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EMC: electromagnetic compatibility

Frédéric Vaillant

Mr. Vaillant graduated from the Ecole Polytechnique in 1984 (X81) and was awarded a PhD in microelectronics in 1987 (thesis prepared under a CIFRE contract with the Saint Gobin company).
His career at Merlin Gerin began in 1987 within the Research Department, where he was in charge of a project concerning static current interruption techniques for medium voltage applications. Since the end of 1988 he has been in charge of Electromagnetic Compatibility within the Electronics Proficiency Centre of the Research and Development Management Division.

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EMC: electromagnetic compatibility

For all electrotechnical equipment, EMC must be considered right from the initial design phase and the various principles and rules carried on through to manufacture and installation.

This means that all those involved, from the engineers and architects that design a building to the technicians that wire the electrical cabinets, including the specialists that design the various building networks and the crews that install them, must be concerned with EMC - a discipline aimed at achieving the "peaceful" coexistence of equipment sensitive to electromagnetic disturbances alongside equipment emitting such disturbances.

This publications is a compilation of more than the years of acquired experience at Merlin Gerin and presents various disturbances encountered and provides some practical remedies.

summary

1. introduction

electromagnetic Compatibility -EMC- a characteristic and a discipline

EMC is a characteristic of equipment or systems that mutually withstand their respective electromagnetic emissions.

According to the International Electrotechnical Vocabulary IEV161-01-07, EMC is the ability of an equipment or system to function satisfactorily in its electromagnetic environment without introducing intolerable electromagnetic disturbances to anything in that environment.

This definition has also been adopted in the NF C 15-100 standard, chapter 33.

EMC is now also a discipline aimed at improving the coexistence of equipment or systems which may emit electromagnetic disturbances and/or be sensitive to them.

today, EMC is indispensable

Equipment or systems are always subjected to and, to some extent, generate electromagnetic disturbances.

These disturbances are generated in many ways. However, the main underlying causes are sudden variations in current or voltage.

The most common electrical disturbances (see fig.1) in the low voltage electrotechnical field are discussed in Cahiers Techniques Publication no. 141. Cahiers Techniques Publication no. 143 discusses disturbances generated when operating medium voltage switchgear.

These disturbances can be propagated by conduction along wires or cables or by radiation in the form of electromagnetic waves.

Disturbances cause undesirable phenomena. Two examples are radio wave interference and interference with control and monitoring systems caused by electromagnetic emissions.

class	type	origin
high energy	voltage dips	■ power source switching ■ short circuits ■ starting of high power motors
medium frequency	harmonics	■ systems with power semi-conductors ■ electric arc furnaces
high frequency	overvoltages	■ direct or indirect lightning strikes ■ switching of control devices ■ breaking of short-circuit currents by protection devices
	electrostatic discharges	discharge of static electricity stored in the human body

fig. 1: the most common electric disturbances.

In recent years, several trends have together made EMC more important than ever:

■ disturbances are becoming stronger with increasing voltage and current values,

■ electronic circuits are becoming increasingly sensitive,

■ distances between sensitive circuits (often electronic) and disturbing circuits (power circuits) are becoming smaller.

In the development of its new products, Merlin Gerin foresaw the necessity of understanding and applying EMC principles. In modern electrical switchgear and controlgear, low and high currents, control and power electronics, electronic protection and electric power devices all reside in close proximity.

EMC is therefore a fundamental criterion that must be respected in all phases of product development and manufacture (see fig. 2), as well as during installation and wiring. Moreover, EMC is now included in standards and is becoming a legal requirement.

fig. 2: EMC application example: a medium-voltage Fluair panel containing a circuit breaker designed to interrupt hundreds of ampere at tens of kilovolts and a SEPAM programmable control, monitoring and protection unit. The complete assembly must remain operational under all circumstances.

The experience and achievements of Merlin Gerin are not limited to the satisfactory operation of electrical and/or electronic systems in their usual electromagnetic environment:
Merlin Gerin designs and builds equipment capable of withstanding harsher conditions such as electro-magnetic radiation generated by high altitude nuclear blasts.

The necessary radiation hardening, i.e. improvement of the immunity of systems exposed to electromagnetic pulses from nuclear sources, requires the most advanced EMC techniques.

EMC theory is complex

Any work involving EMC involves the analysis of a three component system:
■ the disturbance generator or source,
■ propagation or coupling,
■ the device or system affected or the susceptor.

Strictly speaking, the three entities are not independent but for all practical purposes are assumed to be.
Note that installation, described in chapter 5, plays the most important role in the propagation of disturbances.
Theoretical analysis is difficult because it must deal with the propagation of electromagnetic waves described by a set of complex differential equations known as Maxwell's equations.

Generally speaking, they cannot be solved to yield an analytical solution for real devices and dimensions. Even with powerful computer systems, a close numerical solution is often extremely difficult to obtain.

In practice, EMC problems must therefore be dealt with via simplifying assumptions, the use of models and in particular conducting experiments and taking measurements.

2. the source

the importance of identifying the source

The identification and measurement of the source is essential since the type of source will determine which of the following measures must be taken:
■ limit the disturbances generated (e.g. on a contactor, by installing an interference suppressing RC unit in parallel with the A.C. coil, or a diode on the D.C. coil),
■ avoid cross-coupling (i.e. physically separate two highly incompatible elements),
■ desensitize potential susceptors (e.g. using shielding).

Main causes

Any device or physical/electrical phenomenon that emits an electromagnetic disturbance, either conducted or radiated, qualifies as a source. The main causes of electromagnetic disturbances are electric power distribution, radio waves, electrostatic discharge and lightning.

■ in electric power distribution, a large number of disturbances are created by circuit switching operations.
□ in the low voltage field, the opening of inductive circuits such as contactor coils, motors, solenoid valves etc. generates very high surge voltages (up to several kV across the coil terminals) that contain high frequency harmonics (ten to hundreds of MHz).
□ in the medium and high voltage fields, the opening and closing of disconnectors produces waves with a very fast rate of rise (a few nanoseconds). These waves are particularly harmful to micro-processor-based systems.

■ radio waves emitted by remote monitoring systems, remote controls, radio communications, television sets, walkie-talkies etc. are, for some equipment, sources of disturbances in the range of several volts per meter. All of these disturbance emitters are nowadays increasingly common and susceptible equipment must therefore be provided with increasingly effective protection.

■ an electrically charged human body: for example, a person walking on certain types of carpet in a cold and dry climate can be charged up to more than 25 kV ! Any contact with equipment produces a discharge with a very fast rise time (several nanoseconds) which enters the device by conduction and radiation, generating a major disturbance.

Disturbance characteristics

Sources may be intentional (e.g. radio transmitters) or not (e.g. arc welding units). However in general they can be distinguished by the characteristics of the disturbances they produce:
□ spectrum,
□ waveform, rise time or envelope of the spectrum,
□ amplitude,
□ energy.

■ the spectrum, i.e. the frequency band covered by the disturbance can be very narrow as for the case of mobile telephones, or very wide, as for electric arc furnaces.

Pulse type disturbances cover a particularly wide spectrum extending up to 100 MHz or more (see fig. 3). To this last category belong almost exclusively sources such as:
- □ electrostatic discharges,
- □ switching of relays, disconnectors, contactors, switches and circuit breakers in the LV, MV and HV range,
- □ lightning,
- □ nuclear electromagnetic pulses (a special domain).

Since the degree of coupling is directly proportional to frequency, EMC uses the frequency domain to characterize disturbances. This type of representation, for a periodic signal, is similar to a Fourier series decomposition (like a sum of harmonics).

■ the waveform describes the characteristics of the disturbance with time and can, for example, be a damped sine wave or double exponential function. It is expressed as a rise time t_r, an equivalent frequency $1/\pi.t_r$ or simply the disturbance frequency for a narrow band signal or as a wavelength l related to frequency by l = c/f, where c is the speed of light (3.10^8 ms^{-1}).

■ the amplitude is the maximum value the signal reaches in terms of voltage (Volts), electric field (Volts/Meter), etc.

■ the energy is the integral of the instantaneous energy over the time the disturbance lasts (Joules).

an example of a continuous source of conducted disturbances in power electronics

In power electronics, the principal sources of disturbances are more often voltage rather than current transients. The voltages can vary by hundreds of volts in a matter of a few nanoseconds giving dV/dt's in excess of 10^9 V/s. Pulse Width Modulation (PWM) (see fig.4), for example, used to generate a sine wave voltage from a D.C. voltage, works with voltage changes from 0 to Udc (660 V for rectified three-phase) occurring in a very short time, nano to microseconds depending on the technology used. Rapid voltage changes are the source of various disturbance phenomena, the most problematic of which is, based on experience, the generation of currents flowing through any parasitic capacitances.

Taking only the parasitic capacitance Cp into account, the common mode current: Icm = Cp . dV/dT.

With the rise times mentioned earlier, a parasitic capacitance of 100 pF is sufficient to generate currents of several hundred milliamperes.
This disturbance current will flow through chassis ground (0 V reference

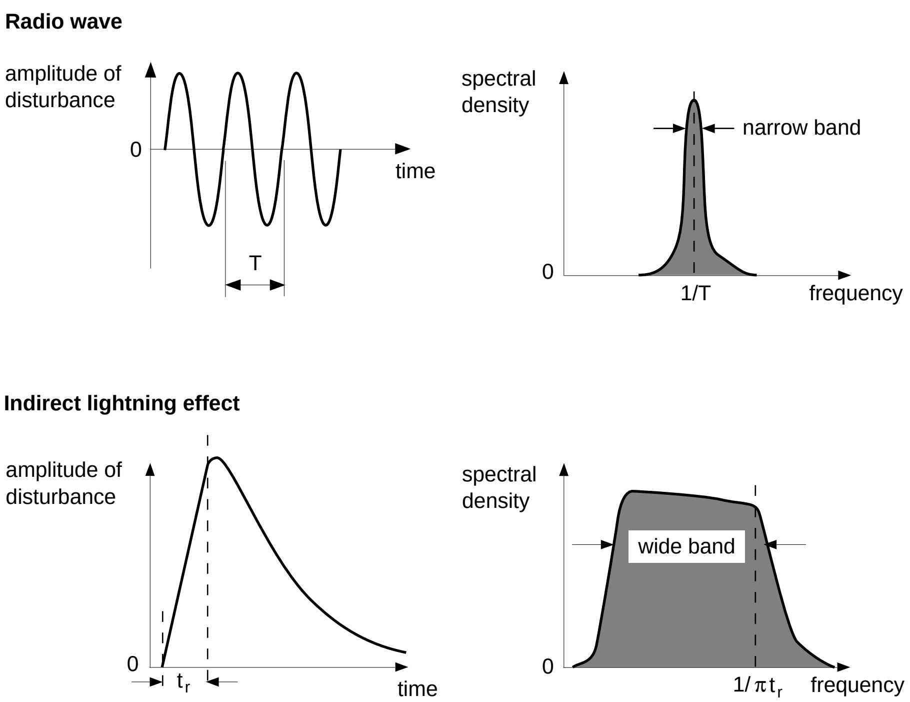


fig. 3: spectral characteristics of disturbances.

