 Stray earth currents (50 Hz)

These originate during insulation faults in MV or HV networks used with an impedance-earthed neutral point connection, and also in certain electrical traction installations where the feedback current passes into the earth.
Special care must therefore be taken with LV installations located near MV/LV transformer substations and electrified railway lines.
They can cause disturbances due to common-impedance in the operation of “low current” systems spread over a wide geographical area, especially if these systems do not have a single potential reference (as is the case with several earth connections).

It should be noted that stray currents have been one of the reasons for the discontinuation of earth voltage relays sensitive to error voltage.

2.3 Breakdown current in MV/LV transformers

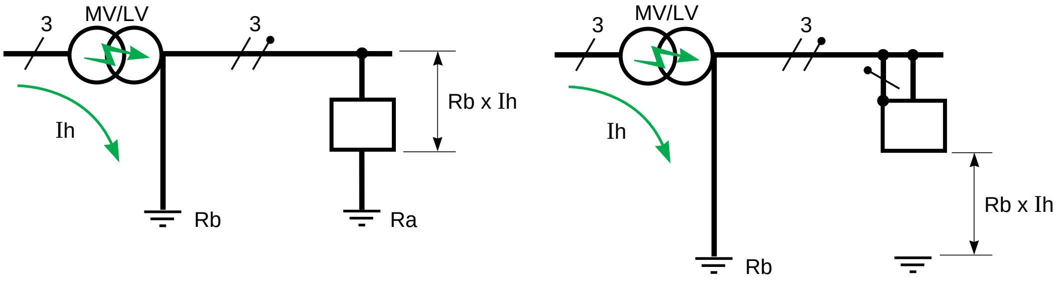
Its intensity depends on the MV network earthing system. Its effect (overvoltage) depends on the interconnection of the exposed conductive parts of LV loads with the neutral earth connection (see **fig. 1**).

Hence in a TT system, to avoid breakdown during feedback from LV equipment, resistance Rb should be less than:

$$Rb = \frac{2U+1000}{Ih_{TM}}$$

Note that publication IEC 60364 replaces the 2U + 1000 (volts) with U + 1200 in TT and TN, and $\sqrt{3}$ U + 1200 in IT. It also indicates that this maximum overvoltage should not last for more than 5 seconds.

In the TN system, to avoid the risk of “indirect contact”, it is necessary for the building to be completely equipotentially bound (eg: high-rise buildings). In IT during breakdown (short-circuiting) of the surge limiter, the same applies if Rb and Ra are mixed up.



a - In **TT**
The live conductors have the potential Rb.Ih in relation to earth. The loads are therefore at risk.

b - In **TN**
The exposed conductive parts of all the loads have the potential Rb.Ih in relation to earth. There is therefore a risk of indirect contact.

Fig. 1 : risks linked to a MV-LV breakdown in the transformer.

2.4 Overvoltages due to switching on the MV network

Overvoltages with an MV origin are significantly attenuated due to the low pass band of the MV/LV transformer (in differential mode). Any effects they may have are totally separate from the choice of earthing system for the LV installation.

2.5 Harmonic voltages

MV networks are disturbed by generators of harmonics found in various subscribers. As a result, distortion occurs in the MV voltage wave, and consequently the LV wave.

LV loads from a non-disturbing subscriber therefore absorb harmonic currents, and currents resulting from an insulation fault are also distorted.

Electricity distributors are nowadays very concerned about deterioration of the MV wave, despite the fact that star-delta transformers (Dy11) do not transmit third order harmonics and their multiples from LV to MV, etc.

The table in **figure 2** gives the maximum harmonic disturbance allowed by Electricité de France (French electricity board). Standard EN 50 160 gives the same values except for third order harmonics and their multiples.

Remember that: $\tau(\%) = \frac{Y_n}{Y_1} 100$

In private LV networks, much higher levels of harmonic voltages and currents are frequently observed.

Odd harmonics not multiples of 3		**Odd harmonics multiples of 3**		**Even harmonics**	
Harmonic order	Harmonic voltage % LV/MV	Harmonic order	Harmonic voltage % LV/MV	Harmonic order	Harmonic voltage % LV/MV
5	6	3	1.5	2	2
7	5	9	0.3	4	1
11	3.5	15	0.2	6	0.5
13	3	21	0.2	8	0.5
17	2	> 21		10	0.5
19	1.5			12	0.2
23	1.5			> 12	0.2
25	1.5				
> 25	02+0.5*25/h				

These limit values, which may seem relatively strict, have been adopted by EDF (French electricity board) based on measurements carried out on networks, and correspond to harmonic levels at which disturbed and disturbing devices can cohabit on networks in acceptable conditions.

Fig. 2 : levels of voltage harmonic disturbances permitted on MV and LV distribution networks.

2.6 Lightning voltages and currents

When lightning directly or indirectly strikes the overhead line supplying an MV/LV substation, lightning arresters placed on the substation MV incoming line limit the voltage wave and disperse the lightning current (see “Cahier Technique” no. 168).

The common mode voltage wave is transmitted onto the transformer LV windings by stray capacitance between the MV and LV windings. This wave, which rarely exceeds 6 kV, appears simultaneously on all live conductors.

Earthing the neutral (directly in TT or TN, or via the surge limiter in IT) can only attenuate the overvoltage appearing on the neutral and causes the appearance of an overvoltage in differential mode (between neutral and phases).

If there is a risk of overvoltage, the use of lightning arresters between all live conductors and earth is therefore strongly recommended, regardless of the earthing system (see “Cahier Technique” no. 179).

The links must be as short as possible:

$\Delta U = L\omega\hat{I}$

where $L = 1\ \mu H/m$ and $\omega = 2.2/tm$, tm being the current rise time.

The lightning current leakage to earth creates overvoltages in the LV network similar to what happens during transformer breakdown (see fig. 1), although with some attenuation due to the stray capacitance as the wave travels over the network.

Remember that IEC 60364 defines four levels of nominal impulse withstand voltage for electrical equipment (wave test 1.2/50 ms): 1.5 - 2.5 - 4 and 6 kV.

2.7 HF disturbances

In addition to lightning strikes, radio-link transmitters (radio, TV, CB, walkie-talkies and GSM) generate permanent or temporary electromagnetic fields.

Normal switching, or short-circuiting, of breaking devices generates pulse electromagnetic fields. For example, 40 kV/m fields have been recorded at a distance of 1 m from an MV cubicle.

These permanent, temporary or pulse fields result in conducted interference, due to antenna or loop effects. This interference may disturb, or even damage, autonomous electronic equipment (if it does not have sufficient immunity) and communicating electronic systems (if the “low current” links have not been created correctly).

3 Disturbances originating within the LV networks

3.1 Harmonic currents and voltages

More and more loads in many spheres generate harmonic currents (see **fig. 3**): industrial (static convertors, etc), commercial (fluorescent lighting, information technology equipment, etc) and even domestic (microwaves, TVs, etc).

- Fluorescent lighting

Standard IEC 60920 defines the maximum levels of emitted harmonics as:

- H3: 25%
- H5: 7%
- H7: ....%

Standard CISPR 150 indicates the level of radiated disturbances that must not be exceeded.
Standard IEC 61547 sets the maximum earth leakage current (via the PE conductor) at 1 mA.

- Graetz rectifiers

Although standard IEC 60146-4 specifies the harmonic currents produced by the rectifiers, there is as yet no standard that sets the levels that must not be exceeded (see “Cahiers Techniques” no. 152 and no. 160).

