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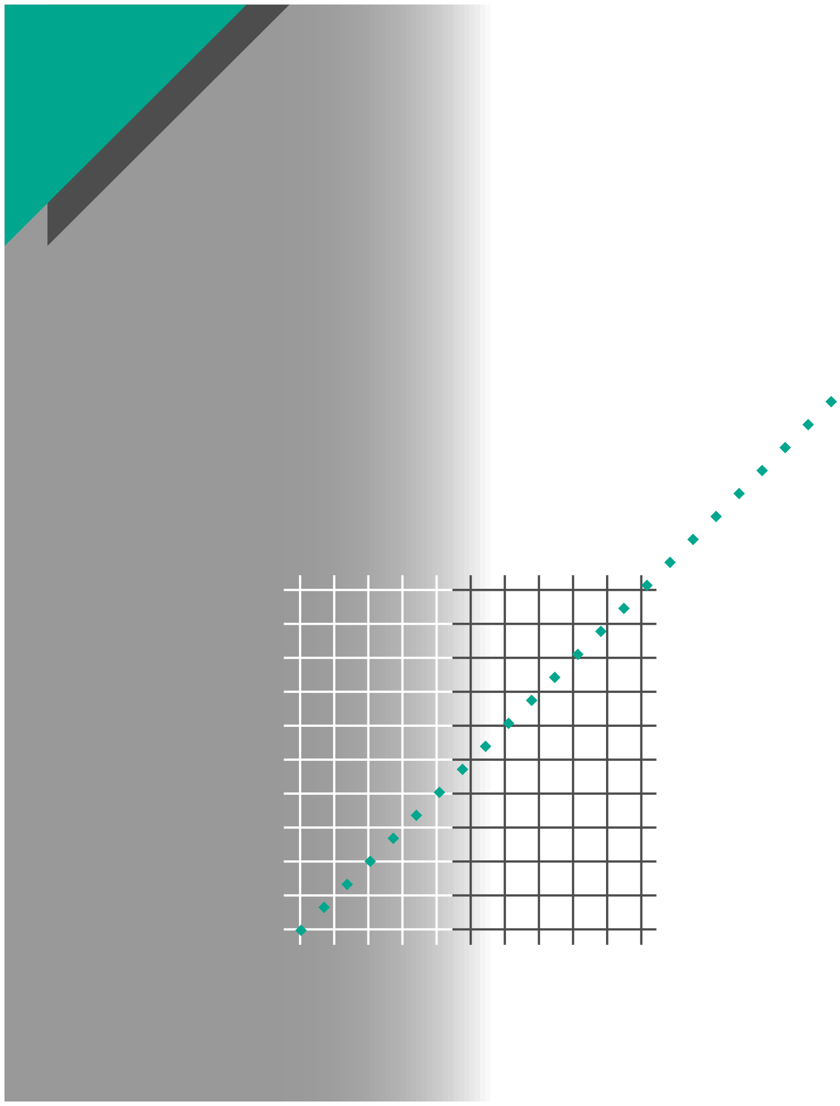
Cahier technique n° 187

Cohabitation of high and low currents



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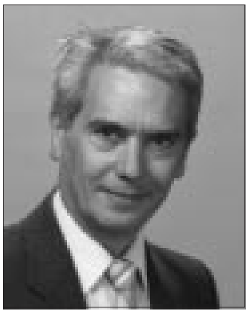
n° 187

Cohabitation of high and low currents



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Glossary

Bus:
A low current link conveying digital signals.

Disturbed device:
Load sensitive to electromagnetic disturbances. See disturbing device.

Disturbing device:
Source of electromagnetic disturbances. See disturbed device.

Earth (ground) loop:
Loop made up of two conductors, one of which is a live conductor (phase and neutral) or a low current link, and the other one of the conductors of an EBS loop.

Electromagnetic compatibility:
The ability of an equipment or system to function satisfactorily in its electromagnetic environment without introducing intolerable electromagnetic disturbances to anything in that environment.

Equipotential Bonding System loop (EBS loop):
Loop made up of two conductors which may be the PE, a parallel earthing conductor, a shield, an additional equipotential bonding, a conductive part (not electrical).

Equipotential Bonding System (IEV 195) (EBS):
Interconnection of conductive parts providing equipotential bonding between those parts.

Exposed conductive part:
From the electrical engineer's viewpoint, VEI 195, NF C 15-100 para. 232-9: conductive part of an electrical device at risk of being touched and which, although not normally live, may become so as a result of an insulation fault.

Extraneous-conductive-part:
Conductive part not forming part of the electric installation and liable to introduce an electric potential, generally the electric potential of a local earth.

Functional earth:
Point of a system or device which must be earthed for reasons other than safety of persons.

High currents:
Currents and links able to convey power and mainly links supplying electrical power from the distribution mains, including the protective conductor.

Loop:
Surface delimited by two conductors, irrespective of their functions, likely to disturb by electromagnetic induction a sensitive and/or communicating load.

Low currents:
Typically buses and Voice-Data-Image signals. All electrical signals conveying information and not power.

Parallel earthing conductor:
Conductive device accompanying a low current link in order to minimise the surface of the loop formed by the low current link and the EBS: it may be a conductor, a trunking or a shield. The parallel earthing conductor is also a functional equipotential bonding.

Pig tail:
Connection in loose wire wound in corkscrew form. Absolutely to be banned for earthing of shields. High HF impedance.

Protective conductor (PE) NF C 15-100 para. 241-1:
Conductor specified in certain protection measures against electrical shocks and designed to electrically connect some of the following parts: (electrical) exposed conductive parts, main earthing terminal, point of the supply connected to the earth or to the artificial neutral point.

Pulse Width Modulation (P.W.M.):
One of its functions is to monitor the mean value of the output signal by converting the input signal into pulses of modulable width.

Screen (IEV 195):
Device intended to reduce the penetration of an electric, magnetic or electromagnetic field into a given region, or to enclose or separate electrical circuits.

Shield (IEV 195):
Barrier or enclosure provided for mechanical protection (≠ screen). This term is still commonly used to mean screen.

Cohabitation of high and low currents

In our society today, the rapid development of digital systems using low current links (bus) has given rise to the critical problem formed by cohabitation of high and low currents.

The real problem is how to reconcile electrical safety and electromagnetic compatibility. The following issues thus arise for which solutions must be found:

- how to treat the problem of exposed conductive parts,
- which earthing system should be chosen,
- which shields, mitigating planes, Faraday cages should be chosen and for what purpose,
- how to organise routing of high and low current circuits,
- and many others.

Although written with electrical engineers in mind, this Cahier Technique will certainly also be of interest to low current specialists since it mainly deals with low frequency disturbances of ≤ 1 MHz.

Contents

1 Introduction

1.1. EMC: a discipline covering many professions

Electromagnetic compatibility (EMC), a rapidly developing field, came into being with the start of radio broadcasting. One of the first applications, a half-century ago, was the shields of spark-plugs of internal combustion engines to avoid interference with radios receivers.

Today, EMC is the subject of numerous studies carried out by experts, particularly in the fields of electronics and telecommunications. Many standards and even an european directive have been published to ensure the cohabitation of disturbing and disturbed devices and systems. For this, they set electromagnetic disturbance emission limits and immunity levels.

In spite of all efforts, there remains a complex field in which not all experts agree:
the cohabitation of high-current and low-current systems.

This concerns non-communicating electronic devices because they are supplied by the electrical distribution system and are sensitive to LF and HF radiated fields as well as to conducted disturbances. However, the subject is of even greater importance to communicating systems making use of distributed intelligence.

In this case, disturbances may affect the dependability of systems designed for information technology, building and energy management (BEMs), power management, automatic process control, etc.

All these systems are increasingly prevalent today and make essentially use of digital communications via low-current media.

In the design and installation of such systems, people working in computing, electrical engineering, automatic control and electronics frequently encounter problems in communicating with each other and in coordinating their respective tasks.
A common understanding of the phenomena involved must be achieved to avoid design and installation errors that can lead to malfunctions or even serious damage to equipment.
The purpose of this Cahier Technique is to contribute to that common understanding which is becoming all the more important with the rapid evolution of techniques, because:

- electrical distribution systems are increasingly powerful, carry more and more harmonic currents and use system earthing arrangements that may have a negative impact,
- digital communication networks are expanding rapidly, with ever lower electrical levels (a few volts) and ever higher bit rate (measured in Mbit).