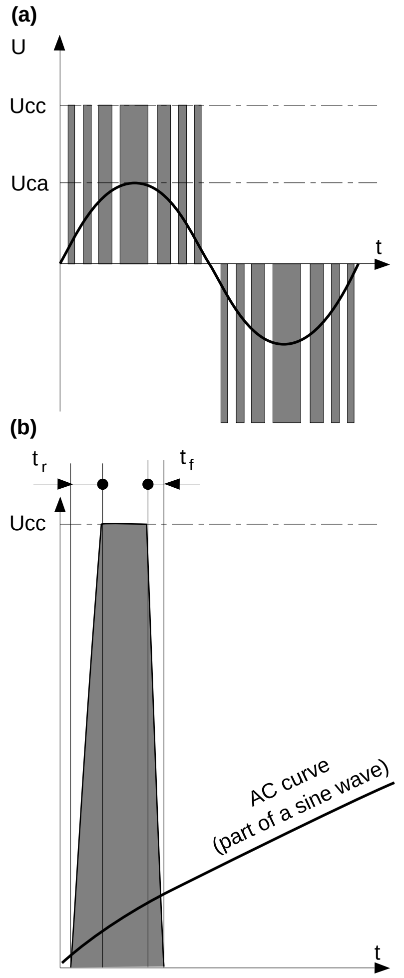


fig. 4: a source of disturbances in power electronics: pulse width modulation.
a: principle,
b: even with the time scale not well chosen for this type of phenomenon $t_r \approx 2$ to $3\ t_f$ (10 ns to 1µs) while the sine wave covers 20 ms.

of the unit) of the electronics and can, via coupling, modify signals (information or controls), be superimposed on sensitive measurements and disturb other equipment by injecting the disturbance back into the public distribution network.

One way of dealing with this type of phenomenon, i.e. of ensuring EMC, is to increase the voltage rise time. However such a solution would considerably increase the switching losses in the transistors, producing harmful thermal stresses. Another effective way of reducing common mode currents consists of increasing the common mode impedance. For example, when mounting electronic power devices, two methods are commonly used:

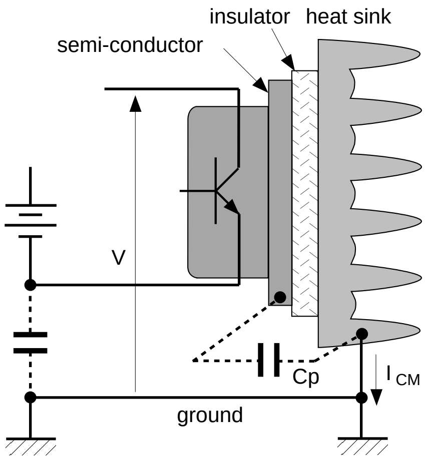


fig. 5: the parasitic capacitance of the heat sink (for cooling of electronic devices) is taken into account in the design of UPS inverter stacks.

- either leave the heat sinks floating (no electric connection), (see fig. 5), if safety regulations are not violated,
- or reduce the parasitic capacitance between the device and the heat sink using an insulator with a low dielectric constant (see fig. 6).

In the field of UPS's - Uninterruptible Power Supplies- for instance, the above precautionary measures make the difference between a «polluting» system and a «clean» system.

For UPS's, note that the low level electronics in the static inverter must be protected against disturbances created by its own power circuits.

It is necessary to understand and control the phenomenon at the source to effectively and economically limit conducted emissions.

Other less frequent sources of conducted disturbances exist such as lightning and switching surges that can generate large dV/dt's and dI/dt's. These disturbances also radiate.

an example of radiated disturbance sources: circuit closing in MT and THT substations

The substation environment, especially in medium and very high voltage applications, can contain very strong pulsed electromagnetic fields.

Certain switchgear operations can generate voltages much higher than the rated value in a very short time. For example, when a 24 kV switch is closed, the preignition phenomenon causes voltage variations of tens of kilovolts in a few nanoseconds (10^{-9} s).

This is discussed in greater detail in Cahiers Techniques Publication no. 153: «SF6 Fluarc circuit breakers and MV motor protection».

Measurements performed at the Merlin Gerin laboratories have shown that during the switching of a 24 kV medium voltage circuit breaker, damped sinusoidal pulsed fields reach peak values of 7.7 kV/m with a frequency of 80 MHz at a distance of one meter from the cubicle.
The field strength is enormous when compared to that of a 1 W portable two way radio (walkie-talkie) which generates 3 to 5 V/m measured at a distance of one meter.

The transients propagate along conductors, busbars, cables and overhead lines. At the frequencies involved, i.e. the rapidity of the phenomenon, the conductors (especially busbars) behave like antennas and the characteristics of the electromagnetic fields they emit are highly dependent on the design of the metal enclosures (partitioning, cubicles).

In metal clad very high voltage substations, the electromagnetic fields are particularly strong.

Metal clad SF6-insulated substations have a coaxial shape and therefore display a constant characteristic impedance. Rapid voltage changes inside the tubular metal enclosures generate standing wave phenomena. They are created by reflections occurring at impedance mismatches due to conic outgoing feedthroughs that cross the shielding for example. The magnitude and duration of the phenomenon is also increased by this effect.

insulating washer for TO3 case	**thickness** (mm)	**parasitic capacitance** (pF)
Mica	0.1	160
Plastic	0.2	95
Alumina	2	22

fig. 6: dielectric constants for the most common insulators used in mounting electronic devices.

The electronic environment at medium and very high voltages requires in depth electromagnetic compatibility studies for the design and installation of relay systems and control and monitoring devices.

This is particularly important because in addition to the radiated disturbances, conducted voltage transients are also generated in substations as discussed at the beginning of this section (see fig. 7).

fig. 7: SEPAM and Masterpact units; MV and HV protection and control and monitoring devices with digital electronics developed by Merlin Gerin and designed taking full advantage of EMC research.

3. coupling

different coupling modes exist

Coupling refers to the linking, transfer or transmission of electromagnetic disturbances from an emitter to a susceptor.

Coupling is expressed in terms of a coupling coefficient k, expressed in dB (e.g. -75 dB), which can be seen as the transmission efficiency of the disturbance from the emitter to the potential susceptor (k = 20 log A (received)/A (transmitted), where A is the amplitude of the disturbance).

It is important to define this coefficient for EMC since the lower the coefficient (the larger its absolute value in decibels) the weaker the disturbance voltage received by the susceptor and the better the EMC.

This coefficient k is only meaningful when the transfer of electromagnetic disturbances is proportional to frequency, which is often the case in practice.

Three well known coupling modes can be distinguished:

- common and differential mode field to wire coupling,
- common impedance coupling,
- differential mode wire to wire coupling or crosstalk.

common or differential mode field to wire coupling

An electromagnetic field can couple into any kind of wire-like structure and generate either common mode (with respect to ground) or differential mode (between wires) voltages or, as is generally the case, both. This type of coupling is called field to wire coupling and is also known as the antenna effect of wiring, printed circuit board traces, etc.

■ common mode coupling generates common mode disturbance voltages or currents.

A conducted common mode voltage disturbance (V_{CM}) is a voltage that affects all active conductors.
It is referenced to chassis or earth ground (typically in electrical systems): all common mode isolation tests on low voltage circuit breakers are therefore performed between earth ground and all phases.

A common mode current (I_{CM}) is a current that flows through all active conductors in the same direction (see fig. 8). The current induced in a LV line by a lightning impulse is a common mode current.

■ differential mode coupling involves voltages and currents in the classic sense, for example, between two phases of a circuit breaker or between two wires which transmit sensor data to the electronics.

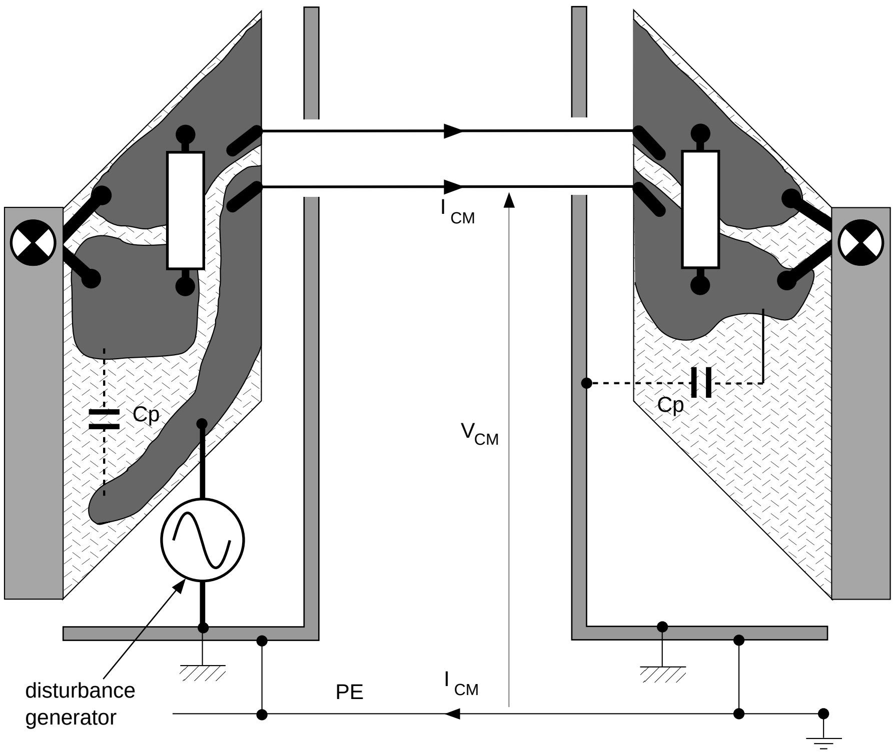


fig. 8: common mode voltage and current between two relays of a low voltage compartment in a medium voltage cubicle.

The equations that govern the coupling between the electromagnetic field (impedance of an arbitrary wave) and a wire-like structure (which can also be arbitrary) are very complex. In most cases they can neither be solved analytically nor numerically.

Nonetheless, one of the simpler and most common types of coupling can be expressed analytically: the coupling between the magnetic component of an electromagnetic field and a loop of area A formed by the conductors (see fig. 9).
The magnetic component H of the field induces in the loop a series voltage equal to:
$e = \mu_0$ 'A' dH/dt,
with μ = the permeability in a vacuum ($4\pi\ 10^{-7}$ H/m).

For example, in a medium voltage substation, a loop (of wire or cable) covering 100 cm^2 placed 1 m from the

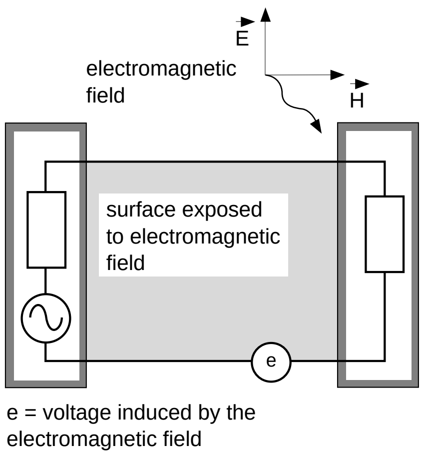


fig. 9: an example of differential mode field to wire coupling.

cubicle (see fig. 10) and exposed to a pulsed field of 5.5 kVrms/m (laboratory measurement) will generate (by induction) a series transient voltage of 15 V.