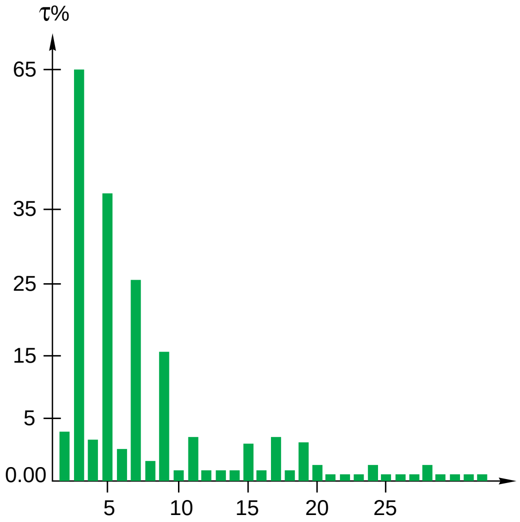
- Switch mode power supply (PWM)

Due to the 10 to 30 kHz switching frequency, these convertors generate harmonic currents with very high frequencies that must be attenuated (HF filters).

Harmonic currents have various and pernicious effects:

- If one or more loads generate third order and their multiples (3 k) harmonic currents, and there is no fault, these currents accumulate and circulate in the neutral. If the neutral is common with the PE (TN-C system), this current disturbs the potential of exposed conductive parts that may damage sensitive loads (stray common mode voltages in relation to earth).
- If there is an insulation fault in a load which is itself generating harmonic currents (static convertors for example), the fault current wave has a very variable shape which depends on its earthing system and the faulty point.
- Insulation fault currents loaded with harmonics may be the cause of malfunctions in protection devices, for which there are a number of solutions:
  - In TN and IT circuit-breakers should have thermal protection sensitive to the actual rms current,
  - In TT RCDs should be class A (capable of operating on pulsed or distorted currents).

a - Switch mode power supply



b - 3-phase variable speed drive

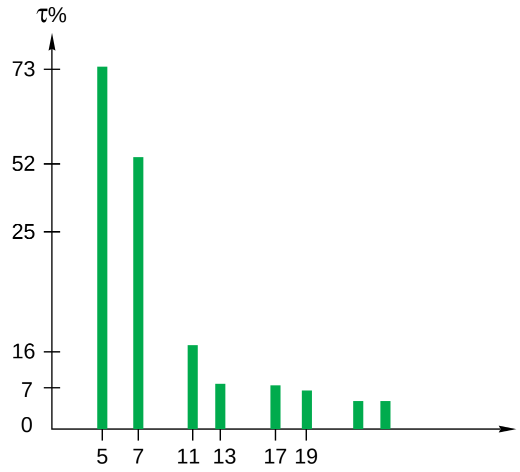


Fig. 3 *: examples of harmonic spectra of loads.*

3.2 Overvoltages due to switching (differential mode) on the LV network

These are mainly the result of breaking of normal or fault currents, for example during:

- Opening of control circuits for contactors and relays not fitted with an RC filter;
- Breaking of short-circuit currents by SCPDs with very high peak arc voltages (certain fuses).

Note that breaking an insulation fault current in the TN system can result in a common mode overvoltage.

These overvoltages can disturb the operation of certain sensitive switchgear… including protection equipment with an auxiliary source, which should have built-in immunity.

3.3 High fault currents

These are mainly short-circuit currents between live conductors (or via the PE in TN and on the second fault in IT).

If the various conductors are ungrouped and single-wire, the magnetic field which is then radiated by the live conductors (and by the PE in TN and IT) can cause accidental operation of electronic equipment, especially when these devices are near electrical trunking or connected by “low current” links.

The table in **figure 4** summarizes the types of disturbances and their effects according to the earthing system.

Disturbances	**Effects**	
Stray earth currents	Creation of a LF voltage difference between two separate earth connections	**TN** : no risk to people and the electronics
		TT : no risk if only 1 earth connection for all uses
		IT : same as TT
MV/LV breakdown in the transformer	Common mode voltage for the LV network $(R_B .Ih_{MV})$	**TN** : risk to people if equipotentiality of the building is not complete
		TT : risk to equipment
		IT : same as TN when the surge limiter short-circuits
Lightning on MV	Capacitive transmission on LV network	**TN** : risk for equipment in differential mode
		TT : same as TN
		IT : same as TN, the limiter only affects a live conductor
Harmonic currents in LV network	Third order harmonic current (and multiples) in the neutral	**TN** : non-equipotentiality of the PEN in TN-C
		TT : no problem
		IT : no problem
Insulation fault currents	Magnetic field Voltage drop in the PE	**TN** : risk for sensitive and/or communicating equipment
		TT : no problem
		IT : same as TN if double fault

Fig. 4 : main types of disturbances and their effects depending on the earthing system.

4 Cohabitation of “high currents” and “low currents”

Electronics are used everywhere nowadays: in sensors, actuators, process control and monitoring systems, of buildings and electrical distribution.

These devices are supplied by the LV network and should not be sensitive to the various types of disturbances seen earlier.

Responsible manufacturers are fully aware of how to provide immunity for these devices, in other words to control their susceptibility to electromagnetic phenomena. To this end, they refer to the electromagnetic compatibility standards, for example, IEC 61000 (see “Cahier Technique” no. 149).

At the same time, standardization aims to minimize interference emitted by disturbing devices. Standard CISPR 11 is an example of this.

Nonetheless, the standardized cohabitation between disturbing devices and disturbed devices has not been resolved since, in the electrical domain, certain questions remain:

- How does an electrical installation behave when it is producing disturbances?

... When the way the installation is created and the choice of earthing system are the determining factors.

- In this context, how can we attenuate disturbances and their effects on sensitive (electronic) equipment?

... This is where the problem lies: the satisfactory coexistence of electrotechnical and electronic equipment, in other words, of high currents and low currents. For this to be satisfactory, disturbances must be minimized at source and couplings between the source and the potential victim avoided.

4.1 Limiting emitted disturbances

As we saw in earlier sections, there are many types of disturbances. They can be in common mode or differential mode, low or high frequency, conducted or radiated (see **fig. 5**). There are various possible solutions for limiting disturbances.

In MV

- Use zinc oxide lightning arresters linked as closely as possible to an earth connection other than that of the LV neutral, to limit overvoltages due to lightning.
- Limit MV zero-sequence currents and minimize the value of the LV neutral earth connection, to avoid feedback breakdowns if there are multiple earth connections.
- Use MV/LV transformers whose coupling blocks certain harmonic currents, to limit harmonic pollution.

At the origin of the LV network

- Avoid linking the neutral earth connection with that of the transformer and the lightning arresters (this separation of earths is practiced in France for “pole-top” substations in rural overhead distribution).
- Place lightning arresters at the origin of the LV network, linked as closely as possible to the neutral earth connection, to limit overvoltages due to lightning passing through the transformer.

	Common mode	**Differential mode**
LF disturbances	■ rise potential in LV network (MV/LV breakdown) ■ high fault current in the PE ■ 3k order harmonics in the PEN ■ value of earth connection Ra too high in TT	■ harmonic currents and voltages ■ short-circuit current
HF disturbances	■ lightning overvoltage and current ■ HV switching overvoltage	■ lightning overvoltage and current ■ breaking of an Isc by an SCPD with a high peak arc voltage

__Fig. 5__ : different types of disturbances depending on the propagation mode and frequency.

- Avoid the TN-C earthing system as the PEN carries harmonic currents (third order and multiples) and therefore disturbs the potential reference provided by the PE for electronic equipment.

In the LV network

To minimize radiated magnetic fields:

- As far as possible, avoid using single-pole cables that generate a significant magnetic field in the event of a short-circuit.
- Do not separate the PE on live conductors, or even better, use cables that incorporate the PE.
- Do not use shielded cables whose casing forms the PE or place the cables in steel tubes acting as a protective conductor (the field radiated by the live conductors is blocked and the PE generates a magnetic field).
- Ideally use earthing systems that minimize insulation fault currents (reduction of the magnetic field).
- Minimize the power-up current of capacitor banks (shock resistors or inductances).
- In IT, if the network is small-scale, use an impedance (impedance earthed) to “fix” the neutral potential to earth.
- Run the power cables along metallic cable trays, paying special attention to the continuity of this “ground plane” and its connection with the main equipotential bonding (horizontal and vertical routing), as this significantly reduces electromagnetic radiation.
- Trap overvoltages:
  - ☐ by placing RC circuits on the coils of contactors, relays, etc.
  - ☐ by protecting sensitive equipment with lightning arresters.