Electricians and electronics experts must work together to optimise EMC conditions in buildings and improve the cohabitation of high and low currents.

In this Cahier Technique we will focus more on LF rather than HF phenomena: the limit between LF and HF is set at 1 MHz.

1.2 Review of disturbances and coupling mechanisms

Disturbances

A wide range of electromagnetic disturbances exist and they may be classed according to a number of criteria.
They may be continuous or transient, sinusoidal or pulsating, low or high frequency (> 1 MHz), conducted or radiated, common or differential mode, and have their cause either inside or outside the building.

The disturbing phenomena studied for EMC are many. This Cahier Technique will concentrate mainly on the following:

- harmonic currents and high fault currents,
- switching surges,
- voltage and current impulses resulting from lightning.

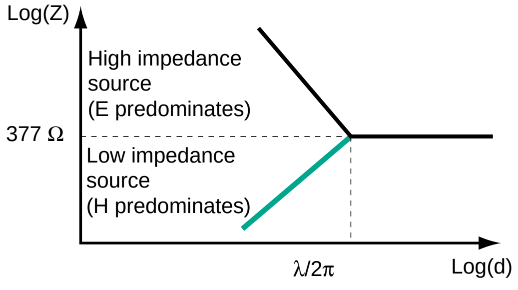


fig. 1: wave impedance Z = f(d).

High voltages and currents generate electromagnetic fields.

Emitter	Frequency (f)	Wave length (λ)	Field
Mains (1 kA, 1 ph)	50 Hz	6000 km	20 A/m at 10 m
Lightning	30 kHz at 3 MHz	10 km	10 A/m at 500 m
Drying oven	27 MHz	11 m	1.5 V/m at 10 m
20 kV switch	75 MHz	4 m	5 kV/m at 1 m
FM radio	100 MHz	3 m	1 V/m at 500 m
Long wave radio	200 kHz	1500 m	30 V/m at 500 m
Walkie-Talkie	450 MHz	66 cm	10 V/m at 1 m
UHF television	600 MHz	50 cm	0.5 V/m at 500 m
Mobile telephone	900 MHz	33 cm	20 V/m at 1 m
Radar	1 GHz	30 cm	40 V/m at 500 m
Microwave oven	2.45 GHz	12 cm	1.5 V/m at 1 m

fig. 2: some emitters of electromagnetic disturbances.

Note that all electromagnetic fields are made up of a magnetic field H and an electric field E.

Near a LF current, the magnetic field is dominant up to a distance of approximately λ/2π… i.e. 1 000 km for a 50 Hz field.

Near a high impedance HF source, the electrical field is dominant. This is often the case for switching surges on electrical distribution systems.

Beyond λ/2π (for sources with small dimensions compared to λ), the ratio between E and H is constant and determines the wave impedance:

$$Z_0 = \frac{E}{H} = \sqrt{\frac{\mu_0}{\varepsilon_0}} = 377\ \Omega \text{ in the air}$$

(see. **fig. 1**).

The table in **figure 2** provides several examples of disturbance emitters with their frequency (average value) and the fields that they are capable of radiating, given their respective powers.

The coupling mechanisms

Note that depending on the nature of the disturbance, the coupling between the disturbing phenomenon and the disturbed device may be one of the following:

- common impedance (conducted disturbance),
- electrical (stray capacitance and radiation),
- magnetic (mutual inductance and radiation).

■ Common-impedance coupling

This is the result of a circuit that is common to two or more devices. The common circuit may be the electrical distribution system, equipotential-bonding system, protective EBS, etc.

Figure 3 illustrates this type of coupling.

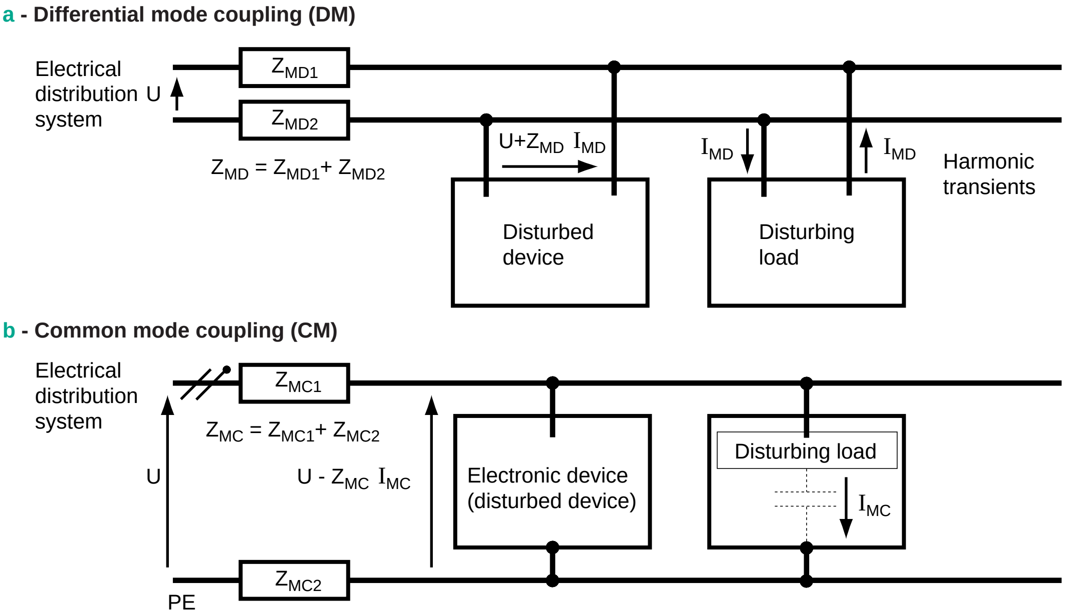


fig. 3: common-impedance coupling. The disturbances generated by a disturbing load have a negative effect on a sensitive load when the power supplies are not decoupled (a) or the EBS are not decoupled (PE) (b).

■ Electrical coupling

This type of coupling is due to the presence of either an external electric field, or a stray capacitance between two circuits or two conductors (see **fig. 4**).

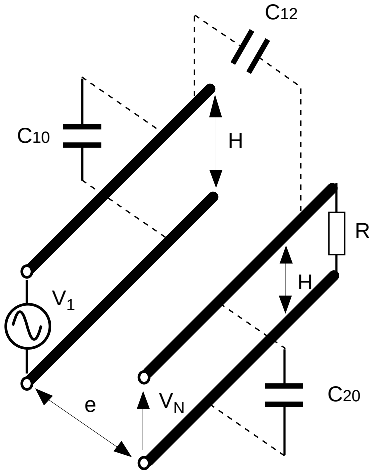


fig. 4: a sudden variation in voltage V_1 between two wires generates a field which, over a short distance, may be considered primarily electric and may induce a voltage V_N in another parallel set of wires. This phenomenon is called capacitive crosstalk.

■ Magnetic coupling

This type of coupling is due to the effect of magnetic field, either external or generated by a cable, on an inductive loop (generated by 2 cables located in the same circuit) (see **figure 5**).

In many cases, several of these coupling mechanisms may simultaneous exist.

Particularly concerning electrical power distribution:

□ short-circuit currents (or insulation fault currents in TN systems) generate very strong magnetic fields. According to Ampere's theorem:

$H = \frac{I}{2\pi d}$, where d is the distance between the conductor and the disturbed device,

□ « switching » of switchgear:
switches, contactors, circuit-breakers and fuses all generate a variety of strong radiated and conducted disturbances which need to be controlled by the manufacturers of the electronic equipment incorporated in electrical switchboards. These « waves » have been characterised by standard-makers (see **fig. 6**),

□ lightning when it falls on or near a building or on an electrical line is a highly disturbing pulsating phenomenon which may generate a magnetic field, an electrical field, a conducted wave or a difference in potential between two electrical points of the installation.

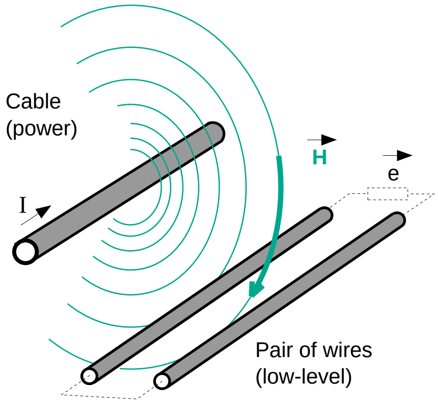


fig. 5: a variation in the current in a cable generates an electromagnetic field which, over a short distance, may be considered exclusively magnetic, in which case it induces a disturbing voltage in wires forming a loop. This phenomenon is called inductive crosstalk.

