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Electromagnetic Compatibility (EMC) Course Notes

Course Notes

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Learning objectives

The main target for this subject is to provide to the students a global vision of all aspects of the electromagnetic compatibility

The objectives of an Electromagnetic Compatibility (EMC) course are to train engineers and technicians capable of designing electronic systems that function correctly in their environment without interfering with other equipment.

This electromagnetic compatibility (EMC) course is intended for first-year Master's students in electrical engineering and embedded systems electronics. The course notes are structured into four chapters.

Currently, the study of electromagnetic compatibility (EMC) in electrical and electronic systems has become of paramount importance. Indeed, all electrical and electronic systems are subject to disturbances originating from stray energy that unintentionally crosses their boundaries; this stray energy is called electromagnetic interference.

Electromagnetic interference is becoming increasingly problematic for electrical and/or electronic systems. This interference can also be a source of disruption for neighboring systems or other users of the same system.

This gives rise to a discipline called electromagnetic compatibility (EMC), that is, the art of making sensitive electrical systems work in a disturbed electromagnetic environment, but also of reducing the disturbances generated by electrical systems from their design stage.

The objective of this course is to explain the basics of electromagnetic compatibility (EMC), and its importance for businesses.

An electronic system that functions compatibly with other electronic systems without producing or being susceptible to electromagnetic interference is said to be electromagnetically compatible with its environment. The objective of this course is to recognize and understand Electromagnetic Compatibility (EMC) challenges.

EMC challenges occur across numerous critical application areas. Examples of non-compliance include mobile telephones interfering with pacemakers or aircraft avionics, broadcast stations disrupting automotive engine management systems, or switching noise in power converters affecting sensitive control circuits. Key application domains where EMC is essential include Power Electronics, Electrical Transportation (automotive, aviation and maritime), Telecommunication and integrated circuit design.

Knowledge of unwanted electromagnetic phenomena, interferences, understand unwanted coupling and to be able to find possible interference mitigation measures. Where understanding the connection between fundamental EM phenomena and real physical situation is the main objective.

In this course, you will learn to recognize non-ideal behaviors in electronic components and explore phenomena, shielding strategies, and methods to control conducted EMI. Additionally, you'll gain

insights into minimizing crosstalk effects, reducing radiated EMI emissions, and enhancing system immunity. CM and DM EMI issues, along with the role of Transfer Impedance in EMC design, will also be covered. This course provides a comprehensive foundation for navigating the intricacies of EMC in electronic design.

Electromagnetic compatibility (EMC) is a discipline that aims to study the problems of electromagnetic coexistence. Its purpose is to:

- To study unintentional energy transfers between electrical and/or electronic systems,
- To develop processes to limit the electromagnetic interference emitted and thereby comply with current regulations,
- To develop processes to increase the immunity of systems to parasites.

Electromagnetic compatibility (EMC) is the science that enables the correct functioning of an electrical or electronic system in the presence of other systems in its environment.

The work was therefore carried out in two parts:

- ✓ **The first part** defines the principle of EMC and its legal framework. A brief review of electronics then helps to understand the difference between electric, magnetic, and electromagnetic fields. We will then be able to understand what electromagnetic interference is and see some methods for verifying the performance of equipment in terms of EMC.
- ✓ **The last part** briefly presents the techniques that can be implemented to protect the equipment.

General introduction

General introduction

Currently, the study of electromagnetic compatibility (EMC) in electrical and electronic systems has become of paramount importance. Indeed, all electrical and electronic systems are subject to disturbances arising from spurious energy that unintentionally crosses their boundaries; this spurious energy is known as electromagnetic interference.

Electromagnetic disturbances are becoming increasingly problematic for electrical and/or electronic systems. These disturbances can also be a source of interference for neighboring systems or other users of the same system.

This has given rise to a discipline known as electromagnetic compatibility (EMC), which is the art of ensuring that sensitive electrical systems operate in a disturbed electromagnetic environment, whilst also reducing the interference generated by electrical systems right from the design stage.