The above equation holds as long as the largest dimension of the loop does not exceed a tenth of the wavelength of the disturbance. Note that such a green/yellow wire loop (see fig. 10) is easily created in the «relay compartment» when the wires are connected in a star configuration to ground.

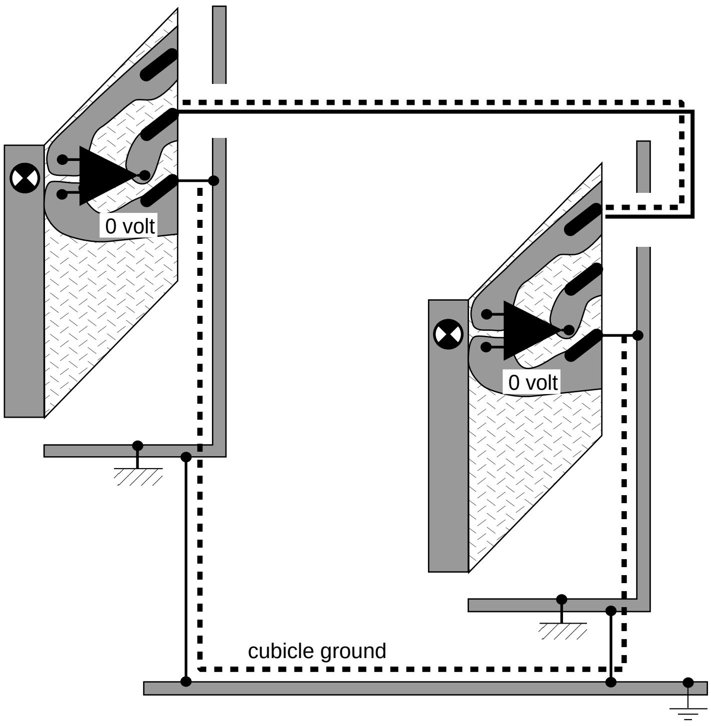


fig. 10: example of a ground loop in a low voltage compartment of a medium voltage cubicle.

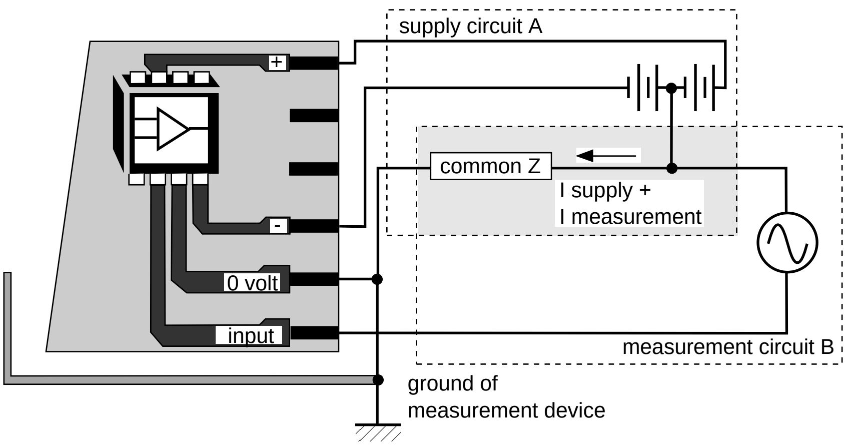


fig. 11: the quantities measured by the operational amplifier will be incorrect because the disturbance current in circuit A (power supply) is high enough to create a disturbance voltage in circuit B (measurement).

common impedance coupling

As the name implies, common impedance coupling results from an impedance that is shared by two or more circuits. The common impedance can be the ground connection, the earth ground network, the power distribution network, the return conductor shared by several low power signals etc...

An example follows showing the effects of this type of coupling (see fig. 11): A disturbance current in circuit A in the tens of mA range is sufficient to generate disturbance voltages in the volt range in circuit B. If circuit B uses point M as its reference (possibly ground), then the reference can vary over several volts. This certainly influences integrated circuit electronics that work with volta-ges of the same order of magnitude.

The example in figure 11 shows that a common impedance can be formed by a wire a few meters in length and which is common to both circuits A and B.
The disturbance has a magnitude
$Uc = Ia \cdot Zc$ where

- Ia is the disturbance current and
- Zc is the common impedance

(see fig. 12).
At low frequencies the common impedance is usually extremely small. For example, safety requirements dictate minimum cross-sectional areas for the PE conductors, i.e. the green/yellow wires, of grounding networks depending on the prospective short-circuit current. The impedance at 50 Hz between two points in the network is therefore always much lower than one Ohm.

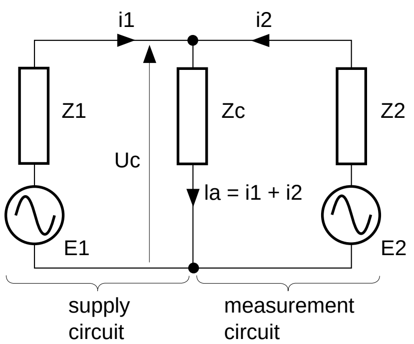


fig. 12: common impedance diagram.

But that same impedance can be much larger at the typical frequencies of the disturbances discussed earlier. Impedances can reach several kilo-ohms or more (see appendix 2).

differential mode wire to wire coupling or crosstalk

Crosstalk is a mode of coupling that resembles the field to cable coupling. It is called capacitive or inductive crosstalk, if a change in current or voltage respectively is its cause.

A rapid voltage change between a wire and a ground plane or between two wires (see fig. 13) generates a field that can nearby, with some approximations, be considered an electric field only.
This field can couple into any other parallel wire-like structure. This is called capacitive crosstalk.

Similarly, a current change in a wire or cable generates an electromagnetic field that with the same approximations can be considered a magnetic field only.
The field can couple into a pair of wires and induce a disturbance voltage. This is called inductive crosstalk (see fig. 14).

Capacitive and inductive crosstalk exists whenever conductors are routed in parallel or reside in close proximity to each other.
Crosstalk can occur in cableways and troughs and especially between power cables carrying high frequency disturbances differentially and twisted pairs used by digital networks such as Batibus.
The crosstalk will be stronger the longer the parallel paths, the smaller the distance between wires or pairs of wires and the higher the frequency of the disturbances.

For example, using the notation in figure 13, the voltage coupling coefficient (capacitive crosstalk) can be expressed as:

$$\frac{V_N}{V1} = \frac{j\,2\,\pi\,f\left|\dfrac{C_{12}}{(C_{12}+C_{20})}\right|}{j\,2\,\pi\,f\,\dfrac{C_{12}}{R\,(C_{12}+C_{20})}}$$

where:

- $V1$: voltage source,
- V_N: disturbance voltage induced by coupling,
- C_{12}: coupling capacitance between two wires which is proportional to the wire length and the distance coefficient Log [1 + $(h/e)^2$] where h is the distance between the two wires of the pair and e the distance between pairs,
- C_{20}: leakage capacitance between the two wires of the pair creating the disturbance,
- R: load impedance of the susceptor pair.

To be more specific, consider two pairs with wires of 0.65 mm diameter running 10 meters in parallel; the wires in the pair are 1 cm apart and the pairs 2 cm away from each other and R = 1 k Ω. For a 1 MHz signal, a coupling coefficient of - 22 dB is found, therefore

$$\frac{V_N}{V1} = \frac{1}{12}$$

In practice, capacitive and inductive coupling of this type is considerably reduced by the use of twisted pairs and shielded cables.

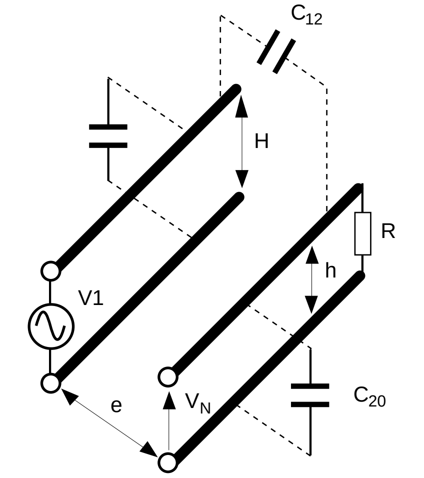


fig. 13: a rapid change in V1 creates a field which at a short distance can be assumed to be purely electric and induces a voltage V_N in another wire-like structure which runs in parallel; this mode of coupling is called capacitive crosstalk.

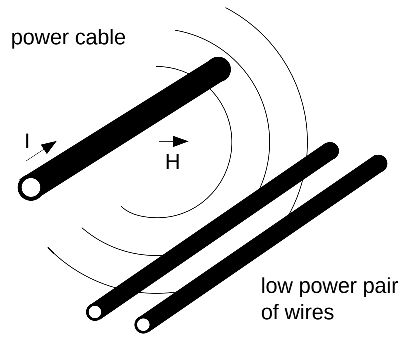


fig. 14: a current change in the cable generates an electromagnetic field which at a short distance can be considered to be purely magnetic and induces a disturbance (voltage) in wires that form a loop; this mode of coupling is called inductive crosstalk.

4. the susceptor

The susceptor is the third participant in the source/coupling/susceptor system and refers to any equipment that may be affected by a disturbance.

It is typically equipment containing some electronics which malfunction because of electromagnetic disturbances occurring in an unexpected frequency band.

equipment malfunction

Equipment malfunctions are divided into four categories and can be:
- permanent and measurable,
- random and non-repetitive, appearing when the disturbances appear,
- random and non-repetitive, remaining after the disturbances vanish,
- permanent equipment failure (components physically destroyed).

The above types characterize the duration of the fault but not its severity.

The severity of a fault is a matter of functionality or, in other words how critical the equipment is. Certain malfunctions may be acceptable for a limited time such as the temporary loss of a display; others may not be acceptable such as security equipment malfunctions.

solutions to the problem

Numerous solutions in terms of how equipment is to be built exist to provide effective and low-cost immunity to electromagnetic disturbances.
Precautionary measures can be taken in:
- the design of printed circuit boards (functional partitioning, trace layouts, interconnects),
- the choice of electronic devices,
- the ground interconnections,
- the wiring.

The choices involve many different disciplines and should be made during the design phase of a project to avoid additional costs which are always high for modifications after the design is completed or when the product is already on the market.

Implementing all of these precautionary measures requires know-how which goes far beyond the standard filtering and shielding techniques often recommended to increase immunity even if their effectiveness has not been proven.