In loads

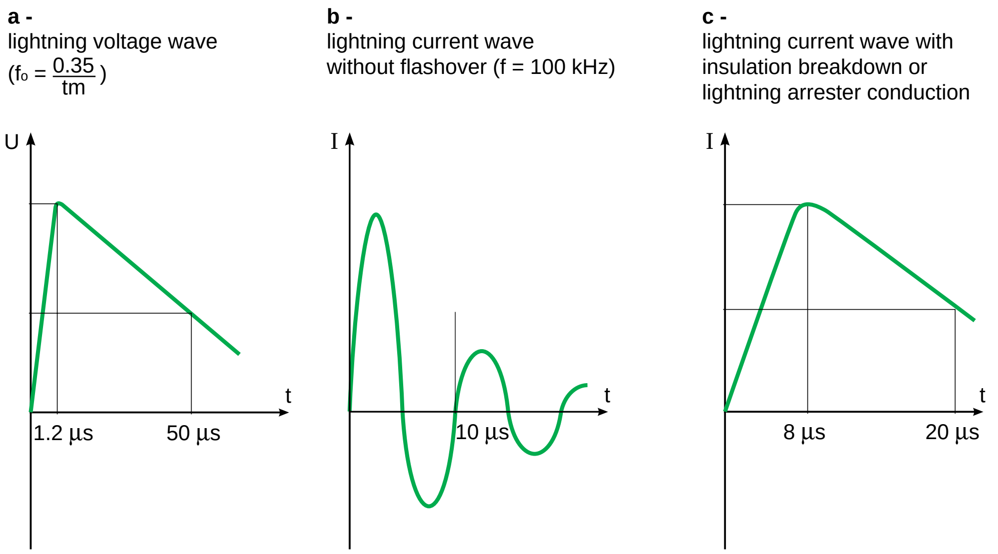
All electrical equipment is covered by standards limiting emission of HF and LF disturbances when connected to the public LV distribution network.
There are numerous solutions for minimizing harmonic currents: passive or active filters, static convertor with sinusoidal sampling, etc.

4.2 Reduction of couplings

Not all disturbances can be attenuated at source: to avoid malfunctions in electronic equipment, transfers between the transmitter and the disturbed device must be minimized.

There are several types of couplings, and to explain them, we will look at the example of the lightning current (see **fig. 6b**).

When lightning strikes an MV or LV overhead line, the peak current at the point of delivery can reach several tens kA. The di/dt and $\int I^2 dt$ are very high.



a -
lightning voltage wave
$(f_o = \frac{0.35}{tm})$

b -
lightning current wave
without flashover (f = 100 kHz)

c -
lightning current wave with
insulation breakdown or
lightning arrester conduction

Fig. 6 *: some standardized lightning waves.*

Common-impedance coupling

Let’s look at the example of a TN system. All the exposed conductive parts are connected (see **fig. 7a**) where:

$\hat{I}$ = 25 kA,

di/dt = 25 kA/8 µs,

an N-PE link of 1 meter with a lineic choke of 1 µH/m; the voltage DV developed between

N and PE is: $\Delta V = L\frac{di}{dt} = 10^{-6} x \frac{25 \text{ x } 10^3}{8 \text{ x } 10^{-6}} = 3 \text{ k}\hat{v}$

This is thus the voltage applied between neutral and the exposed conductive parts of the LV equipment!

The solution consists in creating star connections from the earth connection (see **fig. 7b**), the best way of creating two earth connections (see **fig. 7c**).

More usually an electrical conductor across which an abnormal (fault) current flows generates a potential difference between its ends which may cause disturbance, and this is common-impedance coupling.

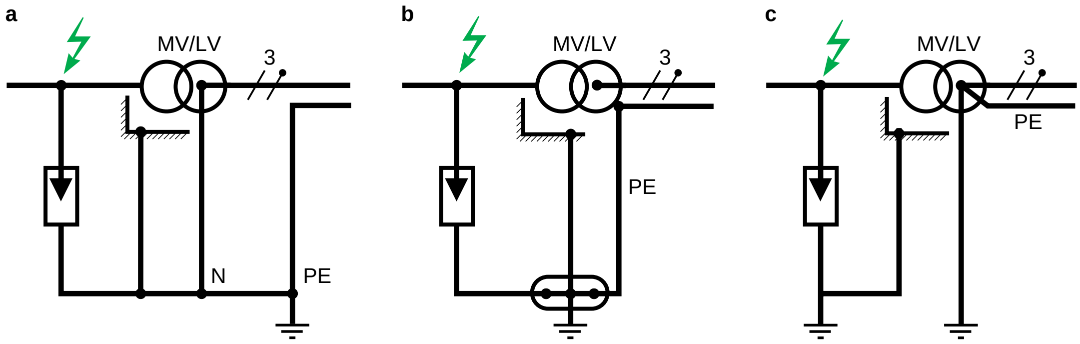


Fig. 7 : avoid common-impedance coupling when dealing with disturbance of MV origin.

Let’s look at another example involving the installation of a lightning conductor. We will assume that the partly metal floors are linked to the lightning rod downcomer (see **fig. 8**):

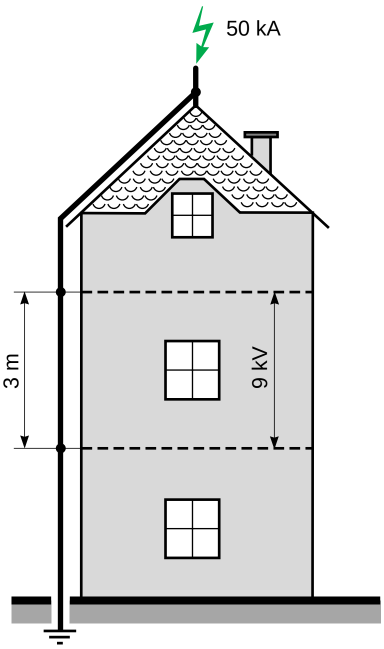


Fig. 8 : “common mode” voltage generated between 2 floors by a 50 kA lightning current.

where:

L = 0.5 mH/m (flat conductor)

length of the conductor = 3 m

$\hat{I}$ = 50 kA

the ΔV between floors will be:

$$\Delta V = L\frac{di}{dt} = 1.5 \text{ x } 10^{-6} x \frac{50 \text{ x } 10^3}{8 \text{ x } 10^{-6}} = 9.4 \text{ k}\hat{v}$$

The equipotentiality in the building may be jeopardized!

One solution is to use multiple lightning conductors and keep them away from all electrical circuits, but a better solution is to use a “bell-shaped” Faraday cage (see **fig. 9**).

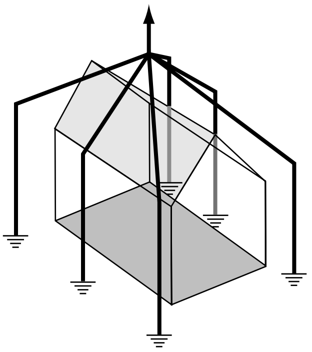


Fig. 9 : lightning conductors arranged in a “bell-shaped” Faraday cage.

Note that in order to attenuate penetration inside the building of the electromagnetic waves resulting from a nearby lightning strike, the distance between the conductors constituting the cage must be less than one-tenth of the wavelength λ. Where a tm = 1 µs,

$$f = \frac{0.35}{tm} = 350 \times 10^3 \text{ Hz}$$

$$\frac{\lambda}{10} = \frac{1}{10} \times \frac{300 \times 10^6}{350 \times 10^3} = 85.7 \text{ m}$$

Capacitive coupling

MV equipment (24 kV) has a lightning impulse withstand voltage (1.2/50 µs wave) of $125\ k\hat{v}$. The capacitive transfer coefficient between the 20 kV and the 400 V is usually 0.04 to 0.1 (IEC 60071-2 states that it can reach 0.4).