CEI 1000-4-2	Electrostatic discharges
CEI 1000-4-3	Radiated disturbances
CEI 1000-4-4	Rapid transient bursts
CEI 1000-4-5	Shock waves (lightning type)
CEI 1000-4-6	Conducted disturbances f > 9 kHz
CEI 1000-4-8	Magnetic fields at power system frequency
CEI 1000-4-9	Pulsating magnetic fields
CEI 1000-4-10	Damped oscillating magnetic fields
CEI 1000-4-12	Damped oscillating waves
CEI 1000-4-13	Harmonics

fig. 6: a few disturbance test standards.

1.3 Distinction between high and low currents

The term « high currents » is applied to normal phenomena such as flow of a 50 Hz electrical current or abnormal phenomena such as lightning currents. **Figure 7** classifies the various electrical links into four groups.

- Group 1 for high currents.
- Group 2 for insensitive, non-disturbing and normally short links.
- Group 3 for digital links (bus) is rapidly growing both in tertiary and industry; mutiple routings between communicating devices mark this group out for cohabitation with the « high current » links.
- Group 4 for high impedance analog links which seldom cohabitate with links from the other groups due to their sensitivity: links are rare and short.

A link belonging to one of the « low current » groups 2 or 3 may disturb a more sensitive link.

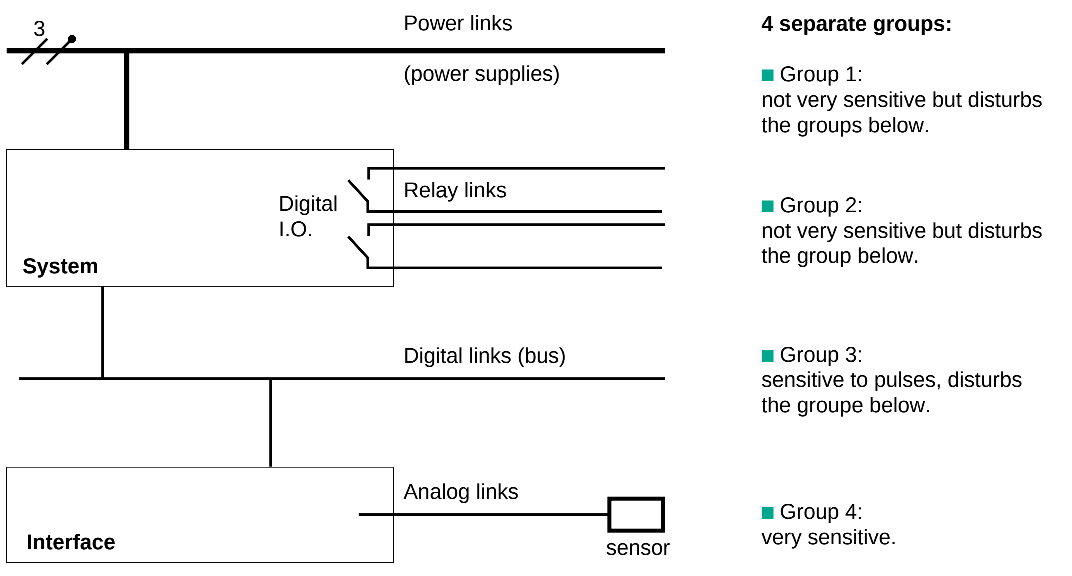


fig. 7: classification of electrical link types in order of increasing sensitivity.

2 Earth and exposed conductive parts

2.1 Earth electrode

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

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

The fault current varies in strength according to the earthing system used, and measures are taken to ensure that contact voltage does not exceed conventional safety voltage for a stipulated time: U_L (50 V in a.c.) (see Cahiers Techniques 172 and 173).

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

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

An example is 50/60 Hz overvoltage in the event of MV/LV transformer breakdown (see **fig. 8**) or overvoltage due to lightning (see **fig. 9**). With reference to the above, NF C 13-100 has laid down limit earth electrode values in France.

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

Naturally multiple earth electrodes should be avoided unless they are interconnected.
The earth electrode may be one or more spikes pressed into the ground or a foundation ditch loop, or a combination of both.

For a spike: $R_p = \frac{\rho}{L}$

For the foundation ditch loop: $R_{FF} = 2\frac{\rho}{L}$

where L is the length of the spike or the perimeter of the loop. The earth electrode must be a solid copper or stainless steel conductor so as to limit oxidation. Ground resistivity (ρ) is an important parameter, varying considerably with ground humidity and nature from 1 to 5000 Ω.m.
It is vital to place the « right » earth at the bottom of the foundation ditch around the loop conductor (see **fig. 10**).

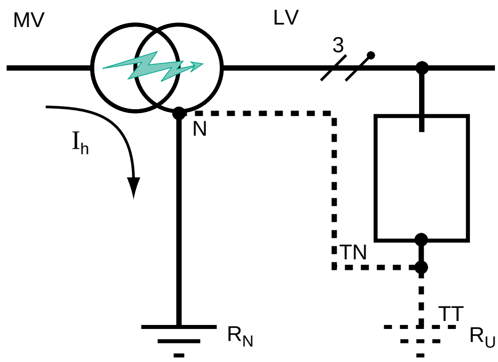


fig. 8: MV/LV breakdown; the power system potential rises with respect to the earth: $U = R_N I_h$ resulting in risk for the equipment in TT system or for persons in TN system if the building is not completely equipotentially bound.

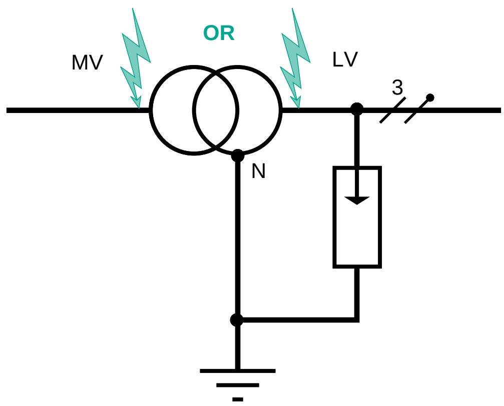


fig. 9: lightning surge: the power system is subjected to pulsating overvoltage on all live conductors, resulting in a high « EMC » risk. Requires use of lightning arresters whatever the earthing system used.

The impedance of an earth electrode varies only slightly between 50 Hz and 500 kHz.
If the building is equipped with lightning rods, the rod downcomers must be connected to earth electrodes in triangular crossbracing. All conductors which might be required to convey lightning currents must be flat conductors in order to reduce the self-induction factor and skin effect and consequently the drop in linear voltage (see **fig. 11**).

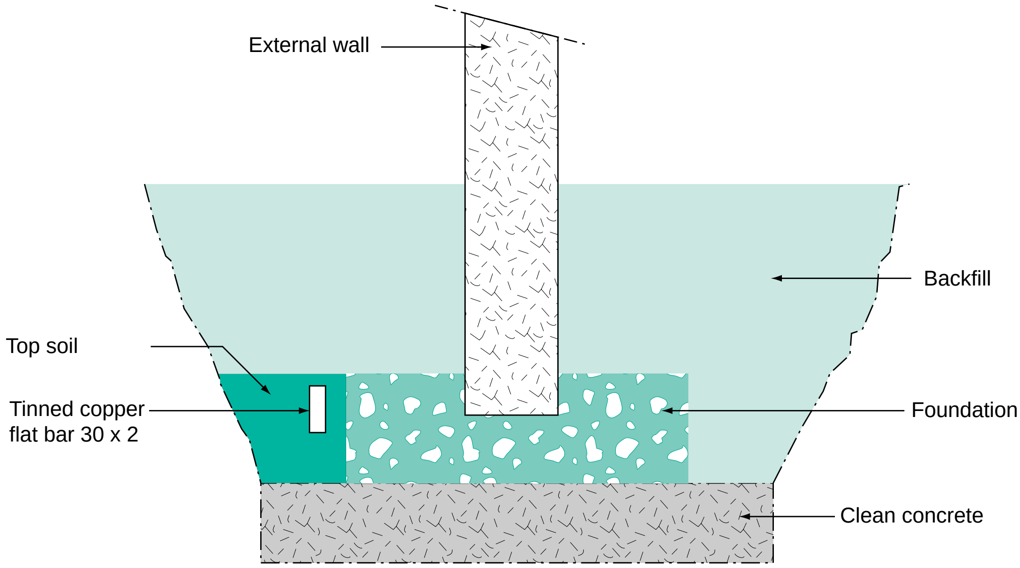


fig. 10: earth electrode: creating a loop in the foundation ditch.