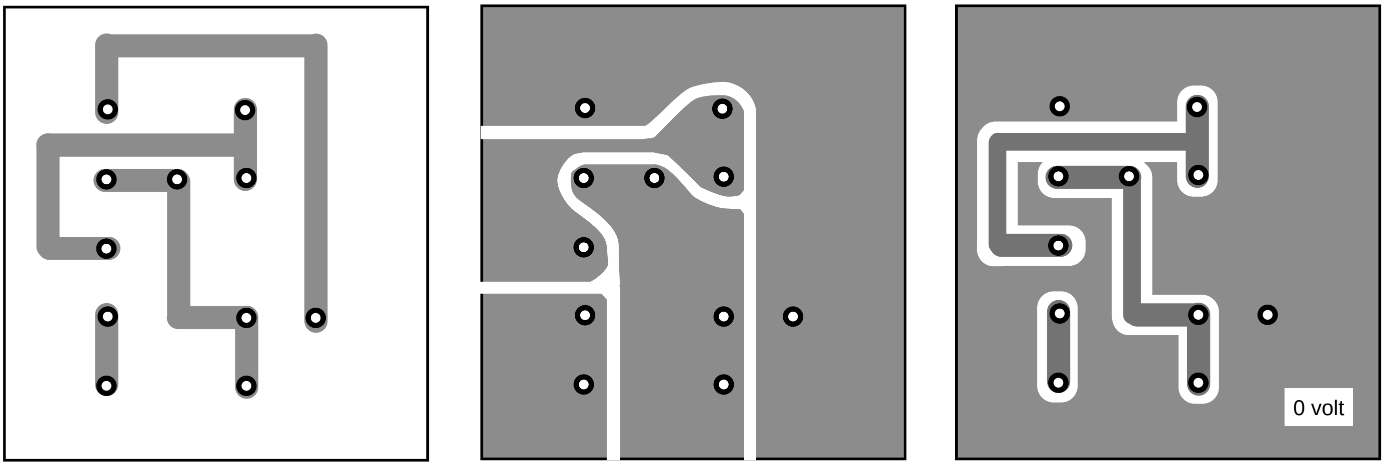
Printed circuit boards

The designer of printed circuit boards must follow certain rules that concern functional partitions and layout.

Starting with component placement, it is already possible to reduce coupling effects related to proximity.

For example, the grouping together of elements that belong to the same circuit category (digital vs - analogue vs - power circuits), according to their susceptibility, reduces interferences.

Furthermore, the layout of circuit board traces (routing) has a dramatic effect on susceptibility: the same electrical schematic implemented in different ways can display orders of magnitude different immunity levels. For example, a «minimum etch» circuit board layout (see fig. 15) reduces radiation effects and sensitivity.



thin circuit layout | minimum etch layout | layout with ground plane

fig. 15: the circuit layout can reduce the electromagnetic susceptibility of a PCB:
either by minimizing impedances (minimum etch),
or by reducing the coupling of the electromagnetic field (ground place).

Electronic devices

Numerous devices are available to provide effective protection against conducted disturbances. Selection is guided by the power level of the circuit to protect (power supply, control and monitoring, etc.) and the type of disturbance. Consequently, for common mode disturbances in a power circuit, a transformer will be used if the disturbances are at low (< 1 kHz) frequencies and a filter if they are at high frequencies.

The table in figure 16 gives a non-exhaustive list of protection devices. All are not equivalent: a filter does not protect against surges, and a surge protector does not protect against high frequency disturbances.

Shielding

Enclosing sensitive equipment in a conductive shield provides protection against electric fields. To be effective, the thickness of the conductive shield must exceed the skin depth at the frequencies of the disturbance encountered (see fig. 17).

The choice of material is of little importance. In some cases a conductive lacquer can be used as a shield. The metal or metal-coated insulator shield constitutes the «ground».

Ground interconnections

When it comes to grounding, good electric conductivity between different parts of the housing is extremely important. They must be carefully and correctly interconnected, for example protecting contact areas from any paint and also by using short, wide wire braids (to reduce impedance to a minimum).

type	device example	applications
surge arrester	spark gap lightning arrester limiter	power supply, control and monitoring ■ in installations
	varistor Zener diode	■ electronic devices
filtering	transformer inductors capacitors filters	power supply, control and monitoring (installations and electronic devices)
shielding	wire grid door braid shielded cables high frequency gaskets current finger	data transmission (cabinet in disturbed area)

fig. 16: list of protection devices.

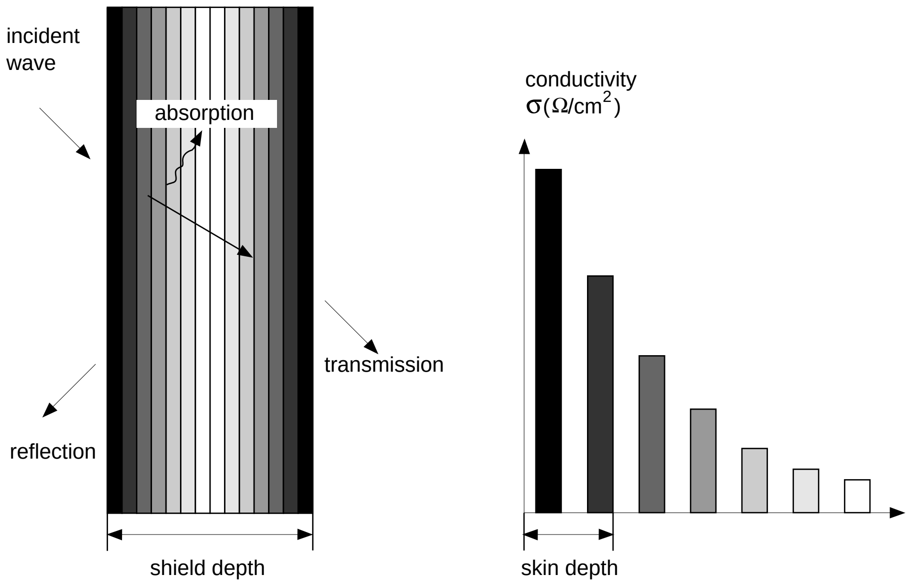


fig. 17: screening effect of a metallic shield.

Wiring

The shielding of wires, sometimes called screening, can be seen as an extension of the conductive envelope placed around sensitive systems.
It therefore has the shortest possible connection and if possible all around its perimeter to protect against high frequency disturbances.

Just as with the coupling between an electromagnetic field and a wire-like structure (see section 3), the theory governing wire shielding is very complex and too vast to be covered in this paper. References to special literature are given in the bibliography.

When all design and manufacturing rules are respected, the system will be sufficiently immune to electromagnetic disturbances in the environment it was built for.

Nevertheless, this immunity can only be validated by actual measurements that determine the effectiveness of different shielding techniques. At Merlin Gerin, for example, different prototype models of electronic trip units for circuit breakers are exposed to rigorous tests representative of the largest disturbances to which they may be expected to be subjected to.

The true objective of these tests is to check that the trip unit does not operate inadvertently and that the circuit breaker opens correctly and in the required time.

The «product» standards now include these specifications: a document is currently being discussed at the IEC , representing an EMC appendix to the IEC 947-2 standard concerning industrial circuit breakers.

5. installation

installation is an important factor in the overall system EMC

Evidence of this fact can be found in the NF C 15-100 general LV installation standards which devotes an entire chapter (33) to electromagnetic compatibility.

The two previous chapters have shown that installation plays an important role in EMC; this is true for both the design and layout phase and the actual installation phase.

design phase

During the design and layout phase two major factors govern EMC: the choice of equipment and their relative locations (see fig. 18).

The first factor concerns the choice of both emitters and susceptors: a given piece of equipment can to some extent generate disturbances and/or be susceptible.

For example, if two units are to operate close to each other they must:

■ either combine an emitter that generates low levels of disturbances and an «ordinary» (i.e. not overly sensitive) susceptor,

■ or combine an «ordinary» emitter that generates moderate levels of disturbances and a low sensitivity susceptor,

■ or form a compromise between the above two extremes.

The second factor that depends directly on the first concerns the positioning of equipment, already selected with respect to their individual characteristics, to satisfy EMC requirements.

It is obvious that this selection must take into account the cost of equipment and of its installation.

installation phase

Electrical and electronic installation work should follow the guidelines already discussed in the previous chapters. In practice, the different coexistent coupling modes must be studied and reduced to satisfy the EMC requirements. Different techniques should be applied:

■ the circuits and the chassis/earth grounds must be laid out in a grid,

■ the circuits must be physically separated,

■ the wiring must be carefully planned.

practical examples:

Grid layout for circuits and chassis/ earth grounds

Today, equipment can be susceptible to very low energy levels. It contains interconnected electronics sensitive to high frequencies. Common impedance coupling frequently occurs and to avoid it, the best possible equipotential grounding system or to be more precise a ground grid, is essential.

This is the first step in providing protection against disturbance problems. In a factory power distribution network, all protection (PE) wires must be joined together and connected to the existing metal structures as specified in NF C 15-100 (see fig. 19).

Similarly, within equipment, all grounds and frames must be connected to a grid-like grounding system in the shortest possible way using low impedance (at high frequencies), wide and short electrical connections (wires or braids).
The wiring of an electrical cabinet is a typical example: all grounds must be connected together.

There is a change to be noted here: the method involving the connection of all grounds to a central point (star configuration), sometimes used for electronic equipment sensitive to 50/ 60 Hz hum, has been replaced by grids which are far more effective in reducing disturbances that affect todays digital systems, protection relays and control and monitoring systems.

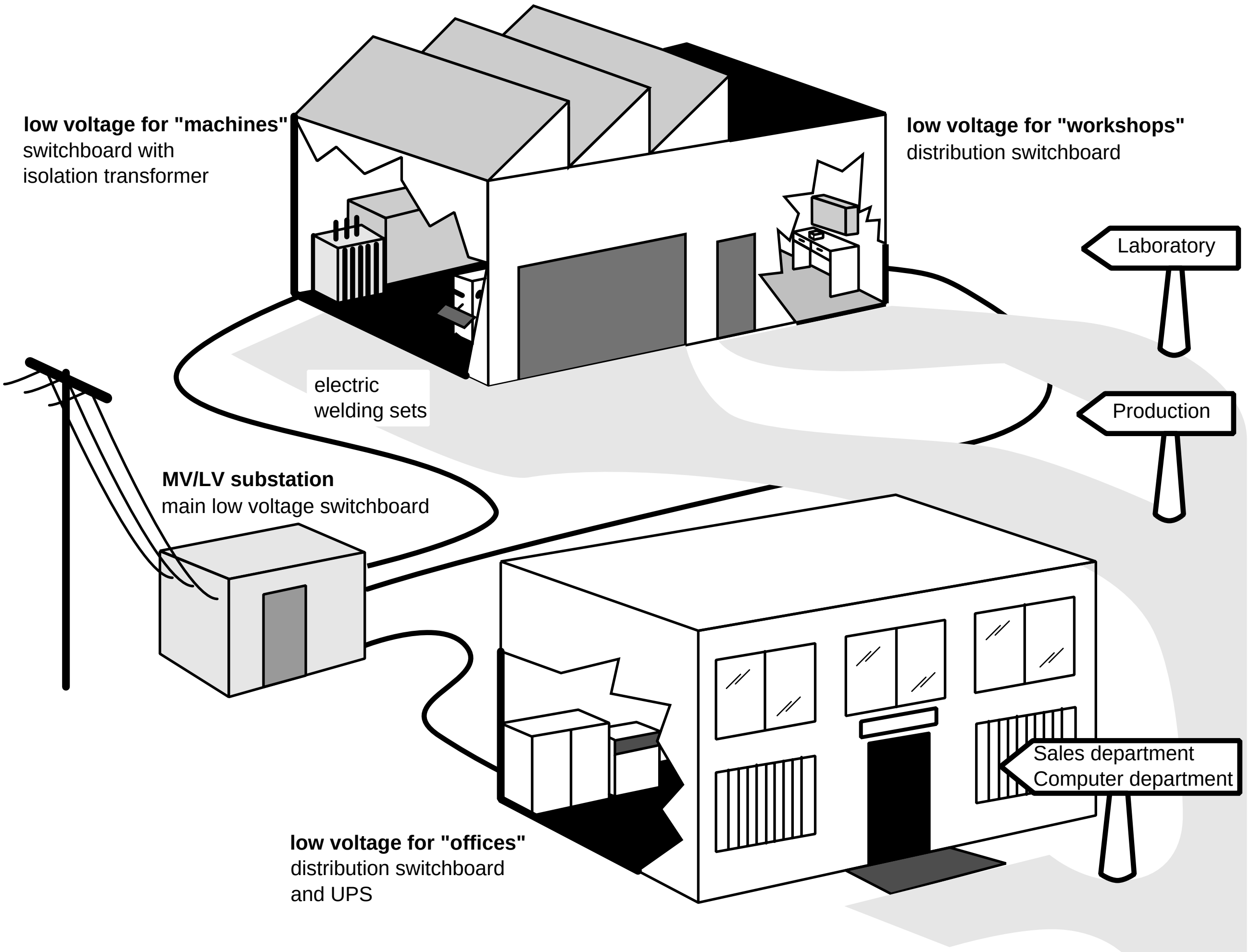


fig. 18: example of electrical equipment layout respecting EMC.