Hence a lightning wave of $100\ k\hat{v}$, with a coefficient of 0.07 transmits a homothetic wave of $7\ k\hat{v}$ to the LV in common mode.

It is for this reason that:

- the substation LV equipment usually has reinforced insulation ($10\ k\hat{v}$),
- electrical cabinets can withstand $12\ k\hat{v}$ the impulse wave (PRISMA and its accessories),
- power circuit-breakers have $8\ k\hat{v}$ withstand in common mode according to standard IEC 60947-2.

The higher the voltage and the frequency, the higher the disturbance capacitive transfers.

Because of the capacitive effect, any “power” conductor transmits a stray voltage to “low current” conductors which are following the same path at too close a distance.

Inductive coupling

Assuming that a building is equipped with a lightning conductor and that a “low current” link runs along the lightning rod downcomer, over a length of L = 5 m and at 50 cm distance (see **fig. 10**).

Surface area S = L x *l* (*l* = space separating the two “low current” conductors ≈ 5 mm) is:

5 x 0.005 = 0.025 m^2.

Using Ampere’s theorem:

$$H = \frac{I}{2\pi R} \; ; \; \phi = B\,S \quad \text{and} \quad u = \frac{d\phi}{dt} \; ;$$

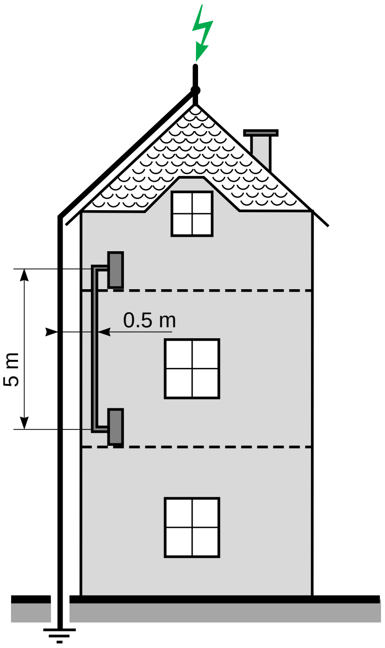


Fig. 10 *: the inductive coupling creates differential mode voltages in the low current links.*

hence: $\hat{u} = -\mu_o\, S \frac{dH}{dt} = -\frac{\mu_o\, S}{2\pi R}\,\frac{di}{dt}$

therefore where di = 50 kA and dt = 8 x 10^{-6} s:

$$\hat{u} = \frac{4\pi \times 10^{-7} \times 0.025}{2\pi \times 0.5} \times \frac{50 \times 10^3}{8 \times 10^6} \approx 60 \text{ V}$$

This pulse voltage is superimposed on the useful voltage (a few volts) and disturbs the link, or even damages communicating electronic equipment.

The solution is to avoid common close paths between circuits with high di/dt and “low current” circuits and to use twisted pairs for data transmission.

Couplings mainly result from the way in which installations are created.
By way of example, appendix 2 details the measures taken in a hospital, to ensure that electroencephalograms are not affected by interference.

4.3 Exposed conductive parts and earths

To assist comprehension of the following sections, here are some definitions:

- earth (deep): conductive part of the earth whose electrical potential at each point is considered, by convention, to be zero;
- earth connection: conducting body or set of conducting bodies in close contact with the ground and providing an electrical link to it;
- earth network: set of protective earth conductors (PE) linked to an earth connection, whose purpose is to prevent the appearance of a dangerous voltage between electrical exposed conductive parts and the earth in the event of an insulation fault (indirect contact);
- electrical exposed conductive part: conductive part of an electrical device that can become live in the event of an insulation fault;
- parallel earthing conductor: EBS or conductive structure (meshed floor, cable tray or shielding, etc) that runs in parallel with a “low current” cable and protects it by mitigating electromagnetic (HF) couplings or common-impedance couplings;
- functional bonding conductor (FBC): conductive part of an electronic device that acts as a screen and often a potential reference (zero volt). Note that a class II device does not have an electrical exposed conductive part, but may have a functional bonding conductor;
- functional equipotential bonding system: set of parallel earthing conductors and conductive structures in a building which provide equipotentiality and act as a screen against disturbances.

It should be noted that the role of an earth system is to protect people with respect to the electrical distribution (50 Hz), and that an EBS has a functional role in data transmission and preventing electromagnetic disturbances (see **fig. 11**).

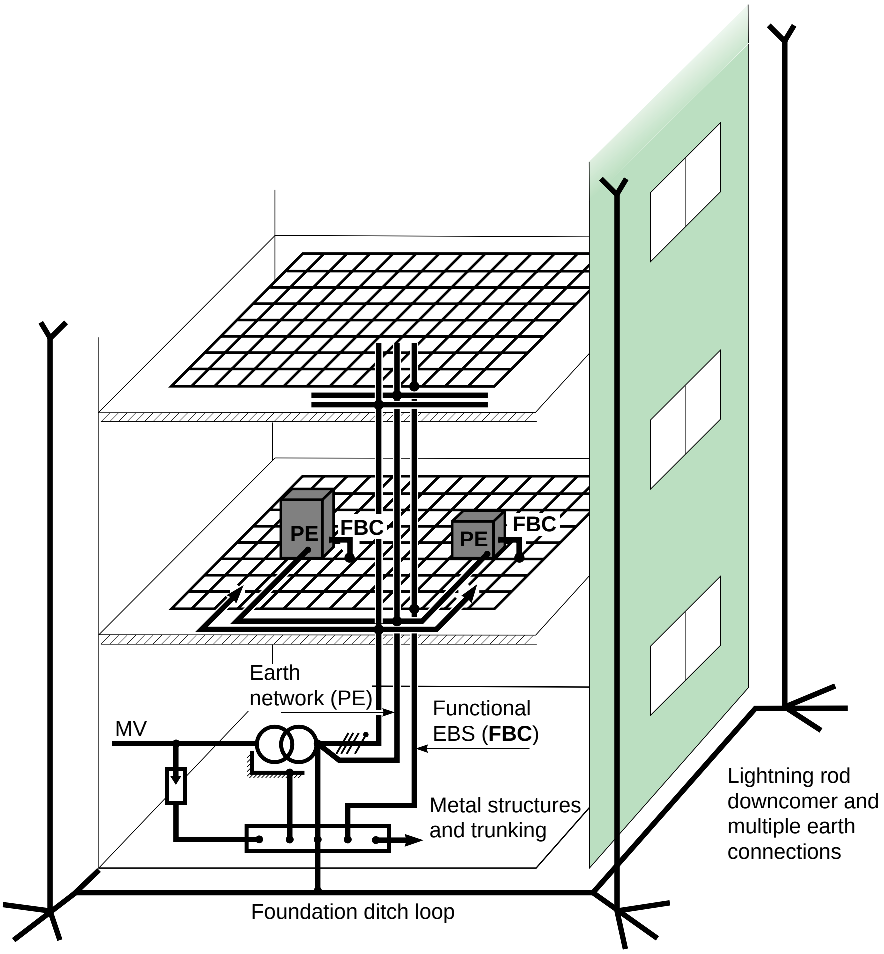


Fig. 11 : example of earthing and EBS system.

4.4 Ideal earth and EBS system

The system in figure 11 is an example of this for the following reasons.

- External disturbances (lightning, switching, HV/exposed conductive part breakdown) have a minor effect on the building equipment, since:
  - there are multiple lightning rod downcomers and multiple triangular crossbracing earth connections;
  - the various “electrical” earth connections are arranged in a star around a single earth connection.
- The PE conductor (regardless of the earthing system) does not disturb the electronic functional bonding conductors, since:
  - there is no common-impedance coupling since the earth network - PE - is separated from the functional equipotential bonding system.
    In practice, this separation is often provided at floor level but not always for risers;
  - its radiated field can be significantly reduced when it is in the same cable as the live conductors, with the cable placed on metallic cable tray with electrical continuity, and this cable tray connected to the PE at the origin of the installation.
- All the “low current” cables running across the meshed floor (mitigating effect) at a distance from the power circuits (⩾ 30 cm) avoid magnetic coupling effects. The same applies to floor feedthroughs (inter-floor links) with “low current” cables circulating in metallic cable tray that follows the “functional bonding conductors”.