■ Continuous resistance of a conductor is $R_C = \rho\ \ell / s$, i.e. R_C = 1.7 mΩ for a 10 m long cylindrical copper conductor with a 100 mm² cross-section. As frequency increases, the skin effect strengthens this resistance. This is because HF currents are concentrated at the edges of the conductor over a depth of $\delta = (\pi\ f\ \mu\ \sigma)^{-1/2}$ which decreases with frequency. δ is known as the skin depth.

For copper, $\delta_{(50\ Hz)}$ = 9.3 mm,
$\delta_{(1\ MHz)}$ = 65.8 µm,
$\delta_{(10\ MHz)}$ = 21 µm.

As a result the real cross-section of the conductor decreases. The ratio between R_{HF} and R_C is given for a cylindrical conductor with a radius r by:

$$\frac{R_{HF}}{R_C} = \frac{1}{4} + \left[\left(\frac{r}{2\delta}\right)^6 + 0.178\right]^{1/6} \approx 0.25 + \frac{r}{2\delta}$$

This formula only applies if the radius r of the conductor is greater than the skin depth δ.

Our copper conductor is such that:

- □ at 50 Hz: $R_{HF} = R_C$ = 1.7 mΩ,
- □ at 1 MHz: R_{HF} = 43.1 R_C = 73 mΩ,
- □ at 10 MHz: R_{HF} = 135 R_C = 230 mΩ.

■ The self-inductance L (µH) of a conductor of a length ℓ is:

□ for a cylindrical conductor:

$$0.2\ell\left[2.303\log_{10}\frac{4\ell}{d} - 1 + 100\mu_r\ \delta\right]$$

□ for a conductor with rectangular cross-section:

$$0.2\ell\left[2.303\log_{10}\frac{2\ell}{w+e} + 0.5 + 0.2235\frac{w+e}{\ell}\right]$$

ℓ, d(diameter), δ, w (width), e (thickness) are expressed in metres.

Dimensions			**Inductance**	**Impedance Z**		
d (mm)	**w (mm)**	**e (mm)**	**L(µH)**	**at 50 Hz (Ω)**	**at 1 MHz (Ω)**	**at 10 MHz (Ω)**
11.28			16.2*	0.0068	90	900
	10	10	14.8	0.00635	93	930
	50	2	12.9	0.00575	81	810
	100	1	11.6	0.00535	73	730
	500	0.2	8.4	0.00435	53	530

Self-inductance and impedance of a 10 m long copper conductor with a 100 mm² cross-section depending on its geometry.

(*) in the table the self-inductance of the cylindrical conductor is given at 50 Hz. In HF the term 100 $\mu_r.\delta$ becomes negligible, and L ≈ 14.35 µH becomes, like the rectangular cross-section conductor, independant of frequency. Finally note that in HF the impedance Z = 2π.f.L becomes preponderant compared with the resistance R_{HF}.

fig. 11: impedance of conductors depending on their geometry and frequency.

It is important for these conductors to be as short as possible. Let us take the example of an LV lightning arrester designed to limit common mode voltage to 1.5 kV. If it is connected between the protected phase and the earth strip by a 1 m long conductor with circular cross-section, a 5 kA current and a 8 µs rising edge, it will develop the following voltage:

$$\hat{U} \approx L\frac{di}{dt} = 1\ 10^{-6}\ \frac{5 \times 10^{3}}{8 \times 10^{-6}} = 625\ V$$

hence a total overvoltage of 2.1 kV which is dangerous as many devices have an impulse voltage withstand of 1.5 kV. The solution is to connect the application directly to the terminals of the lightning arrester (see **fig. 12**).

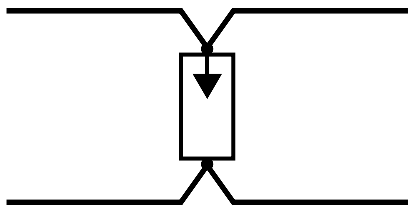


fig. 12: optimum connection of a lightning arrester.

2.2 Equipotential bonding system

Types of conductive parts

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

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

Like the earth, the EBS have two functions:

First function:
protection of persons

Dangerous potentials may be present between metal casings, gas or water pipes and the metal structures of buildings. To ensure protection of persons, all simultaneously accessible exposed conductive parts must therefore be interconnected and the building must be made equipotential. It is with this in mind that installation standards stipulate that all the above-mentioned exposed conductive parts must be connected to the main equipotential bonding regardless of the earthing system (see **fig. 13**). The earthing of load exposed conductive parts forms a star-shaped protection equipotential-bonding system, with tree-structured distribution of the protective conductors (PE) as they are in the same cables as the live conductors.

Second function:
dependability of electronic systems

Electronic systems are more sensitive than people to differences in potential and electromagnetic radiation. In addition to conducted disturbance blocking devices, they require ground planes, shields and Faraday cages to block the electromagnetic fields, as well as equipotential-bonding system, particularly in the case of devices communicating via data transmission bus. In this case equipotential bonding must be optimum in the building since communicating devices, whether used for control/monitoring or computer purposes, may be located geographically at some distance from each other on the same floor of a building or even on different floors.

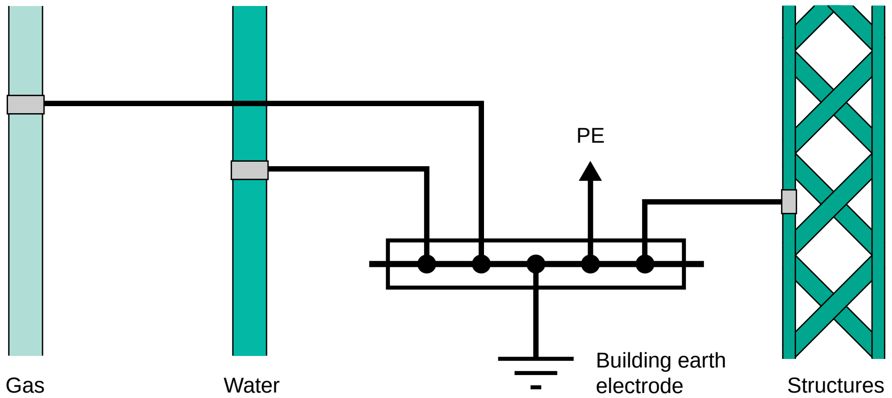


fig. 13: connection of all exposed conductive parts to the main equipotential bonding.

Solution

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

■ the fight against lightning electromagnetic fields.

Lightning may directly strike the building. If this happens, if only one lightning rod downcomer conductor is used, the lightning current will result in:

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

□ a pulsating electrical field due to the very high voltage developed in the downcoming conductor

$(v = \ell L \frac{di}{dt})$.

The solution is vertical mesh bonding with a downcoming conductor every 10 m for example.