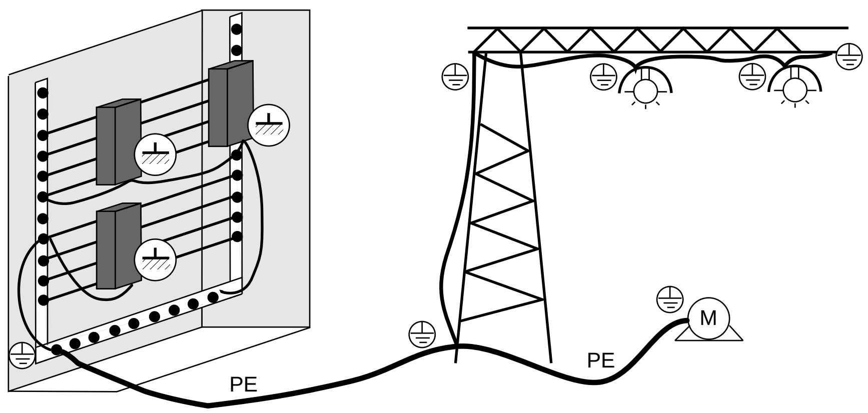


fig. 19: the grids forcircuits and for chassis/earth grounding systems are often combined in electrical cabinets.

Separation of electrical circuits

This technique consists of separating the energy sources (usually 50 or 60 Hz). The aim is to avoid interference on a sensitive device caused by conducted disturbances generated by other systems connected to the same power source. The principle is to create two separate power sources isolated by impedances that are high at the frequency of the disturbances.

Transformers (not auto-transformers) are effective isolators, especially at low frequencies: MV/LV transformers, isolation transformers and any input transformer for electronics stop conducted disturbances.

Sometimes an isolating filter is required to eliminate high frequency disturbances. If the sensitive equipment also requires emergency power, it can be supplied by an uninterruptible power supply (UPS) as long as the UPS contains the required isolation transformer(s).

Rational wiring

The effects of the three coupling mechanisms discussed earlier can be reduced if the wire and cable routing adheres to the following rules:

■ in all systems that cannot be separated physically for economic reasons, wires/cables must be grouped together by category. The different categories should be routed separately: in particular, power cables should be on one side and low power cables (telephone, control and monitoring) on the other.

If a sufficient number of cableways or troughs are available, power cables carrying more than a few amperes at 220 V should be routed separately from the low power signal cables. Otherwise, a minimum distance of at least 20 centimeters must be kept between the two.

Any element common to these two categories of cables must be avoided.

Circuitry using low level signals should have, whenever, possible its own return wire (0 Volts) to avoid common impedance coupling. The majority of systems that communicate over buses require pairs of wires reserved exclusively for data exchange.

■ in any case, the overall loop area formed by the conductor and its return must be minimized. In data transmission, twisted pairs reduce the susceptibility to differential mode coupling. The twisted pair is to be preferred over straight wires.

■ cables used for measurements and low signal level data transmission should be shielded, if possible, and unless specially instructed by the manufacturer, their shield connected to ground at a maximum number of points.

■ the cable routing troughs should be, if at all possible, made out of metal. The troughs should be correctly electrically interconnected, e.g. screwed together and connected to the grounding grid (see fig. 20).

■ the most sensitive cables (e.g. those used in measurements) should be placed in the corner of the trough where they can benefit from maximum protection against electromagnetic radiation. Their shielding, if any, should be connected to the trough at regular intervals.

The use of prefabricated cable trunking assemblies in which the cables are positioned and connected correctly, such as Telemecanique's Canalis system with built-in control wires, are highly recommended.

All these cabling techniques, which effectively avoid EMC problems, only increase costs slightly when applied at design or installation time. Later modifications of an existing installation showing excessive electromagnetic coupling are far more expensive.

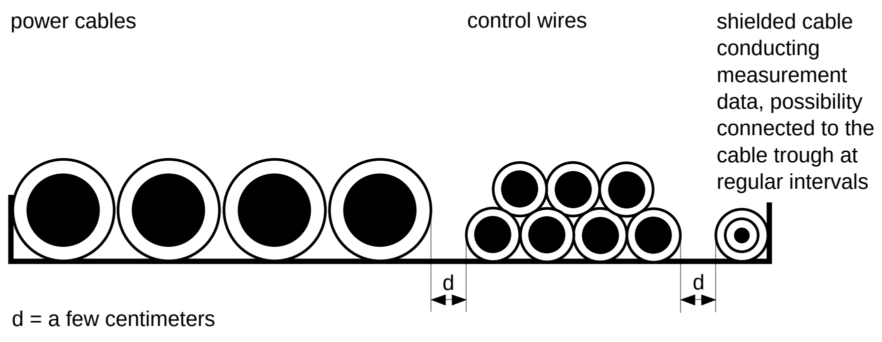


fig. 20: cable routing example.

6. standards, test facilities and tests standards

standards

Documented standards that regulate electromagnetic compatibility of systems have long been in existence.

The first regulations were issued by the International Special Committee on Radio Interference (CISPR). These regulations covered only the maximum acceptable power level that could be emitted by different types of equipment, mainly to protect radio transmission and reception.

National Committees and the International Electrotechnical Commission (IEC) have issued documented standards that cover all aspects of EMC emission and susceptibility encountered in the civilian domain.

Military standards on EMC have been compiled in the GAM EG 13 series in France and in the MIL-STD series in the United States.

The increasing importance of EMC and the forthcoming unification of Europe are changing the landscape of civilian standards.

The European Council published a Directive (reference 89/336/EC) in May 1989 on this subject. It relates to unifying the EMC legislation of the member countries. Every member country is committed to include it in its national legislation and make its use and application mandatory.

The European Directive not only imposes limits on emitted disturbances but also sets the minimum immunity to electromagnetic disturbances. The Directive makes reference to standards not yet ratified; standards that define maximum acceptable disturbance levels, minimal immunity levels and measurement methods. A Technical Committee, TC 110, has been created for this purpose by the European Committee for Electrotechnical Standardization (CENELEC). Its duty is to bring together the existing standards that are in accordance with the Directive and to write or rewrite those that are not. Without anticipating the work of TC 110, it seems likely that it will be based on existing standards already in use in the industrial community (see fig. 21).

For emission tests, the German standards VDE 0871 and VDE 0875 were used for some time as a reference. The recent European standards EN 55011 and EN 55022 are now replacing them.

For immunity tests, the IEC 801 publication is currently used as a reference. It will be included in the IEC 1000 publication which gathers all material on EMC written by the IEC in the framework of Committee 77.

Publication 801 contains several parts for different types of disturbances that may affect a system or equipment. The parts are respectively:

■ 801-1: general introduction,
■ 801-2: electrostatic discharge requirements,
■ 801-3: radiated electromagnetic field requirements,
■ 801-4: electrical fast transient/burst requirements,
■ 801-5: surge immunity requirements (proposed),
■ 801-6: current injection (proposed).

Parts 801-2, 801-3 and 801-4 relate to typical disturbances encountered in the modern electrotechnical world. They are widely accepted in the international community and Merlin Gerin has decided to adopt them for its products.

The following section describes in more detail the tests that relate to these standards.

test facilities

As mentioned before, to respect regulations, standardized measurements and tests must also be performed.
Due to its field of applications, Merlin Gerin made EMC one of its major concerns long ago. Large installations such as Faraday rooms have been in use since the seventies.

In 1988 a new dimension was reached with the opening of the EMC laboratory at the DTE Research and Development Centre in Grenoble. This centre makes full use of skills and knowledge and promotes the exchange of information. It also offers measurement services and is involved in special projects, training, and standards work as a recognized expert. As a centre offering services to outside customers, it performs measurements in all EMC fields: electrostatic discharge, conducted and radiated emissions, susceptibility to conduction or radiation. As with any other measurements, electromagnetic compatibility measurements must be reproducible both in time and in space, which means that two measurements performed at two different laboratories must yield the same results. In the EMC discipline, this means large facilities requiring considerable investments and a strict quality policy.

application field	**french standards**	**original international standards**
■ susceptibility	NF C 46-02x	IEC 801 - (x + 1)
example	NF C 46-022	IEC 801 - 3
■ emission	NF C 91-0xx	EN 55 0xx
example	NF C 91-022	EN 55 022

fig. 21: table of main standards in use in France and their international counterparts.

The quality program at the Merlin Gerin EMC laboratory is based on a Quality Manual and a set of procedures. These procedures concern calibration and the connection to calibrated standards in addition to each type of measurement itself. The list of tests for standards that can be performed at the laboratory are listed in appendix 4.

The fact that the laboratory has been accredited by the Réseau National d'Essais (National Testing Network) acknowledges the quality assurance policy.

tests

Electrostatic discharge

These tests are designed to check the immunity of circuit boards, equipment and systems to electrostatic discharge.

Electrostatic discharges are the result of charge accumulated by a person, for example, walking on a floor covered with an electrically insulating material. When the person touches an electrically conducting material connected via an impedance to ground, he discharges suddenly through the impedance.

Several studies have shown that the waveform is a function of the characteristics of the emitter (the source of the discharge) and of the circuits involved, but also of other parameters such as relative humidity (see fig. 22) or the speed at which the charged body approaches, in our example the hand of the person etc.

This research has led to standardized discharge tests. They are performed with an electrostatic gun that simulates a human being in predetermined configurations (see fig. 23). Discharges are performed on all accessible parts of the device under test, in its immediate environment and repeated a sufficient number of times to make sure that the device resists electrostatic discharge.

These measurements require an appropriate test bench.

All tests are completely defined by standard IEC 801-2 (revised in 1991) with severity levels shown in the table of figure 24.

Conducted electromagnetic susceptibility

Susceptibility tests are used to verify the resistance of equipment to disturbances reaching it via external equipment cables (inputs, outputs and power supply). As mentioned before, these disturbances differ depending on the type and installation characteristics of the cable. The electromagnetic signals or pulses used in these tests have characteristic amplitudes, waveforms, frequencies etc.