The aim of this course material is to explain the basics of electromagnetic compatibility (EMC) and its significance for businesses.

Electromagnetic compatibility (EMC) is a discipline that aims to study electromagnetic coexistence issues. Its purpose is to:

- Study unintended energy transfers between electrical and/or electronic systems,
- Develop methods to limit emitted electromagnetic interference and thereby comply with current regulations,
- Develop processes to increase the immunity of systems to interference.

Electromagnetic compatibility (EMC) is the science that ensures the correct functioning of an electrical or electronic system in the presence of other systems in its environment.

This field is currently particularly important because electrical and electronic devices are becoming increasingly numerous, complex and critical, and are therefore vulnerable to electromagnetic pollution, with potentially very serious consequences.

Our work was therefore carried out in two parts:

✓ The first part defines the principles of EMC and its legislative framework. A few reminders

in electronics then help to explain the difference between electric, magnetic and electromagnetic fields. We can then understand what electromagnetic disturbances are, and look at some methods for verifying the performance of equipment in terms of EMC.

✓ The final part briefly outlines the techniques that can be used to protect equipment.

This electromagnetic compatibility (EMC) course material is intended for first-year Master's students in Electrical Engineering. The handout is structured into four chapters as follows: In Chapter 1, we provide a state-of-the-art overview focused primarily on introducing this field of study, an introduction to EMC: we review the terminology, definitions, contexts and key issues.

In Chapter 2, we will examine disturbances, couplings and protection techniques in EMC; we will review the propagation modes of conducted disturbances, then we will study the consequences of these disturbances.

In Chapter 3 (EMC Standards and Measurements), we will present the concepts and the main categories of existing standards; this naturally leads us to the regulations defining emission limits, and we will therefore present the principle of disturbance measurement, including descriptions of the categories of measurement devices used in EMC, such as measurements of conducted disturbances and measurements of radiated disturbances.

Chapter 4 will provide a detailed description of the mitigation and protection against electromagnetic disturbances.

Chapter 1:

Introduction to EMC: Terminology, Definitions, Context and Issues.

1.1 Introduction

This chapter sets out the basic concepts of EMC and the principles associated with this field.

The art of electromagnetic compatibility (EMC) consists of ensuring the correct and optimal operation of any electrical device in the presence of others, so as to limit the interference they emit and improve their resistance to external disturbances.

Three key areas of interest arise from this definition: the study of disturbance sources, the study of couplings and, finally, the study of the impact of disturbances on a 'victim'. The aim of EMC studies is to improve the coexistence of components that may emit electromagnetic interference and/or be susceptible to it. We will therefore begin by defining exactly what EMC is. Next, we will examine its fundamental aspects and the origins of interference, and finally we will outline the activities related to electromagnetic compatibility.

1.2 Introductory concepts to electromagnetic compatibility

1.2.1 Definition of Electromagnetic Compatibility (EMC)

Electromagnetic Compatibility (EMC) is the ability of a device, apparatus or system to maintain its function in an electromagnetic environment, whilst producing a level of interference compatible with its environment.

Electromagnetic compatibility thus has three aspects [1, 2, 4]:

- ✓ Every device operates satisfactorily in its electromagnetic environment
. This means that each device withstands the disturbances originating from the environment, and is therefore immune to them: its level of immunity is sufficiently high.
 - ✓ no device must itself produce electromagnetic disturbances
that are intolerable to anything in its environment. It follows that its level of disturbance emission into said environment must be sufficiently low so that everything in that environment is unaffected by it.
-

✓ It must not interfere with itself (self-compatibility).

Figure 1.1 shows a modern environment consisting of systems operating with radio waves and others connected to power or even communication networks [9-10].



Figure 1.1: Electromagnetic environment.