Note

- A parallel earthing equipotential bonding conductor can replace a meshed floor or enhance its effect to minimize the effects of any HF loops.
- The earth network - PE - and the functional equipotential bonding system can constitute a single network given two essential conditions:
  - if there is no HF disturbances, high dv/dt and high di/dt,
  - if the fault currents in the PE or PEN are weak and free of harmonics.

Certain EMC specialists indicate that even if these conditions are not met, the EBS and earth networks can be closely linked. This is on condition that the floors, structures and trunking are **correctly** meshed (pursuit of total equipotentiality by dividing currents and minimizing loops).

This solution is difficult to implement in large-scale projects (interconnection of reinforcing rods and all metallic door frames), but may be suitable for very specialized buildings such as computer centers and telephone exchanges.

5 Earthing systems and communicating electronic systems (CES)

In the previous section, we discussed cohabitation of electrotechnical installations and electronic switchgear. The situation becomes more complicated with the development of digital links that bring electronic devices together in communicating control and monitoring systems.
In this section, we will examine in more detail the problems that LV network earthing systems can cause for communicating electronic systems.
However it should be remembered that:

- Before the development of microprocessors, there were few communicating systems, and these were locally based (links between sensors and measurement apparatus). They used low frequency analog signals (0-10 V, 4-20 mA, etc) and were sensitive to LF disturbances, hence the connection of exposed conductive parts in a star to avoid common mode couplings.
In addition, there were little HF disturbances, and the induced voltages were easy to filter out.
- Nowadays, links between electronic devices are digital (bus), high frequency and with a very low electrical level. They are increasingly numerous and cover wider and wider areas (PC networks, “intelligent” sensors-actuators, technical management system, etc).
- Depending on the earthing system used, the method of connecting functional bonding conductors and related runs of “low current” links in relation to the power distribution, the following may be observed:
  - the existence of common-impedance disturbance due to fault currents in the PE,
  - the creation of extended loops (with digital links) which are therefore highly receptive to disturbance emitted by devices transmitting high frequency signals (normal or interference).

5.1 Earthing systems, CES and Low Frequency - LF - disturbances

Electronic equipment frequently requires an electrical power supply, and its electrical exposed conductive parts and functional bonding conductors are therefore linked to the earth network (PE), a network that follows the electrical network tree structure. LF disturbances then appear in the network by common-impedance type coupling, or by induction (close parallel runs).

Common-impedance coupling

According to the scheme in **figure 12** , when an insulation fault causes a current to circulate in the PE, between the points connecting a device (1) and its sensor (2), a voltage drop appears between C and D. This voltage (u) is between (1) and (2) and may disturb signal transmission.

If, for example, the cable is coaxial, the voltage imposed on the cable duct will be in differential mode (u’) in the link! This phenomenon exists to a greater or lesser degree depending on the type of cable used, and depends on the cable’s “transfer impedance” in the frequency range in question.

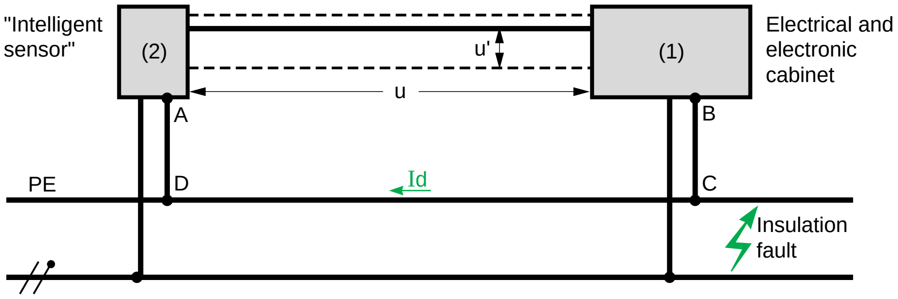


Fig. 12 : the voltage drop in the PE, due to the fault current, disturbs the link between communicating devices (it can exceed Uo/2 in the TN system - SPE < Sph).

- In TN-C, currents circulating in the neutral, therefore in the PEN, cause significant variations in the potential reference of the various devices in the CES. This earthing system is not suitable, especially if harmonic currents are circulating in the neutral, unless the functional equipotential bonding system is separated completely from the earth system, which is undesirable in terms of the equipotentiality of the installation.
- In TN-S and also in TN-C, insulation faults result in the circulation of short-circuit currents (with high di/dt) in the PE which:
  - modify the potential reference of CESs (see previous example),
  - may cause circulation of disturbing currents in the metal structures of the building (hence the advantage of linking the structures to the main earth terminal rather than to the earth network, at various points).
- In IT, on the first fault, the fault currents are usually less than 1 A and do not therefore cause a problem. In the event of a double fault, if the first fault has not been located and eliminated, the situation is the same as in TN-S.
- In TT, it is clear that if communicating systems are linked to different earth connections, the problems of equipotentiality are as significant as in TN. Therefore the presence of a communicating system involves a single earth connection for all uses. In this case, insulation faults cause the circulation of fault currents of approximately 20 A in the PE, which cause little disturbance (but 20 kA in TN!).

To avoid the appearance of these disturbances between communicating devices, the solutions consist of:

- avoiding earthing systems that cause a high current to circulate in the PE;
- insulating the electronic 0 Volt (functional bonding conductors) from the electrical exposed conductive parts (therefore using an isolation transformer if necessary); it should be remembered that data processing equipment should include an isolation transformer (IEC 60950) and that IEC 60364 requires the functional bonding conductors of data processing equipment to be connected directly to the main earth terminal;
- use class II equipment, which removes the need for links to the PE;
- avoid multiple earth connections (in TT and in IT) if there is a risk of stray currents in the earth.

Inductive coupling (inductive crosstalk)

Remember that, according to the laws of electromagnetism, any current circulating in a conductor generates a magnetic field. If this field is variable it results in a variation in flux and therefore a stray voltage in a nearby loop.

To prevent the appearance of magnetic fields:

- the live conductors and the PE must be in the same cable (the fields radiated by the various conductors cancel one another out). Remember that insulation fault currents in TN can be characterized by $\Delta i \approx 50$ kA with a $\Delta t \approx 5$ ms,
- it is not advisable to allow structures to participate in the feedback circuit, otherwise the vectorial sum of the currents in the cable will not be zero.

And to limit couplings it is necessary to:

- avoid any parallel close run of a conductor with high di/dt (lightning rod downcomer, protective earth conductor) with a “low current” link,
- use links with twisted pairs for low currents (the voltages developed in successive loops cancel one another out).

5.2 Earthing systems, CES and High Frequency - HF - disturbances

Digital systems distributed throughout buildings are very sensitive to HF disturbances, whether permanent or transient, radiated or conducted.

Radiated HF disturbances

These disturbances are due to frequency signals usually higher than 1 MHz. They originate from welding machines, arc furnaces, walkie-talkies and other transmitters such as certain HV breaking devices or electronic ballasts.

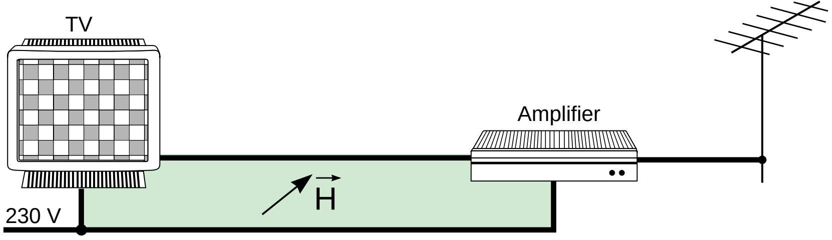
In fact there are standards limiting HF emissions (eg: CISPR 11 and EN 55011), but not all devices are affected.