Disturbance measurements performed on numerous sites have led to the selection of two tests.

The first test, covered by IEC 801-4, simulates typical disturbances generated by the operation of controlgear. The test uses bursts consisting of a number of fast transients. The burst repetition

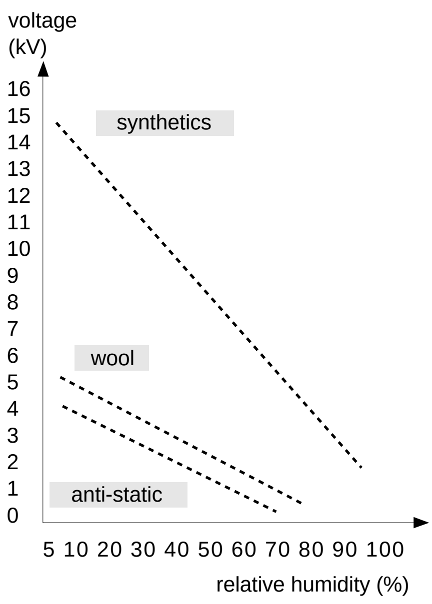


fig 22: the effect of relative humidity on the electrostatic discharge voltage for three types of floor materials.

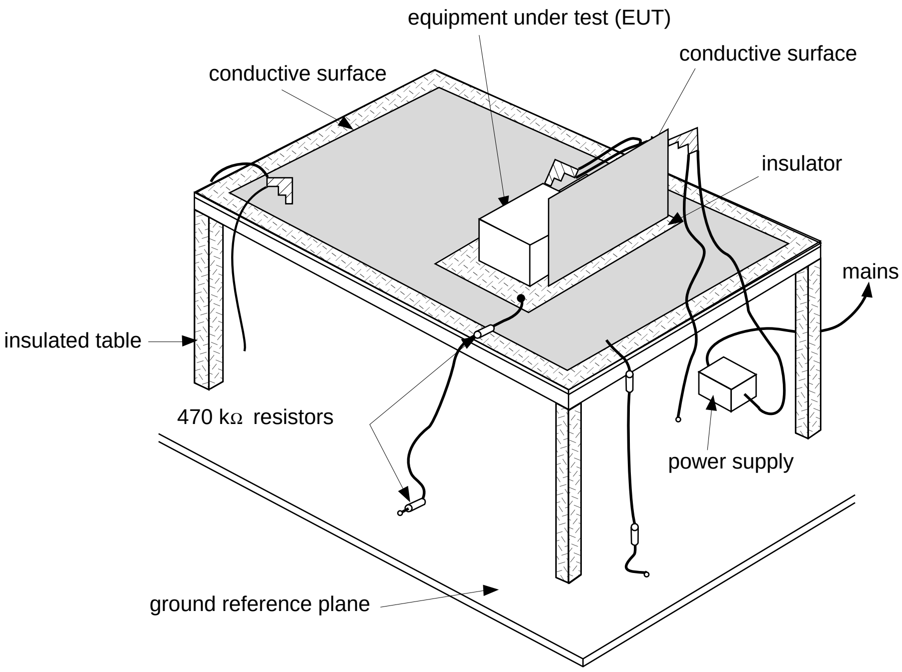


fig. 23: electrostatic test site as defined by standard IEC 801-2.

frequency is approx. 3 Hz. Each burst contains approx. 100 transients every 100 µs . Each transient rises steeply (5 ns) to an amplitude of several kV, depending on the required severity level (see fig. 25 and 26).

All cables can be subjected to fast transients. This type of disturbance couples into wiring very easily e.g. crosstalk (see the chapter on «coupling»). It takes only one cable generating such disturbances in a cable or wire trough to pollute all other cables running along the same path. The test must therefore involve all cables and wires: a common mode test is performed on all wires with artificially induced disturbances (cables other than the power supply) and a common and differential mode test on cables connected to the mains. Disturbances are injected into the tested cables either via direct capacitive coupling (power supplies), or via a coupling clamp consisting of two metal plates that enclose the secondary cables (see fig. 27).

The equipment under test must not show a malfunction over a predetermined period (1 min). This test is the most relevant one for device immunity because fast transients are the most frequent ones encountered.

The second test is representative of secondary effects created by phenomena such as lightning. It simulates conducted disturbances appearing on LV power lines after lightning strikes (801-5 draft).

These disturbances consist of energy that is transformed into:

■ voltage impulses 1.2/50 µs, if the impedance of the tested device is high, with amplitudes that can reach several kV,

severity level according to IEC 801-2	tests voltage ± 10 % (kV)
1	2
2	4
3	8
4	15

fig. 24: electrostatic discharge voltages that devices must withstand to comply with standard IEC 801-2.

severity level according to IEC 801-4	applied test voltage (± 10 %) in kV without malfunctions occurring (open circuit output): on power supply	on input/output lines (signal, data, control)
1	0.5	0.25
2	1	0.5
3	2	1
4	4	2
x	special	special

level x is defined contractually between manufacturer and client.

fig. 26: table of severity levels defined in IEC 801-4.

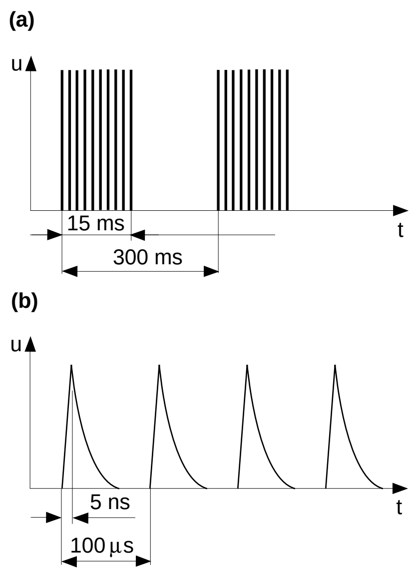


fig. 25: shape of the bursts (a) and their fast transients (b).

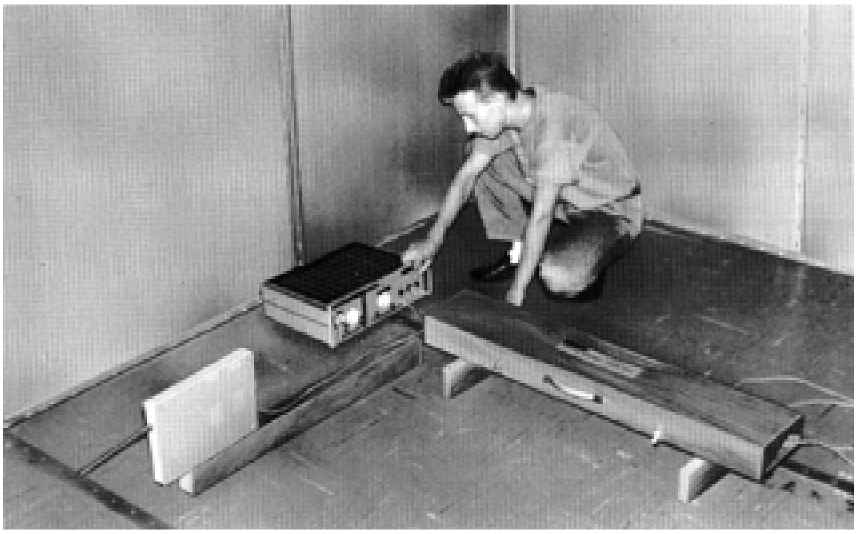


fig. 27: susceptibility to fast transients, measured on an Isis master control unit (test 801-4) in a Faraday room. This photo shows the disturbance generator being adjusted by an operator, the wooden case containing the coupling clamp and the Isis master control unit connected to the Batibus network.

■ current impulses 8/20 µs if the impedance is low, with amplitudes reaching several kA.

The rise time of this type of disturbance is in the order of a thousand times longer, in the microsecond range, than for bursts of fast transients (see fig. 28). Crosstalk type of coupling is therefore less prevalent and this second type of test only applies to cables directly connected to the mains. The common and differential mode tests use capacitive coupling and appropriate levels. The procedure resembles the fast transients test: the equipment under test must not malfunction.

Susceptibility to radiated emission

The susceptibility tests for radiated emissions were devised to ensure the satisfactory operation of equipment when exposed to electromagnetic fields.

Since these tests are particularly environment sensitive, the means deployed and competency levels required to produce reliable and reproducible susceptibility measurements are very high. The surrounding environment must be sufficiently «clean» and free of waves normally present, since (as discussed in the «source» chapter) electromagnetic fields with strengths in the several V/m range are frequent (e.g. two-way portable radios) and pulsed electromagnetic fields with even higher levels are common in industrial environments. These tests must therefore be conducted in Faraday rooms with walls covered by high frequency absorbing materials. The rooms are called anechoic chambers when all walls including the floor are covered and semi-anechoic when the floor is not.

In the chambers, the fields are generated by different types of antennae depending on the type of field, the frequency range and polarization. The antennae are driven by a wideband power amplifier controlled by a R.F. generator (see fig. 29).

The generated fields are calibrated using broadband isotropic sensors (field strength monitors). The diagram in figure 30 shows a typical test setup.

Standards define the acceptable disturbance levels. In particular, standard 801-3 (currently being revised) recommends tests using frequencies in the range of 27 to 500 MHz at three severity levels. (1.3 and 10 V/m).

Note that the test conditions that can be created at the Merlin Gerin laboratories are much more severe: the frequency range that can be covered extends from 10 kHz to 1 GHz. From 27 MHz to 1 GHz devices can be tested against fields reaching 30 V/m and 80 % modulation. Standardized measurements for pulsed electromagnetic fields do not yet exist. In this domain, Merlin Gerin uses its own internal procedures.

severity levels according to draft IEC 801-5	test open-circuit output voltagerr (kV)
1	0.5
2	1
3	2
4	4
x	special

level x is defined contractually between manufacturer and client.

fig. 28: severity levels as defined in project IEC 801-5 (generator impedance = 2 Ω).