1.2.2 Some definitions of e

- a) Electronic or electrical components:** A single element with an intrinsic function intended to be assembled with other elements to form an electronic or electrical device.
- b) Devices:** A finished product consisting of a set of components and possessing an intrinsic function, intended for end use and/or for installation in a system.
- c) System:** A combination of several devices designed to operate together and/or to be integrated into an installation.
- d) Electronic or electrical device:** A set of components, i.e. devices, and also a set of devices, i.e. a system.
- e) Installation:** The setting up of appliances or systems in a given location.

f) Electromagnetic interference: Any unwanted signal produced by equipment that is likely to interfere with the operation of other equipment, the interference being a signal propagating by radiation or conduction.

There are two types of propagation of this parasitic signal:

- ✓ propagation by radiation (referred to as radiated coupling).
- ✓ propagation by conduction (conduction mode coupling)

g) Radiated mode coupling: Propagation of electromagnetic interference through the air; this is coupling via electromagnetic waves generated by currents and voltages. This mode of coupling is described by Maxwell's equations, which are a generalisation of Ampère's and Faraday's laws.

h) Conduction mode coupling: Current flow in conductive media; this is coupling that occurs via conductors and their associated electrical components. This mode of coupling is governed by the classical laws of electricity, the loop theorem, and the Thevenin and Norton theorems, where parasitic phenomena are generated by elements (capacitive, inductive, resistive) that must be identified.

In practice, problems are addressed using the source/sink concept (Figure 1.2). Indeed, when analysing an electromagnetic disturbance, it is observed that the problem involves three elements [1,5-7]:

- 1) A disturbance source that emits electromagnetic energy,
- 2) A coupling channel through which the energy of these disturbances
- 3) A receiver that captures this energy, processes it and superimposes it onto its normal function.

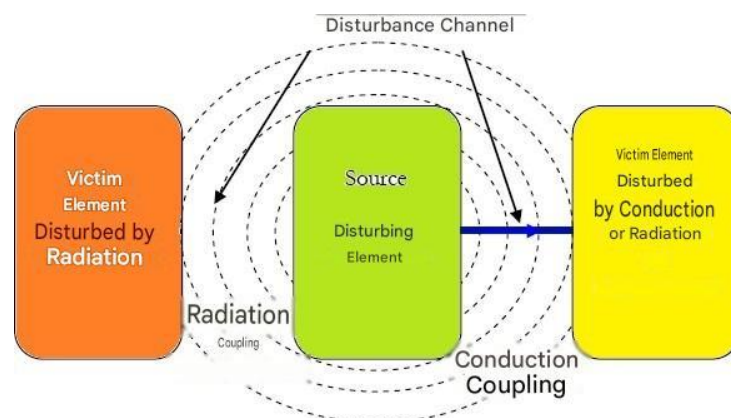


Figure 1.2: Transmission of electromagnetic disturbances

If the disturbances received by the latter are too strong and cause interference, the

latter is said to be a victim of these disturbances.

1.3 Improving EMC-

EMC improvement is achieved through various types of measures [1, 7, 10]:

1 Reducing external sources:

For example, we can reduce disturbances caused by electrostatic discharges by increasing the humidity in the premises, using an antistatic floor, etc.

2. Increasing immunity:

An electronic system can be ‘hardened’ by selecting components that are less sensitive to disturbances (different technology families: TTL, CMOS, etc.).

3. Reducing couplings:

For a given external source, the level of interference received by a device depends on the coupling, i.e. the propagation path between the source and the target.

1.4 Compatibility levels

The fundamental relationship between disturbance level and immunity level. In the same vein, a compatibility level is conventionally defined as the maximum specified value of the disturbance level that may be applied to a device, equipment or system operating under given conditions.

a) Emission:

The generation and propagation of electromagnetic disturbances. Alternatively, ‘emission’ (aerospace standards) or ‘disturbances’ (industrial standards) refer to signals, whether intentional or not, whose propagation is likely to impair the proper functioning of devices or the health of living beings in the vicinity; this is the disruptive power of electrical equipment

b) Immunity:

The satisfactory operation of a device, system or installation in an electromagnetic environment. Alternatively, immunity refers to a device’s behaviour in response to an external disturbance, deemed

incompatible with normal use. Immunity is also referred to as susceptibility (i.e. the ability of a device to be disturbed by external factors).