If the inconvenience caused to CESs by these disturbances is independent of the earthing systems, it is absolutely vital to avoid loops that the "low current" networks may make with the electrical circuits (see **fig. 13**).

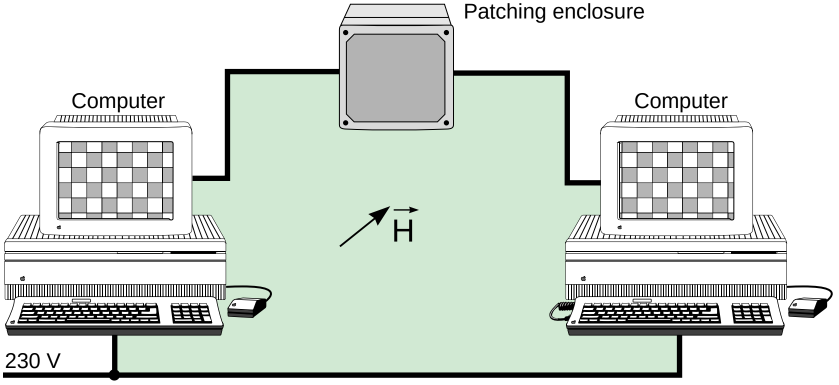
In fact, a radiated electromagnetic field induces a current in the loop, which generates stray voltages in "low current" transmissions. And the bigger the loop, the more disturbance is created.

Lightning is a very powerful natural phenomenon: a 50 kA lightning strike 100 m away can generate a voltage of 100 V in a 1 m^2 open loop and, if the loop is closed, a current of more than 20 A.

a - TV with amplifier



b - networked computers



c - computer and printer

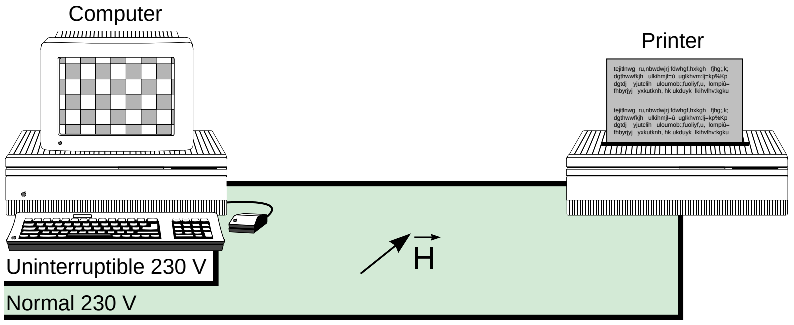


Fig. 13 : examples of inductive loops causing breakdown of communicating electronic systems.

On the scheme in **figure 14** , in the absence of a parallel earthing conductor, a voltage is developed between both ends of the “low current” link. This disturbs the transmitted signals.

The parallel earthing conductor forms an inductive loop with the “low current” link. This loop has a very small surface area (S2), much smaller than the initial surface area (S1 + S2), and hence the disturbance is significantly reduced.

Several solutions may be considered, depending on the installed equipment:

- Use an isolation transformer and avoid stray capacitance between the electronics and the electrical exposed conductive part.
- Minimize the loop surface area:
  - either by making both circuits (the “low current” and the power supply) follow the same path but approximately 30 cm apart (see chapter 4),
  - or by adding a parallel earthing conductor if the “low current” link is not shielded.

Note that the ground planes perform the same function as the parallel earthing conductor (metallic cable tray, finely meshed floors).

- For digital links, use twisted conductors (reduction of the transfer impedance) circulating in metallic cable tray which acts as a parallel earthing conductor.
- In difficult situations add decoupling at both ends (input and output) of the digital link using optical couplers or a pulse transformer, and connect the digital link shielding to the electronic bonding system (see **fig. 15**).
- Lastly, in very disturbed environments, the solution is fiber optic transmission…

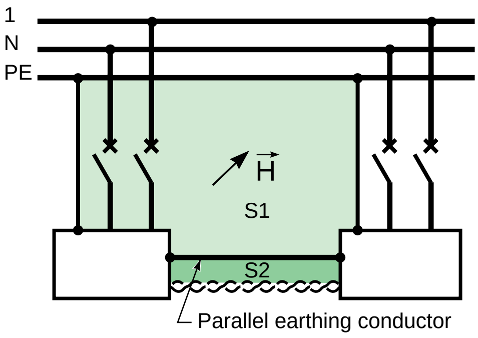


Fig. 14 : reduction of the loop surface area by a parallel earthing conductor (in this example the functional bonding conductors and PE are linked. This does not pose a problem in the TT system).

Conducted HF disturbances

This disturbance is due to signals whose frequency is typically between 10 kHz and 30 MHz. It originates from lightning, overvoltages due to switching and certain switch mode power supplies.

- Lightning

In this case, the problem is identical regardless of the earthing system: the lightning surge which arrives at the origin of the LV installation is essentially in common mode (it involves all the live conductors simultaneously). The further it moves away from the source, the more it is attenuated by the stray capacitance. Therefore, when two communicating devices are installed at a distance, one close to the source and the other at a distance, an HF potential difference appears between the power supplies of these two devices. This may lead to disturbance of digital communications.

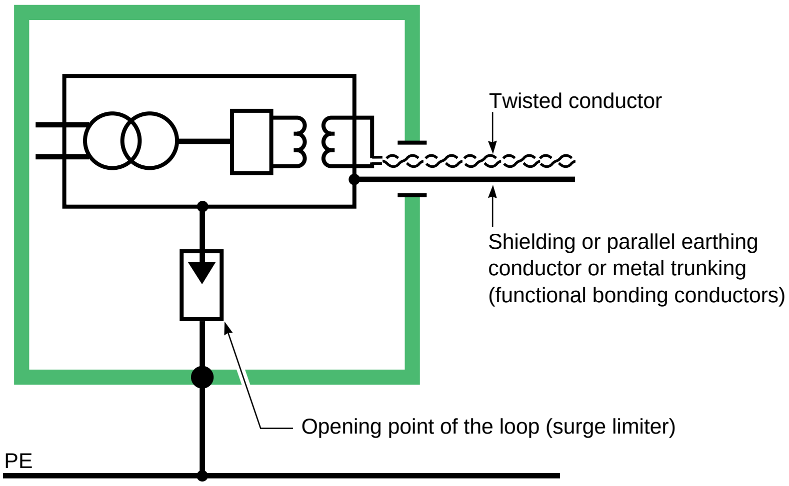


Fig. 15 : example of steps taken to avoid disturbances due to HF loops.

The minimum response to this problem is to install lightning arresters between each live conductor and the earth at the origin of the LV installation (near the MV/LV transformer), except:

□ on the neutral in TN and TT, because the neutral is linked to earth (the overvoltage flows directly to earth), but it is important to have the shortest possible link between the neutral earth connection and the PE (see previous section)

□ on the conductor to which the surge limiter is connected (usually the neutral) in IT, as this limiter eliminates this overvoltage

Note: In TN-S, IT and TT, it may be necessary to add lower voltage lightning arresters in the LV installation, even on the neutral, because of capacitive coupling between the live conductors. For implementation, see “Cahier Technique” no. 179.

■ Overvoltages due to switching (breaking of inductive currents)

These are essentially in differential mode. All earthing systems are similarly affected. The only solution is to attenuate these overvoltages as soon as they are emitted.

■ Disturbances due to switch mode power supplies

Certain equipment such as the electronic ballasts of certain fluorescent lamps and tubes, TVs, PCs etc, use switch mode power supplies (with Pulse Width Modulation - PWM -). These generate HF harmonic currents which can disturb sensitive equipment.

If this is the case, there are three solutions:

□ Insert an isolation transformer with a screen.