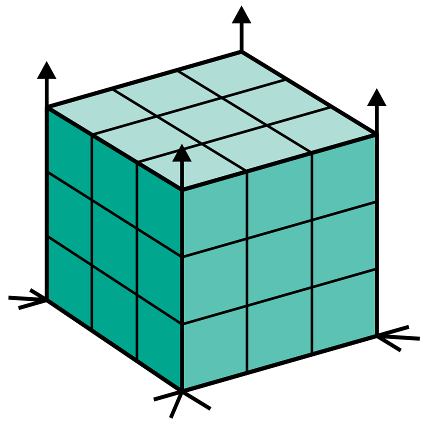
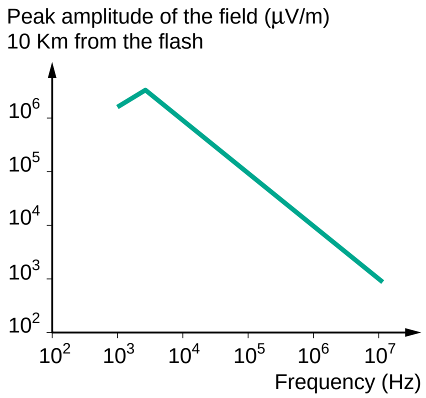


fig. 14: horizontal and vertical mesh bonding of the building. It forms a Faraday cage.

a - Mean spectral amplitude density of the electromagnetic fields of lightning flashes (PIERCE curve)



b - Frequency spectrum of the standardised lightning wave (1.2 / 50 µs)

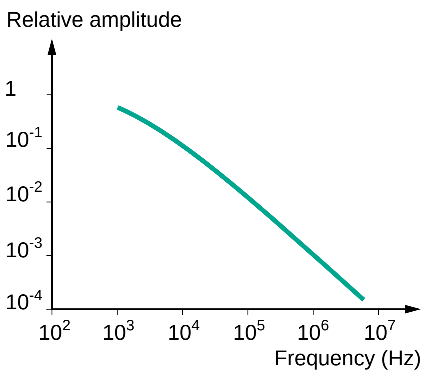


fig. 15: frequency spectrum of the " lightning " electromagnetic phenomenon.

The return arc can be likened to a vertical aerial several kilometres high through which a peak current of several dozen kiloamps flows. This aerial radiates an electrical field and a magnetic field which decrease by 1/D beyond a distance:

$$d = \frac{\lambda}{2\pi} = \frac{c}{2\pi f}$$

d = 50 m at 1 MHz.

The return arc is a pulse current with an extremely rich frequency content (broad frequency spectrum) and varying considerable from one lightning stroke to another. **Figure 15a** shows the graph for the average spectrum characterising lightning flashes, obtained from many field measurements at several points of the world.

IEC standard-makers have chosen for induced voltages on electrical distribution systems, a 1.2/50 µs wave whose spectrum is given in **figure 15b**. It is very similar to Pierce's curve.

The advantage is the division of currents and hence of magnetic fields, and the self-attenuation of these fields inside the building due to their mutual opposition.

Lightning may fall near a building. If this occurs, protection of the installations inside this building requires creation of a Faraday cage and thus addition of a horizontal mesh bonding to the vertical mesh bonding (see **fig. 14**).

If we consider that the frequency spectrum of lightning (see **fig. 15**) is essentially, from an energy point of view, less than 1 MHz and that the cage is effective for a pitch of λ/30, the mesh must be $\frac{c}{30f} = \frac{3 \times 10^8}{3 \times 10^7} = 10$ m

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

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

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

- Minimisation of bonding impedances between any two points.

The impedance of a copper conductor rises with the frequency of the current that it conveys (inductance and skin effect). Thus at 1 MHz, Z is of the order of 10 Ω a metre. Equipotential-bonding is considerably improved if the disturbing current is able to choose between a large number of routes.

2.3 Mesh bonding between protective ESB and other ESB

We have seen above that earthing arrangements dedicated to the protection of persons are star structured (tree-structured for the protective conductor) and that a single meshed EBS is required for dependability of electronic systems. In theory these circuits can be separated in the building even if they are connected to the same earth connection.

Even if standards define several types of potential references (see **fig. 16**), in practice few electrical and electronic devices and systems make such distinctions. For example the notion of a noise-less exposed conductive part is questionable and rapidly going out of use in view of the development of communicating systems and the large number of interconnections.

In high frequency, stray capacitances make these distinctions even more illusory. The equipotential protection system (electrical exposed conductive parts) and the equipotential functional system (other exposed conductive parts) thus need to be connected in the new buildings to form one single system of equipotential bondings. This system must guarantee the integrity of the protective links (PE) to ensure protection of persons. There is no need to oppose high current star-shaped systems and the meshed systems required for low currents.

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

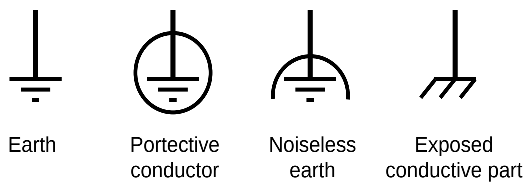


fig. 16: examples of earth and exposed conductive part symbols as in NF C 03-202.

3 EMC in non-communicating electronic devices

The term « non-communicating » means that no low current circuits enter or leave the device. The adjective « isolated » is not applicable because the device is supplied with power from the electrical distribution system, is in contact with its electrical environment via stray capacitances and is influenced by electromagnetic fields.
One example is a personal computer (without a printer).
This would appear to be a simple case, because manufacturers must observe standards defining emission and immunity levels.

The question is whether, in spite of compliance with standards, the device still risks being disturbed and whether precautionary measures should be taken when the electromagnetic environment is particularly severe or when very sensitive loads are placed nearby.

Such measures are indispensable when there is a risk of self-induced disturbances or the presence of radiated fields or conducted disturbances due to « high currents ».

3.1 Self-induced disturbances

A wide range of devices today use power electronics. An example is switch-mode power supplies which are now commonly used in the residential, commercial and industrial sectors. **Figure 17** shows the general layout of this type of device and the disturbances that it generates. These devices use power transistors operating at frequencies of several dozen kHz and even much higher for low-output devices, with surprisingly high di/dt and dV/dt values (e.g. a few hundred amperes per microsecond). Inherent EMC is required to ensure correct operation and is generally taken into account account right from the design stage: circuit board

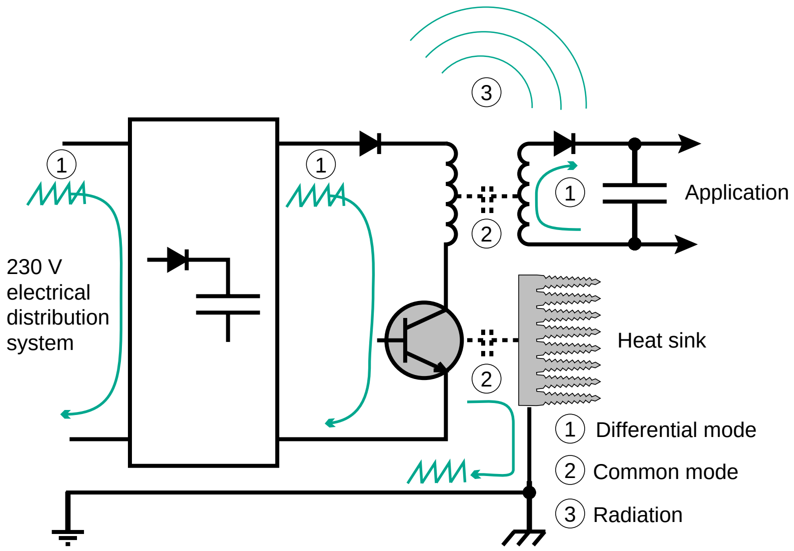


fig. 17: different disturbances produced by a switch mode power supply.

routing (see fig. 18), limitation of stray capacitances, shields, HF filters on the mains side, minimum distances from disturbing cables, etc, with tests to ensure compliance.
In spite of all the above, the risk of self-induced disturbances remains, due in particular to devices frequently being implemented differently from standard test implementation: for example insufficient earthing links which are too long and suitable for common-impedance coupling, etc.

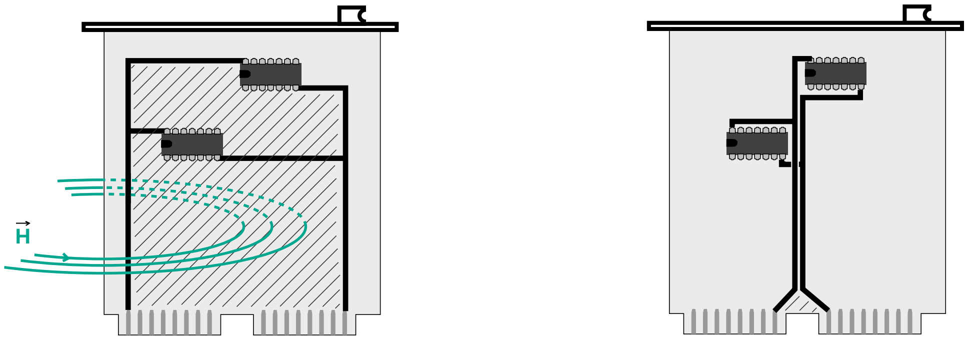


fig. 18: inductive couplings due to loop presence: the lefthand line shows two large loops to supply the two circuits; the righthand line is preferable.