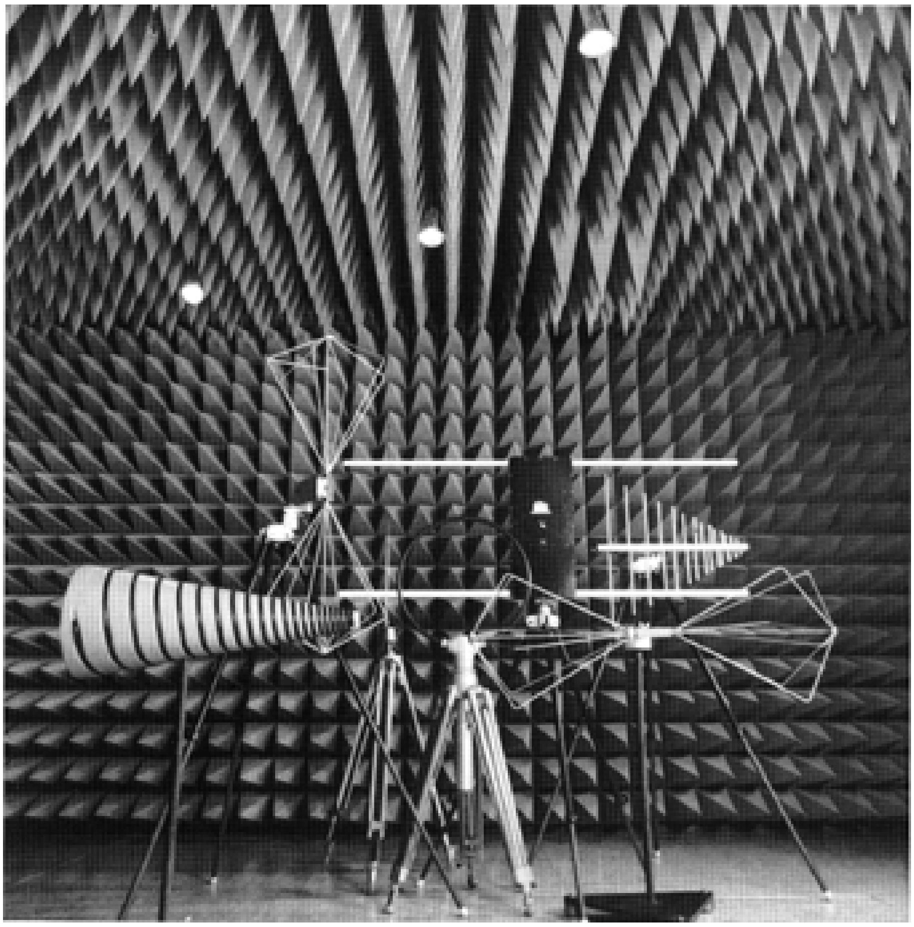


fig. 29: Faraday room: semi-anechoic chamber and a several antennae of the Merlin Gerin EMC laboratory.

Conducted emission

Conducted emission measurements quantify the disturbances that the equipment under test reinjects into all cables connected to it.

The disturbance strongly depends on the high frequency characteristics of the load connected to it since the equipment under test is the generator in this case (see fig. 31).

To obtain reproducible measurement results and especially to avoid problems with the characteristic impedance of the network, the conducted emission measurements are performed with the help of a Line Impedance Stabilizing Network (LISN). A high frequency receiver is connected to the network to measure emission levels at each frequency.

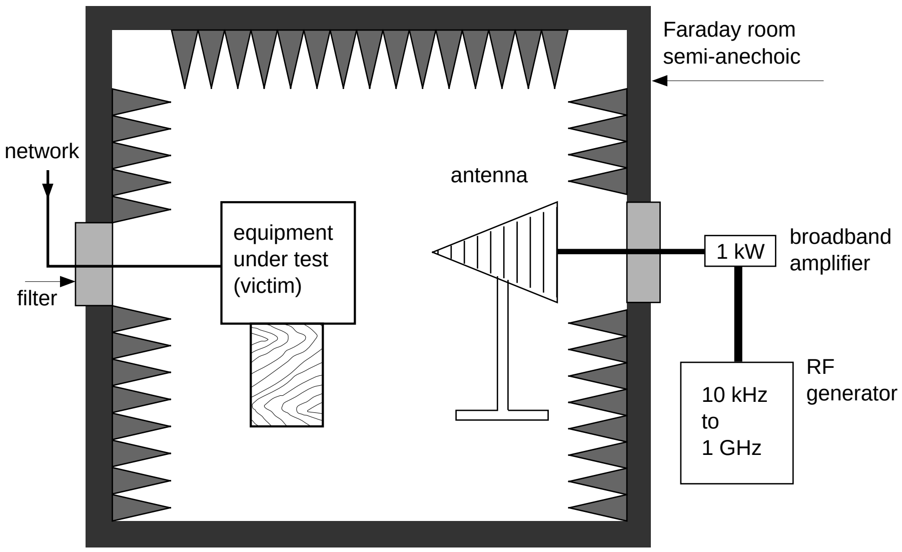


fig. 30: typical test setup in a Faraday room. Measurements are performed in two stages:
1 - calibration of the filed for a given frequency range, without the EUT,
2 - verification of the EUT immunity.

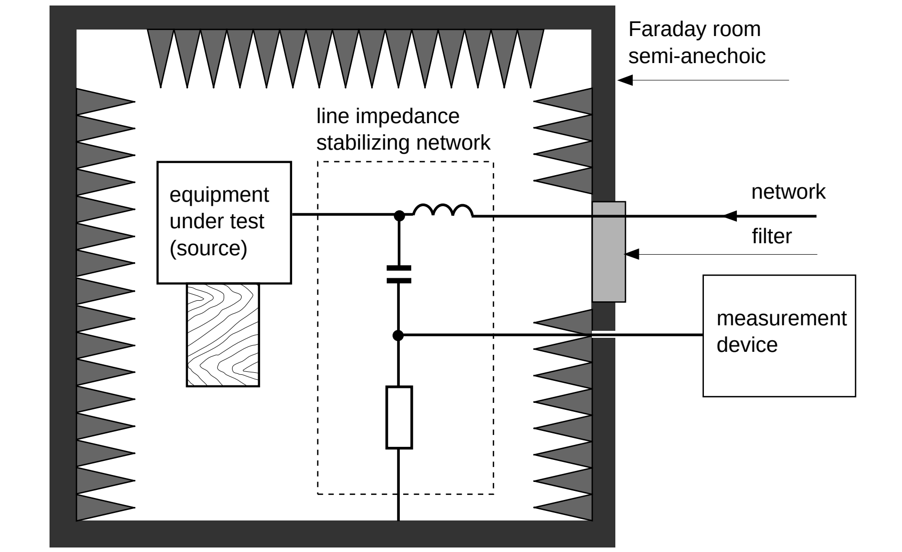


fig. 31: measurement configuration for conducted emissions. The EUT (equipment under test) is the generator, the line impedance stabilizing network is the load.

The level of disturbances reinjected may not exceed the limits defined in the standards. These limits depend on the type of cable and the environment. The graph below (see fig. 32) shows the results of a measurement performed on an uninterruptible power supply and the levels defined in standard EN 55 022 for comparison.

Radiated emissions

Radiated emission measurements quantify the level of disturbances emitted by a device in the form of electromagnetic waves.

Just as with radiated susceptibility tests, radiated emission tests must be performed in the absence of waves normally present such as CB, radio etc. and must not be modified by reflections from surrounding objects. These two conditions are contradictory and this is the reason for the existence of two test methods.

The first method consists of placing the EUT in a field free of obstacles within a given perimeter. The environment is uncontrolled.

The second method is implemented in a Faraday room; the reflections from the walls are deliberately attenuated by high frequency absorbing materials (see fig. 29). The environment can be perfectly controlled.

The Merlin Gerin laboratory uses the second method. It offers a key advantage in that measurements can be automated and that equipment handling is minimized, since emission and susceptibility level measurements can be performed at the same site with just few setup changes.

As for conducted emissions, the emission levels must be less than the limits set by specifications or standards.

Measuring pulsed fields

Standardized tests are performed to measure emission levels or test the susceptibility of devices or systems to the most common types of electromagnetic disturbances encountered in an industrial environment.

However, the environment for devices developed by Merlin Gerin has certain characteristics not yet covered by standards.

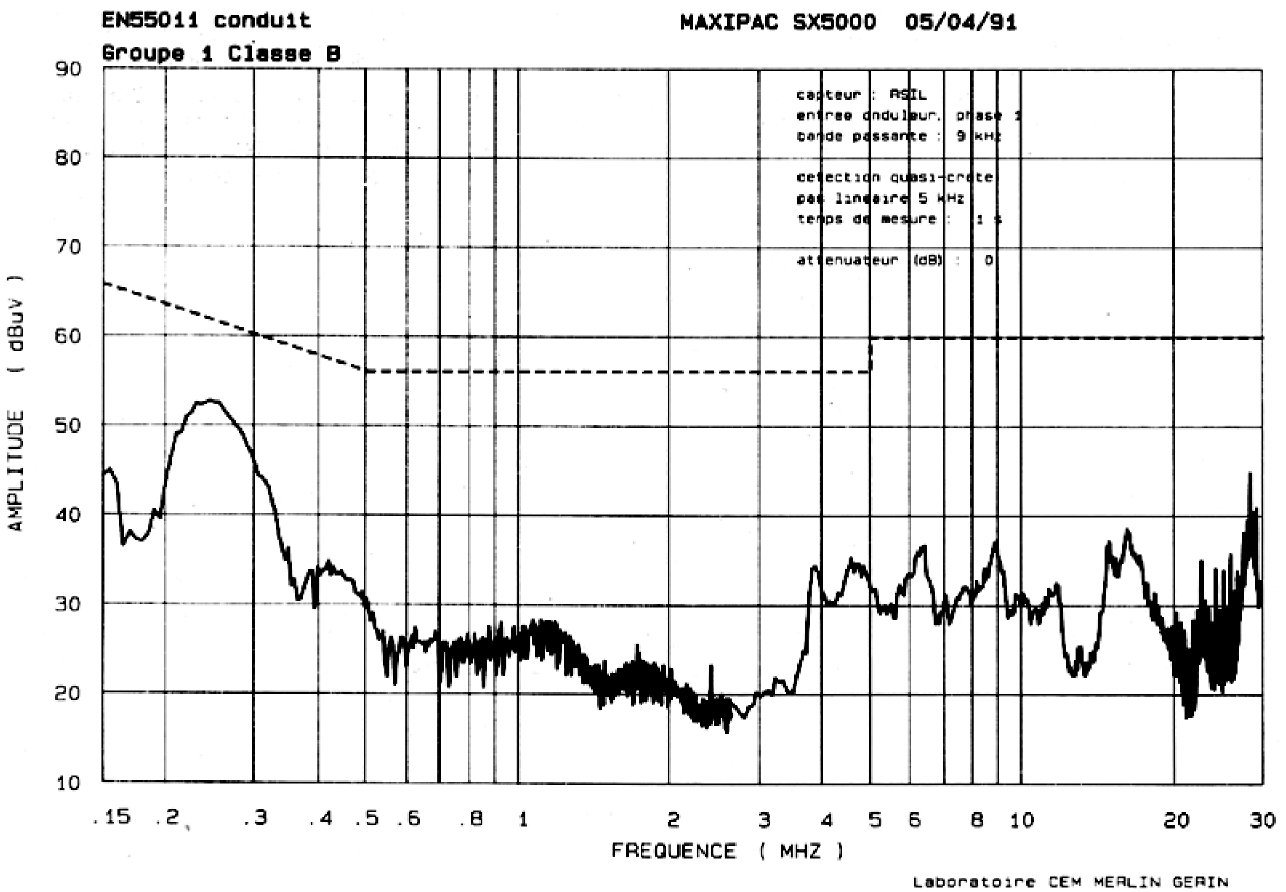


fig. 32: results of measurements performed on a Maxipac SX5000 uninterruptible power supply.

For example, specific EMC test procedures for equipment in medium voltage substations do not yet exist.

This is why Merlin Gerin performs a series of measurements to better understand the typical disturbances that exist in the vicinity of the equipment it manufactures, especially near low, medium and very high voltage switchgear.

In a second phase, in-house tests using special test systems have been developed. They allow testing of the electromagnetic compatibility of devices without having to revert to full scale tests. These tests are easier to reproduce and less costly. They are performed early in the design which minimizes costs for EMC protection.