□ Use ferrite cores. These attenuate disturbances of several tens of MHz in magnetic materials, due to the Joule effect (see **fig. 16**).

□ Use filters such as, for example, the filter in figure 17. This solution is often employed by manufacturers of sensitive switchgear. The use of filters does, however, present certain difficulties that it is important to be aware of when creating an electrical installation, in particular when choosing the correct earthing system.

Specific features of using filters

Filters usually incorporate capacitors - Cy - whose technical characteristics mean that:

■ Standard filters often have a much lower voltage withstand than that of the electrotechnical equipment.

□ These filters are therefore more vulnerable to common mode overvoltages: they may need closer protection by a voltage suppressor (varistor). This poses the more global problem of coordination of insulating devices in LV.

□ These filters are at the origin of 50 Hz leakage currents which, although limited by product standards, should be taken into account when defining the protection to be installed on the electrical distribution.

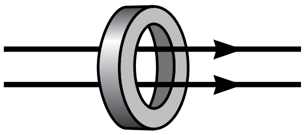


Fig. 16 *: a ferrite core attenuates common mode HF disturbances.*

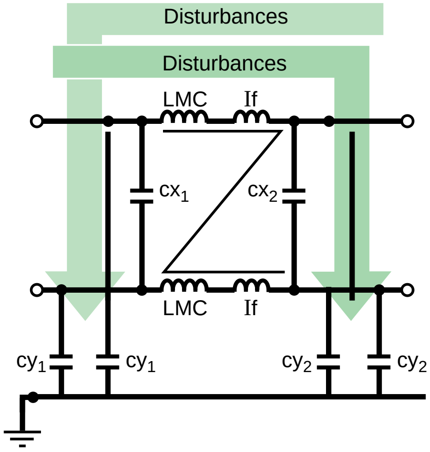


Fig. 17 *: high-frequency filter.*

These leakage currents vary in practice from 0.2 to 1 mA for equipment supplied via a power socket, but can be higher for power equipment in a fixed installation. For example, there are filters with a leakage current of 2.85 mA for In = 50 A at 50 Hz. However, certain computer equipment conforming to IEC 60950 (mainframe computers, computers marked “high leakage current”) can have higher leakage currents, as this standard permits values up to 5% of In, which explains the need to divide up their electrical distribution, usually in a TN earthing system.

Remember that for these types of equipment, IEC 60364 stipulates a direct link to the main equipotential bonding.

Influence of filtering capacitors on the various earthing systems

■ In TN, they do not hamper the circuit-breakers and fuses and therefore do not affect the protection of people provided by these devices.

■ In IT, they do not increase the disturbance of short-circuit protection devices. But if there are large amounts of electronic equipment incorporating these filters, they may hamper the

operation of LF current injection PIMs.
DC injection devices are therefore preferable.

- In TT, leakage currents due to the filters, when there are large amounts of electronic equipment, can cause accidental operation of high-sensitivity (30 mA), or even medium-sensitivity (0.3 A) RCDs. It is for this reason that in normal practice no more than three power sockets are protected by one 30 mA RCD.

Note that protection equipment has been the subject of numerous improvements.
For example, nowadays RCDs:

- are unaffected by steep edge disturbances and transient currents,
- are immune to pulsed unidirectional currents,
- allow overvoltages due to lightning to flow to earth via the lightning arrester without tripping (RCD with slight delay on tripping).

Conclusion

The various earthing systems are equivalent in terms of protection of people.
But, with the development of communicating digital systems and the proliferation of disturbing devices, the design of electrical installations requires that the cohabitation of “high currents” and “low currents” is controlled and hence that installation methods are reconsidered, as well as the choice of earthing system.

At installation level

At this level, it is necessary to reduce both the sources of disturbances (power and radiation), and the sensitivity of devices and especially of “low current” links.

For this it is important to:

- Avoid connecting lightning rod downcomers and MV exposed conductive parts to the neutral earth connection (elimination of common mode overvoltages resulting from common-impedance coupling).
- Ensure that the PE runs along the live conductors (reduction of inductive couplings) and is only connected, in the distribution, to the exposed conductive parts of electrical loads, especially in TN.
- Use equipotential metallic cable trays in relation to the main equipotential bonding (reduction in radiation from the electrical power cables and effect of the parallel earthing conductor and ground plane for sensitive circuits).
- Clearly separate “low current” links from power cables if they are on the same support, or preferably place them on different neighboring cable trays.

In reality, the “high current” and “low current” links often have different paths. Therefore, a parallel earthing conductor (or equivalent) must be used for “low current” circuits and thus a functional equipotential bonding system is created.

At earthing system level

The TN-C system, already prohibited in areas at risk of fire and explosion, must not be used since the neutral currents circulating in the PEN disturb equipotentiality.

Moreover, if some of the neutral and fault currents circulate in the metal structures of the building, these stray currents, as well as the phases + PEN cable become generators of disturbing magnetic fields.

For the TN-S system, in view of the high disturbing fault currents, it is advisable to create a functional EBS, separated from the earth circuit (PE) and therefore truly equipotential (see fig. 10) which, with the conductive floors and structures, will constitute a mitigating ground plane effect and Faraday cage.

The IT system offers the best continuity of service with a very low disturbance level, but if the occurrence of the double fault is taken into account, the specifications are the same as in TN-S.

The TT system generates the least amount of disturbances in the event of an insulation fault. It makes it possible to continue to mix both functional bonding conductors and electrical exposed conductive parts closely and to make the most of the meshing and equipotentiality.

Without doubt, faced with the new problem of systems communicating via digital links, the whole problem concerns the equipotentiality, in LF and HF, of all the exposed conductive parts in the entire installation.

The answer in terms of implementation of earthing systems is:

- For all earthing systems: create mitigating ground planes (floors, metallic cable trays), interconnect them and avoid “high current” - “low current” loops.
- For TN-S and IT earthing systems (2nd fault), separate the earth network (PE) from the equipotential bonding system or very strongly mesh all the exposed conductive parts in order to divide the 50 Hz fault currents and the HF disturbing currents.

Closely connecting anything metal is a solution usually put forward by the English. In practice it is only applicable in “mainly metal buildings”, developed vertically and where construction is closely monitored.

- The TT system is the one which best solves the problem posed by the proliferation of digital links in buildings, as long as the earth connections of the loads are interconnected by the PE.

Appendix 1: earthing systems according to IEC 60364

The three earthing systems standardized at international level are nowadays included in many national standards.

These three neutral systems are studied in detail in “Cahier Technique” no. 172 with, for each one, a presentation of the risks and associated protection devices.

A brief summary of their protection principles is given below.

The TN system (see **fig. 18**)

- The transformer neutral is earthed.
- The exposed conductive parts of the electrical loads are connected to the neutral.

An insulation fault is transformed into a short-circuit and the faulty part is disconnected by the short-circuit protection device (SCPD).

If the outward circuit impedance equals that of the return circuit, the fault voltage (exposed conductive part/deep earth) known as “indirect contact” is ≈ Uo/2. Above the conventional limit voltage (U_L) which is usually 50 V, the higher Ud is in relation to U_L the quicker the disconnection must be.

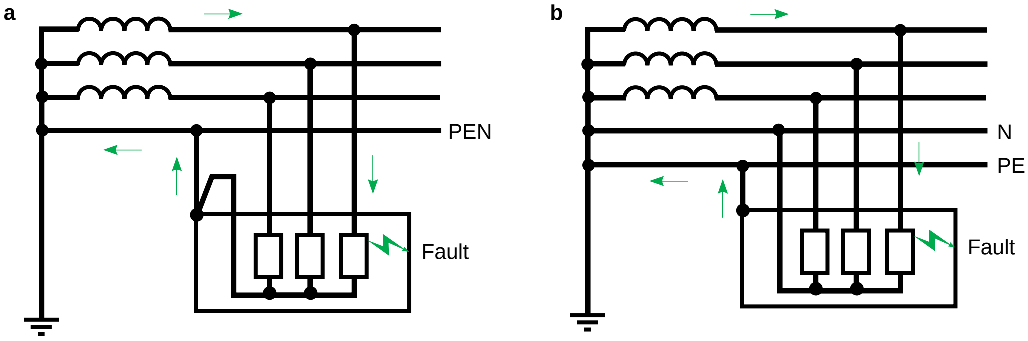


*Fig. 18 : TN-C -**a**- and TN-S -**b**- systems.*

The TT system (see **fig. 19**)

- The transformer neutral is earthed.
- The exposed conductive parts of the electrical loads are also connected to an earth connection.