3.2 Exposure to radiated fields

Electric fields

Surrounding electric fields can disturb a device and its supply circuits (50/60 Hz) via the antenna effect.

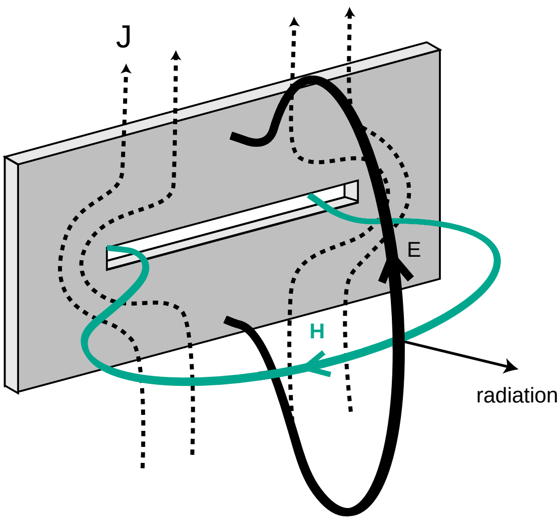
Counter-measures include:

- minimising the antenna effect (for example, no conductors with free ends, conductors near EBS conductive parts),
- using HF filters on the power supply cable to stop incoming disturbances,
- shielding the building by limiting the size of openings.

Magnetic fields

The attenuation resulting from shields depends mainly on absorption which is reversely proportional to skin depth (δ). For steel this is 0.07 mm at 30 kHz and 1.7 mm at 50 Hz, whereas for copper it is 10 mm at 50 Hz! (attentuation is 8.7 dB where shielding thickness e = δ).

The above makes clear that effective shields in low frequency is very difficult and costly. What is more, some openings or slots allow penetration of induction by magnetic dipole effect (see fig. 19).



An opening of length ℓ in a shield acts behaves like a dipole of the same length (Babinet's principle) and re-radiates part of the incident field from the other side of the shield. Opening transparency becomes total when $\ell \geq \lambda/2$. Beneath its resonance frequency, i.e. when $\ell < \lambda/2$ (a condition encountered in low frequency phenomena) a slot can be likened to an inductance which equals roughly 1 nH/cm. A surface current J broken by such a slot generates a difference in potential between its edges and lets through some magnetic field. It then radiates an electric field E at right angles and a magnetic field H (dominant) parallel to its length.

fig. 19: slot coupling.

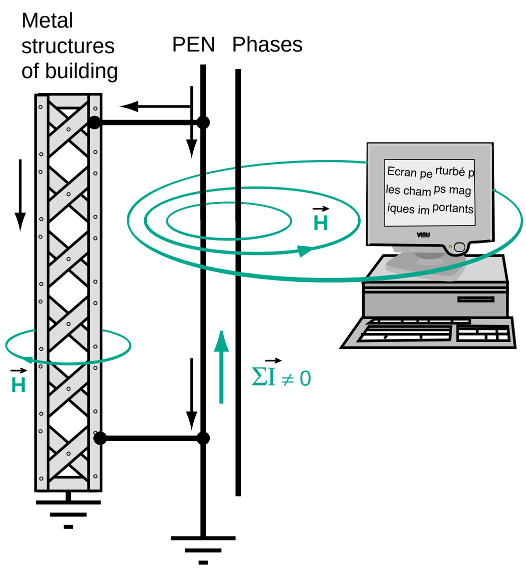


fig. 20: magnetic radiation due to neutral or fault current in TN-C system.

The magnetic field penetrating the system and/or the magnetic fields generated in the cubicle by high currents, induce common mode and differential mode voltages in the loops.

Note that attenuation of LF magnetic disturbances arriving via the power supply cable, using standard filters (termed « HF »), is very limited.

In buildings, radiated magnetic fields may have a number of sources, notably lightning, transformer leakage flux, incoming and outgoing circuits of static converters as well as the protective conductors of TN-C systems. This case is illustrated in **figure 20**.

Take the case of a power cable running in a building void. The system is TN-C. The load imbalance current flows continuously through the protective conductor (PE), which is also the neutral conductor (N), along with the third order harmonic currents and their multiples. Use of non-linear loads such as static converters and in particular switch mode power supplies is responsible for the increasing importance of these harmonic currents.

Due to the current drawn off to the metallic structure of the building, the vectorial sum of the currents in the cable is not equal to zero.

This differential current, which may amount to several dozen amperes, generates, over a distance d, a disturbing magnetic field $H = I/2\pi d$.

For example a 63 A current generates, over 10 metres, a 1 A/m field which is sufficient to disturb not only cathode ray tubes but also certain magnetic components, given that HF shields do not block LF magnetic fields.
Note that the magnetic field developed in the event of an insulation fault, still in the TN system, is very strong (Id = Icc).

For low frequency magnetic fields, the counter-measures are:

- distance,
- power cables incorporating the phase, the neutral and the protective conductor. Single-core cables must be avoided wherever possible,
- a suitable system earthing arrangement,
- metal trunking (mitigating plane),
- use of metal enclosures, preferably ferro-magnetic.

3.3 Conducted disturbances

Above 1 MHz, the impedance of cables rapidly limits the level of disturbances (L = 1 µH/m). Troublesome disturbances are therefore made up essentially of harmonics, overvoltages due to switching and lightning voltages and currents.

- Harmonic voltages are, generally speaking, not troublesome for non-communicating devices. They may disturb controlled rectifiers (variation of zero crossing point).
- Harmonic currents may generate, through inductive crosstalk, conducted disturbances in low current circuits.
- Overvoltages due to switching or lightning may cause malfunctions or even the destruction of components. The counter-measure is the use of surge limiters (lightning arresters) or wave absorbers combining filters, lightning arresters and a shielded transformer. The latter attenuate HF disturbances and, above all, block common-mode LF voltages.

4 EMC in communicating electronic devices

Communicating systems are more sensitive to disturbances than non-communicating devices because digital links involve very low voltage levels and are more exposed to disturbances generated by common impedance and radiation.
Digital signals are particularly sensitive to transient phenomena.
Their susceptibility is increased by the increasing lengths of connections and number of sources of disturbances.

For disturbances with frequencies less than 1 MHz, the phenomena that must be taken into account are, once again, primarily the 50 Hz mains disturbances and harmonics, overvoltages due to switching and the effects of lightning.
Switching overvoltages are generally differential mode and are best blocked where emitted using surge limiters (RC circuits-ZnO limiters, etc).
This subject will not be dealt with in this Cahier Technique (see CT 179).

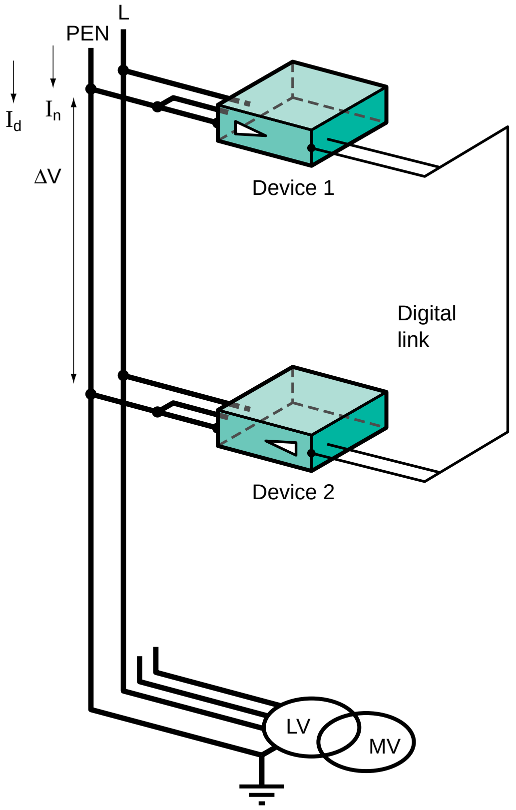


fig. 21: TN-C system; the neutral current develops differences in potential which disturb the voltage references of the digital links; the fault current (several kA) develops a destructive ΔV.