7. conclusion

The use of electronics in a large number of applications, and especially in electrotechnical equipment, has introduced a new and important requirement: electromagnetic compatibility. Trouble-free operation in disturbed environments and operation without producing disturbances are essential to product quality requirements. To achieve both these goals, the complex phenomena involved in the sources, coupling and susceptors must be well understood. A certain number of rules must be followed in the design, industrialization and manufacture of products.

The site and installation characteristics also play an important role in electromagnetic compatibility.
This explains the importance of carefully considering the location and layout of power components, cable routing, shielding etc. right from the intitial design phase. Even if equipment offers satisfactory EMC, a well designed installation can extend the compatibility safety margins.

Only measurements requiring a high level of expertise and sophisticated equipment can produce valid results quantifying the electromagnetic compatibility of equipment.

Compliance with standards therefore provides the certainty that equipment will operate satisfactorily in its electromagnetic environment.

appendix 1: glossary

Electromagnetic compatibility, EMC (abbreviation) (IEV 161-01-07)
The ability of an equipment or system to function satisfactorily in its electromagnetic environment without introducing intolerable electromagnetic disturbances to anything in that environment.

(Electromagnetic) compatibility level (IEV 161-03-10)
The specified maximum disturbance level expected to be impressed on a device, equipment or system operated in particular conditions.

Note: In practice the electromagnetic compatibility level is not an absolute maximum level but may be exceeded by a small probability.

Electromagnetic disturbance (IEV 161-01-05)
Any electromagnetic phenomenon which may degrade the performance of a device, equipment or system, or adversely affect living or inert matter.

Note: An electromagnetic disturbance may be an electromagnetic noise, an unwanted signal or a change in the propagation medium.

Disturbance level (not defined in IEV 161)
Level of an electromagnetic disturbance of a given form measured in particular conditions.

Limit of disturbance (IEV 161-03-08)
The maximum permissible electromagnetic disturbance level, as measured in a specified way.

Immunity level (IEV 161-03-14)
The maximum level of a given disturbance incident on a particular device, equipment or system for which it remains capable of operating at a required degree of performance.

(Electromagnetic) susceptibility (IEV 161-01-21)
The inability of a device, equipment or system to perform without degradation in the presence of an electromagnetic disturbance.

Note: Suceptibility is a lack of immunity.

Decibel
The decibel is a unit of sound pressure that is also used to express amplitude ratios according to
$X/Xo\ (dB_{@}) = 20 \cdot \log_{10} X/Xo$,
with
X = measured amplitude,
Xo = reference amplitude,
@ = mesure unit for X and Xo.
A few sample values are given in the table below (see fig. 33).

amplitude ratio X/Xo	dB
1	0
1.12	1
1.25	2
1.41	3
2	6
3.2	10
4	12
5	14
10	20
100	40
1000	60

fig. 33: amplitude ratios expressed in decibels.

appendix 2: impedance of a conductor at high frequencies

The level of EMC in equipment depends on coupling between circuits. Coupling is directly related to the impedance between circuits, especially at high frequencies. To improve EMC, these impedances must be determined and then reduced.

A few approximating formulae exist to determine the high frequency impedance of typical conductors. These formulae are cumbersome and their results meaningless if the exact position of all involved elements is unknown. But who knows the exact position of a wire with respect to the others in a cable trough? The answers to this and similar questions come from experience together with basic knowledge of the theory of electrical phenomena.

First of all it is important to keep in mind that the impedance of a conductor is mainly a function of its inductance and becomes preponderant starting at a few kilohertz for a standard wire.
For a wire assumed to be infinitely long, the inductance per unit length increases logarithmically with the diameter, therefore very slowly: for wires that do not exceed 1/4 of the disturbance wavelength, an inductance of one µH/m can be used irrespective of the diameter (see fig. 34).

This value is much lower when the wire is correctly run against a conductive plane. It becomes a function of the distance between the wire and the plane and the inductance can easily be decreased by 10 dB. At very high frequencies the wire must be considered as a transmission line with a characteristic impedance of around one hundred ohms.
In this light, a common inductance of several µH can easily be created, for example, with a few meters of green-yellow (grounding) wire. This translates into a few ohms at 1 MHz and a few hundred ohms at 100 MHz.

Conclusion

A conducting metal plate represents the electrical interconnect offering the lowest impedance, independent of thickness as long as it is greater than the skin depth (415 µm at 10 kHz for copper). A copper plate displays an inductance of 0.6 nH (at 10 kHz) and a resistance of 37 µΩ per square.

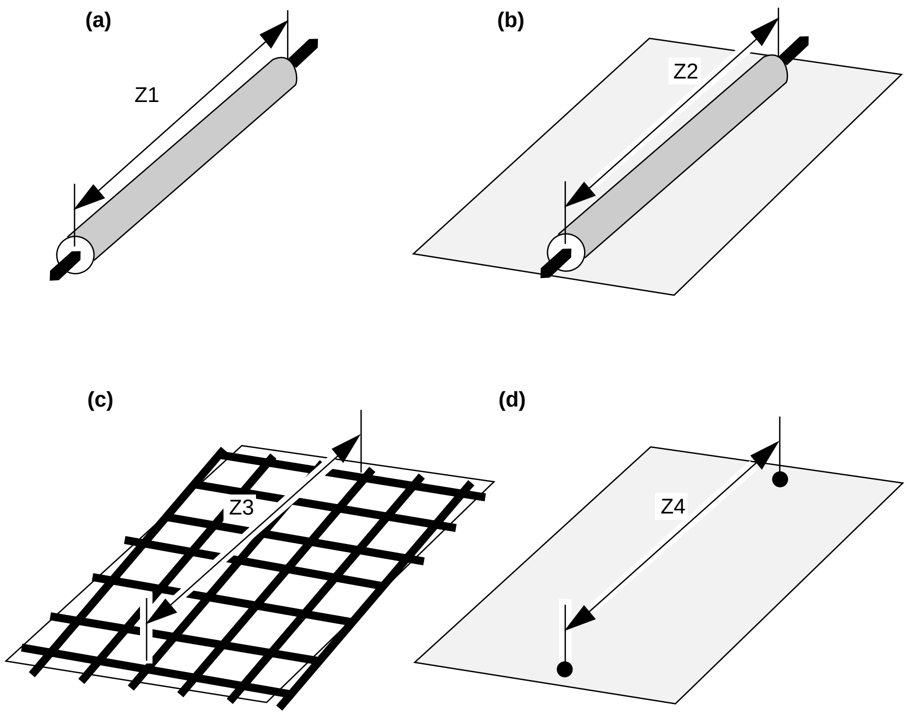


fig. 34: at equal lenghts, the different impedances:
a: wire in air (l ≈ 1 µH/m),
b: cable placed on a metal plane,
c: metal grid with electrical contact at each node (e.g. welded concrete rebar),
d: metal plane,
have a per unit lenght impedance Z1 > Z2 > Z3 > Z4.

appendix 3: the different parts of a cable

The technical terms used to describe different parts of a cable can have slightly different meanings depending on the cable's field of application (power transmission, telephone, data or control and monitoring),
(see fig. 35).

The IEC definitions are in italics.

Jacket

The jacket's most important role is to protect the cable from mechanical damage. That is why it usually contains two helically stranded soft steel sheets (NF C 32-050).
For data transmission cables, it also serves as an electrostatic and more often electromagnetic shield.

Shield

Same as a screen; i.e. device designed to reduce the intensity of electromagnetic radiation penetrating into a certain region.
A jacket or screen of a cable, whether for power or data transmission, can form a shield.

Screen

A device used to reduce the penetration of a field into an assigned region

It has multiple functions:

- creation of an equipotential surface around the insulator,
- protection against the effects of external an internal electrostatic fields,
- draining the capacitive current as well as earth leakage fault currents (zero sequence short-circuits),
- protection of life and property in the event of a puncture.

That is why it is generally made of metal and is continuous (lead tubing, braided wire, helically wound bands).

For cables carrying data, the screen, more often called a shield, consists of copper or aluminum wire bands or braids, wrapped around to form a shield against electrostatic or electromagnetic fields.

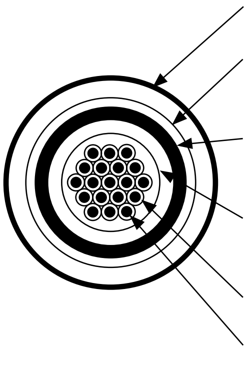
It can be an overall shield, for all conductors in the cable, when the disturbances are external to the cable.

It can also be partial, for a limited number of conductors, to protect against disturbances emitted by the other conductors in the cable.

Insulator

The insulator renders the cable water and/or air tight.

Telephone cable



Medium voltage power transmission cable

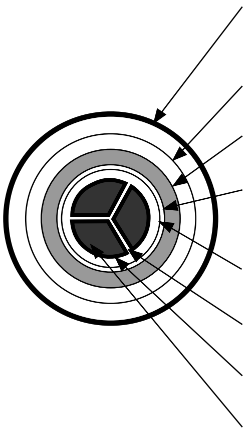


fig. 35.

appendix 4: tests performed at the Merlin Gerin EMC laboratory

The Merlin Gerin EMC laboratory has the required equipment and expertise to perform a large number of tests.

standards compliance tests

Immunity

■ IEC 801-2 (1984)
Electromagnetic compatibility for industrial-process measurement and control equipment - Part 2: Electrostatic discharge requirements.

■ IEC 801-3 (1984)
Electromagnetic compatibility for industrial-process measurement and control equipment - Part 3: Radiated electromagnetic field requirements.

■ IEC 801-4 (1988)
Electromagnetic compatibility for industrial-process measurement and control equipment - Part 4: Electrical fast transient/burst requirements.

■ NF C 63-850 (October 1982)
Programmable controllers 10-2-8-1 and 10-2-8-3: electromagnetic compatibility tests.

Emission

■ EN 55 011 (to be published)
Limits and methods of measurement of electromagnetic disturbance characteristics of Industrial, Scientific and Medical (ISM) radio-frequency equipment.
[conducted emission part]

■ EN 55 022
Limits and methods of measurement of radio interference characteristics of information technology equipment.
[conducted emission part]

■ VDE 0871 (June 1978)
Disturbance suppression for Industrial, Scientific and Medical (ISM) or equivalent high frequency equipment.

Specific standards

■ Telecommunications centres

□ I 12-10 (1988)
published by the Committee for Equipment Specifications (CSE), France Telecom.
Electromagnetic environment of equipment in a telecommunications centre.
[the parts on immunity of equipment to radiated disturbances, radiated and conducted disturbances created by equipment].

■ military

□ GAMEG13
62C1*, 62C2, 62R1*, 62R2, 62R3**, 63C1, 63C2, 63C3, 63C4, 63R1, 63R2, 63R3**,

□ MIL STD 461/462
CE01*, CE03, RE01*, RE02**, CS01, CS02, CS06, RS01, RS02, RS03**
* : low frequency limit = 10 kHz
** : high frequency limit = 1 GHz

non-standardized tests

Within the limits of available expertise and facilities, the laboratory can perform tests complying with other standards.

appendix 5: bibliography

Standards

- IEC 1000-2-1
- IEC 1000-2-2
- IEC 801-1 to 801-4
- EN 55 011, CISPR 11
- EN 55 022, CISPR 22
- NF C 15-100

Merlin Gerin Cahiers Techniques Publications

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