The insulation fault current is limited by the earth connection impedance.

The faulty part is disconnected by an RCD.

The error voltage is:

$$Uc = Uo\frac{R_A}{R_B + R_A}$$, above the U_L voltage,

the RCD comes into action as soon as $Id \geqslant \frac{U_L}{R_A}$

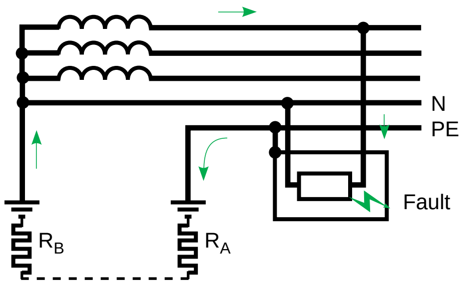


Fig. 19 : TT system.

The IT system

- The neutral of the transformer is not connected to earth. In theory, it is isolated. In fact, it is connected to earth by the stray capacitance of the network and/or by a high impedance ≈ 1500 Ω (impedant neutral).
- The exposed conductive parts of the electrical loads are connected to earth.

If an insulation fault occurs, a weak current develops due to the stray capacitance of the network (see **fig. 20** - 1st fault). The voltage developed in the earth connection of the exposed conductive parts (at most a few volts) does not present any danger.

If a second fault occurs (see fig. 20 - 2nd fault -), while the first has not been eliminated, there is a short-circuit and the SCPDs provide the necessary protection. The exposed conductive parts of the loads concerned then have the potential developed by the fault current in their protective earth conductor (PE).

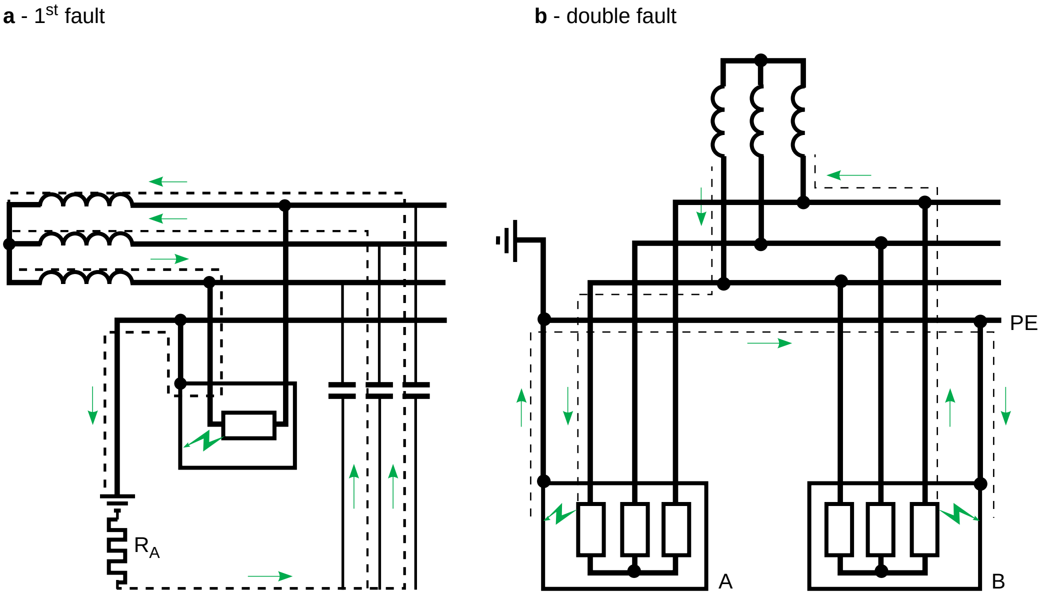


Fig. 20 : IT system.

Appendix 2: Example of creating a location free from electromagnetic disturbances

This is a room in which electroencephalograms are performed.

The equipment used for these recordings detects voltages of a few µV, and is therefore particularly sensitive to electromagnetic disturbances.

Relevant information

On site, the following was noted:

- the voltages between the patient’s “bed” and the exposed conductive part of the monitor;
- the voltages between the exposed conductive parts of the various components of the measurement system, then between these and the metal conductive parts located in the patient’s environment;
- the field measurements in different parts of the room show:
  - electrical fields from a few mV/m to 150 mV/m
  - HF magnetic fields from a few mA to 10 mA (presence of a scanner nearby and a radion-link transmitter some distance away),
- high LF magnetic fields;
- monitor-sensor links forming loops and antennae.

The work to be undertaken should therefore reduce or even eliminate the electrical fields, magnetic fields and voltage variations noted all at once.

Efforts to prevent electrical fields

- creation of a “Faraday cage” - faradization - mesh on the walls, floor and ceiling (+ antistatic carpet on the floor),
- replacement of fluorescent tubes with incandescent lamps,
- replacement of the triac controller with a variable autotransformer,
- interference suppression on switches.

Efforts to prevent magnetic fields

- relocation of high-current trunking, using the TN-C system, which was running through the area,
- shielding of the inter-floor cableway which contains the high-power electrical trunking (sum of the currents in the cable not to zero, due to the fact that the neutral current returns in part to the source via the metal conductive parts of the building).

Efforts to prevent potential variations in the exposed conductive parts and PE in the room

- links to the Faraday cage from the central heating radiators isolated from the rest of the installation by insulated sleeves,
- relocation of the medical gas pipework outside the room,
- decoupling, by an HF filter and screened LV/LV transformer, of all the electrical sockets involved in the distribution network (previously these sockets were powered by several circuits, leading to a risk of the creation of loops),
- decoupling of all the exposed conductive parts and the PE in the room using a choke (less expensive solution than taking the PE directly to the building earth connection to achieve a “noiseless earth”).

The electrical network in this specialized room has therefore changed from the TN-C system to the impedant TT system with zero risk of indirect contact (Z_L replaces R_B).

In this example (illustrated by **figure 21**), which corresponds to an actual example, the action of an enlightened specialist has enabled implementation of the majority of the solutions, therefore successfully avoiding any disturbance of sensitive electronic equipment.

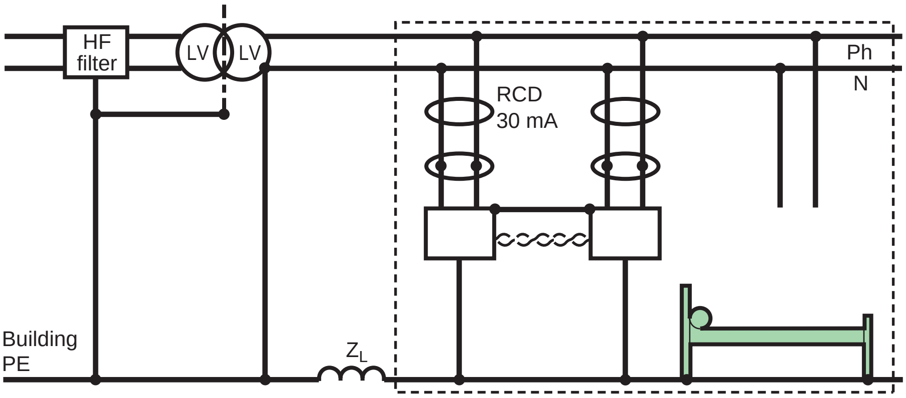


***Fig. 21** : power supply for a room with no electromagnetic disturbances.*

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