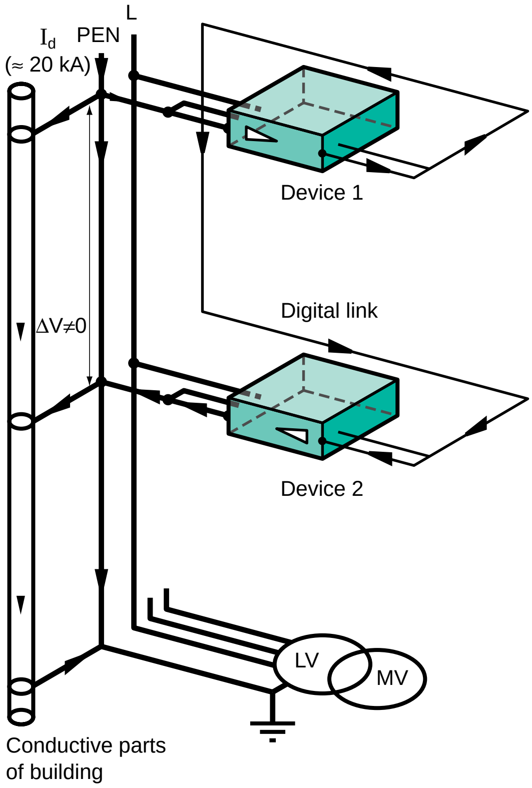


fig. 22: TN-C system with mesh bonding: the permanent ΔV (unbalance, harmonic multiples of 3) and temporary ΔV (fault) is attenuated, but there are « stray currents »: risk of fire and disturbing magnetic fields, including at power cable level (see fig. 20).

4.1 Example of a disturbance caused by common impedance

Consider two communicating devices that are part of a « distributed intelligence » system and supplied by the same electrical distribution system.
What happens when an insulation fault occurs (see **fig. 21**):
If there is no mesh bonding in the TN-C system, the insulation fault generates a short-circuit current I_d.
The voltage drop Δd in the electrical equipotential bonding conductor may exceed half phase voltage (PE cross-section < phase cross-section). This voltage is also present between the exposed conductive parts of the two devices, which disturbs communication and may even seriously damage the transmitters/receivers of the digital link if appropriate protection is not provided. This is because in cases where the low current cable is coaxial, ΔV will be applied in differential mode. The **figures 22, 23 and 24** show what happens if the conductive parts are meshed in the various earthing system possibilities (on the second fault in the IT system the risks are the same as those present in the TN-S).
Note that if the mesh bonding of all conductive parts is very dense, the problem of the ΔV ceases to exist in the TN system, but the insulation fault current is now greater than 3Ph Icc (very small impedance of the neutral return circuit).
What conclusions must be drawn for existing and new buildings where conductive part mesh bonding is insufficient?

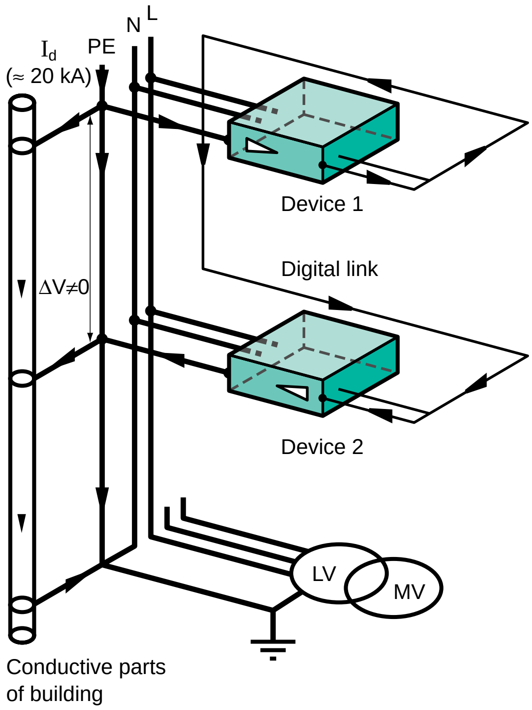


fig. 23: TN-S diagram, temporary ΔV; the fault current in the protection cable temporarily destroys equipotential-bonding. As the PE is connected to the structures, division of currents and magnetic fields occurs as in figure 20 .

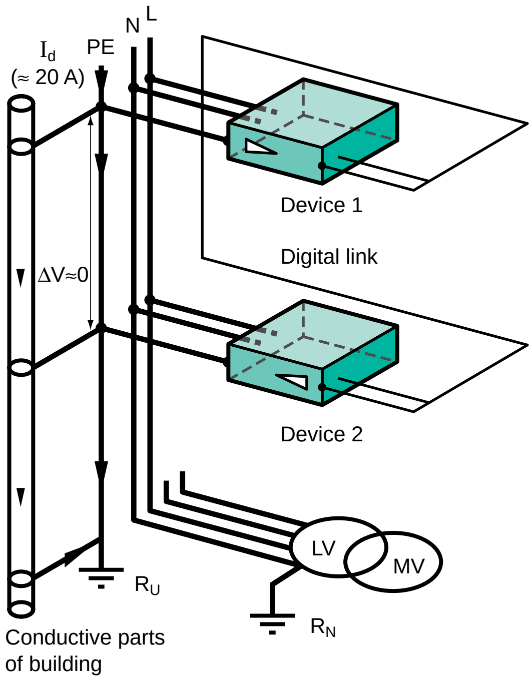


fig. 24: TT system; the low current in the PE does not disturb the equipotential-bonding of the potential references of the communicating electronic devices (R_{PE} is low compared with R_U and R_N and I_d small; the magnetic fields and ΔV are 1000 times smaller than in TN-C or TN-S.

■ Avoid system earthing arrangements which, in the event of an insulation fault, generate a short-circuit current (see **fig. 24**).

■ Divide the fault currents by making numerous connections between the exposed conductive parts and the metal structure of the building. The ΔV is reduced to a minimum… however, the radiation of the power cables, including the PE conductor, must be controlled (see the section on radiated fields in the preceding section).

■ Use twisted shielded pairs where possible because the current flowing in the shield has limited effects in view of the small transfer impedance.

4.2 Example of a disturbance caused by radiation

For two computers interconnected by a network (see **fig. 25a**), what happens when lightning strikes?

Consider a lightning strike 200 m from the building with di/dt = 25 x 10^9 A/s
($\hat{I}$ = 25 kA, t_m = 1 µs).

If the loop, formed by the 50 Hz distribution system and the digital links (see **fig. 25a**) forms a surface area of 50 m^2 for the impulse field, the resulting EMF is equal to:

$$e = \frac{d\phi}{dt} = \mu_0 S \frac{dH}{dt} = \frac{\mu_0 S}{2\pi d}\frac{di}{dt}$$

$$e = \frac{4\pi \ 10^{-7} \ 50}{2\pi \ 200} \ 25 \ 10^9 = 125 \text{ kV}$$

That is a dangerously high level for the digital transmitters/receivers. If the loop is closed, it is the resulting current that causes the damage.

What counter-measures can be used?

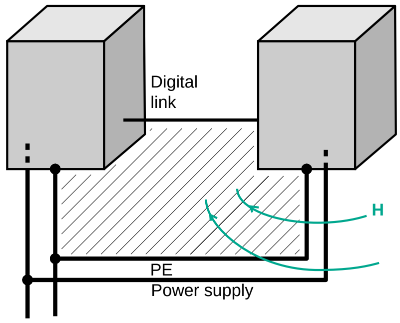
Minimisation of loop surface, power cables, low current cables: the problem is that if the loop is open, a voltage which is dangerous for electronic devices is developed and, if it is closed, the induced current (transfer impedance) will disturb the signal or even destroy the transmitter-receiver circuits. **Figure 25a** shows that the loop may be a large one.

A parallel earthing conductor, trunking or metal tube (see **fig. 25b**) can be used to minimise loop surface.

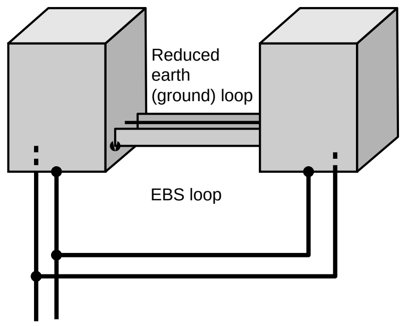
A word of warning, however, as this creates an EBS loop. The conductive link between the two communicating devices must therefore be a low impedance one to prevent developing induced voltage between the exposed conductive parts of the communicating devices (avoid pig tails). Note that if this link impedance is small, a large part of the fault current will flow through it should an insulation fault arise.

The solution is once again to mesh the exposed conductive parts as densely as possible in order to divide the currents and/or an earthing system with low fault current.

a - Loop formed by the electrical distribution system and the digital link



b - The trunking, connected to the exposed conductive parts of both devices, minimises the induced current effect with the digital link



c - Using parallel trunkings for the power supply and digital link: reduced loops, mitigating planes and effects attenuated by mesh bonding

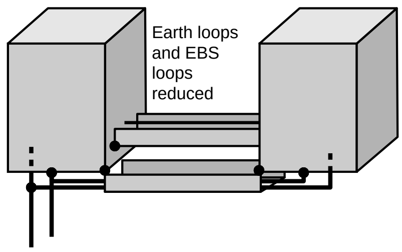


fig. 25: disturbance of a digital link by inductive loop and the solution.

Whatever the circumstances we recommend that you apply the solution shown in **figure 25c** in which the high/low current loop is removed as is also the EBS loop. Three conductors are connected in parallel: the two trunkings and the protective conductor (PE). The trunkings should preferably be separate, follow the same route and run close to one another: for example a riser. On a floor of a building (high currents of reduced strength) the power and signal cables can run on the same trunking (see **fig. 26**).

The distance between power and signal cables on a metal trunking depends on a number of factors:

- the level of immunity of the communicating devices,
- the capacity of the communication protocols to manage disturbed messages,
- the distance over which the cables run together,
- the current flowing in the power cables,
- whether the cable contains the PE or single-pole conductors,

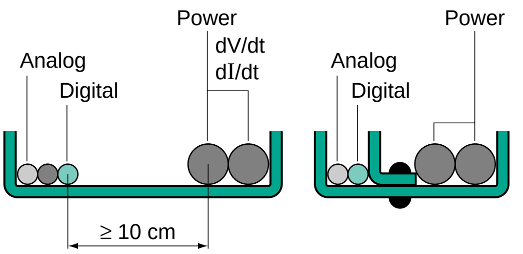


fig. 26: *separation of conductors of different types in the same trunking.*

- the electrical characteristics of the signals (electrical level, frequency, impedance…).

Communicating equipment manufacturers recommend a minimum distance,
normally 30 cm. However the distance to be used in a given case should always be validated by an expert.

5 Conclusion

This Cahier Technique has shown that a variety of professions are concerned by the cohabitation of high and low currents. We have not dealt with communication softwares for which designers must find solutions for the disturances which could affect them. Electronic, electrical, automatic control and software experts must join forces and work together to design and produce installations. In France Sub-Committee 15D of the UTE is currently working on the guide designed to meet this need.

Electronic engineers know that preference should be given to shielded twisted cables, that there should be no conductors with free ends, that cables should be flattened against an equipotential metal surface, that pig tails should be avoided and that great care must be taken with choosing and implementing cable glands. However they are not always aware that it is highly advisable for low current cables to follow the paths of high current ones, that copper links between two buildings are dangerous even if their respective earth electrodes are connected by a 35 mm^2 conductor (L = 1 µH/m) and that exposed conductive part mesh bonding, if required, may cause problems (for example risk of fire in TN-C).

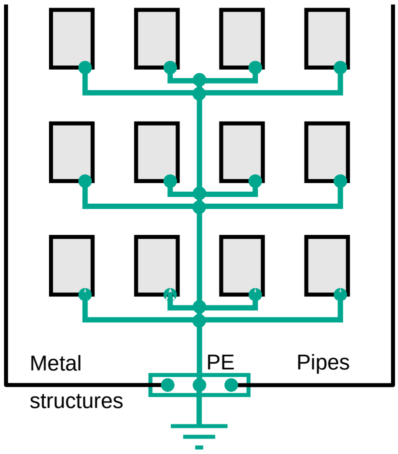
Electrical engineers are disturbed by the distinction made between protective EBS and EBS. They do not always understand the importance of total mesh bonding and do not always grasp why interconnection of exposed conductive parts and continuity of trunkings need to be ensured with such care.

We have shown that non-communicating devices, even when correctly designed and in compliance with emission and immunity standards, are nonetheless affected by the disturbances and coupling mechanisms found in installations and not always perfectly elucidated.

Communicating systems, increasingly numerous and wide-spread, clearly pose the problem of how to make use of high currents and low currents in a specific building. Inductive loops must be avoided or shunted by a parallel earthing equipotential bonding conductor. The best possible equipotential bonding must be achieved for both high and low frequencies, not only on each floor, but also between floors to form a complete equipotential bonding mesh. In all cases correct use of cableways, trunkings and metal skirting boards is vital.

Figure 27 reflects the electrical engineer's vision, that of the EMC expert, and offers a minimum, inexpensive solution for existing buildings.

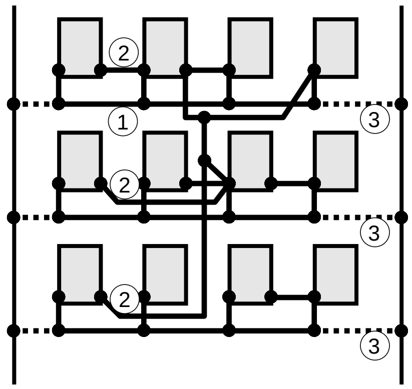
Electrical safety



a - Equipotential protection system with a bus (between floors) and star (on each floor) topology. The same applies to electrical power distribution.

■ Purpose: safety of persons/indirect contact
■ Attributes:
- no EBS loops,
- possible calculation of fault current,
- monitored fault current routing,
- low impedance at 50 Hz but high in HF,
- no common impedance coupling (except in TN at the riser).

EMC equipotential-bonding



(1) Equipotential-bonding conductor encircling the floor of a building.
(2) Shield or parallel earthing conductor, metal trunking.
(3) Additional equipotential bonding conductor.

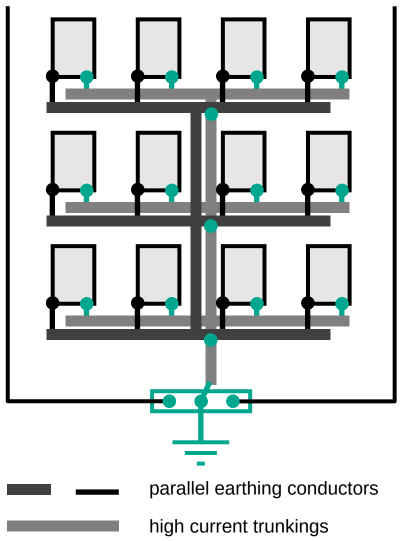
b - Meshed equipotential bonding system

■ Purpose:
- equipotential-bonding in HF,
- low impedance in LF and HF.
■ Attributes:
- random, multiple routing of 50 Hz fault currents and neutral currents (TN-C) as earths in PE,
- small earth loops (HF),
- common impedance coupling,
- increased fault current in TN.

NB: to ensure efficiency, particularly in HF, mesh bonding must be very dense.

Type 3 links, if made, create EBS loops which will affect devices located on different floors.
Thus, if links of this type are made, the equipotential bondings between floors must be multiplied in order to minimise the surface of the EBS loops.

Safety and EMC



c - Minimum protection and equipotential-bonding system. Optimum use of trunkings.

■ Purpose: same as in **figures 22a and 22b**.
■ Attributes:
- does away with high current/low current loops, earth loops and EBS loops,
- HF equipotential-bonding,
- LF equipotential-bonding (if low I_d),
- no stray currents,
- mitigating plane effect/EM fields.

NB:
- can be completed by local meshed ground planes,
- does not prevent direct links between two loads close to each other (with parallel earthing conductor),
- at floor level, a single trunking may be enough,
- the riser in the centre limits external influences.

■ On the upper floors, type 3 links must be provided if the electrical equipment is less than one metre away from the metal structures outside the building.

fig. 27: searching for equipotential bonding in LF and HF.

Appendix: bibliography

Standards

■ IEC 1000-4: sections 2 to 13: Electromagnetic compatibility (EMC), part 4: testing and measurement techniques. (see **fig. 6**)

■ European Directive CEM 89/336/CEE

■ UTE C 90-490: recommendations for cabling intelligent buildings, October 1995

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■ REE November 95

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