All electrical equipment is both a source of disturbances (emission aspect) and a victim of disturbances (immunity aspect), and this equipment can emit or receive disturbances via three distinct pathways: by conduction and/or by radiation and/or by ionisation of insulators (mainly air).

1.5 -compatibility margin

To ensure EMC compliance, the electromagnetic environment of the systems must be analysed, i.e. the emission and immunity levels, and their proper functioning must be verified by ensuring they fall within the limits set by EMC standards, as illustrated in Figure 1.3. [7, 13, 18].

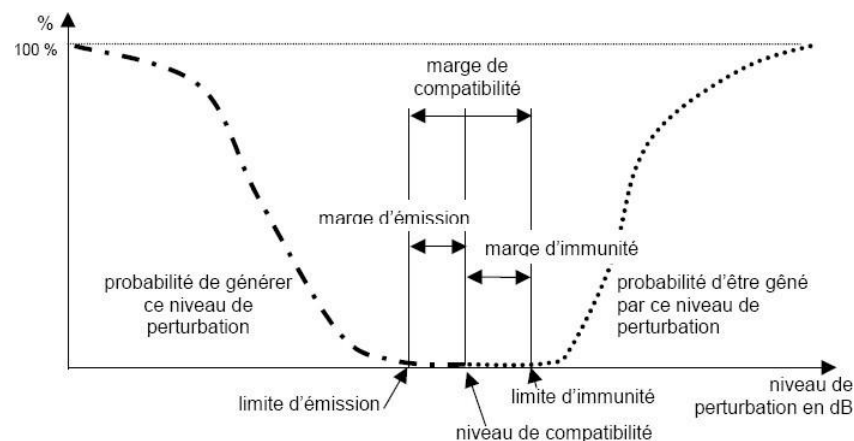


Figure 1.3: Compatibility margin as a function of disturbances.

- 1) **Immunity level:** This is the level at which a piece of equipment or a system begins to malfunction
- 2) **Compatibility level:** This is the maximum level of disturbance that can be expected in a given environment.
- 3) **Emission level:** This is the maximum level of disturbance emission that equipment must not exceed.
- 4) **Immunity margin:** This is the margin between the compatibility level and the immunity limit level.

5) **Emission margin**: this is the margin between the compatibility level and the emission limit level.

The compatibility level should not be regarded as a defined disturbance level, but as a conventional reference value, which will be used as a basis for coordinating the disturbance level and the immunity level (testing).

1.6 Scope of EMC

The scope of EMC is very broad; a distinction is made between [3-7]:

- Physical phenomena (lightning, electrostatic discharges, radiation, conducted currents),
- Areas of application such as telecommunications, space and military equipment, control systems, instrumentation and power electronics, etc.
- The frequency range (from a few Hz to several tens of GHz).

We can therefore identify three main areas of study, as shown in Figure 1.4 [3, 5, 8]:

- Sources of disturbance
- Their coupling and propagation modes
- The effects of disturbances on affected systems, which correspond to the concept of electromagnetic susceptibility.



Figure 1.5: Overview of an EMC problem.

1.7 The aim of EMC-

Electromagnetic compatibility (EMC) is the discipline concerned with studying electromagnetic coexistence issues; its purpose is [3,7]:

- ✓ To investigate unintended energy transfers between electrical and/or electronic systems;

- ✓ To develop methods to increase the immunity of systems to interference within limits that are also subject to regulations.

1.8 Conclusion

This chapter brings together a range of information that enables us to broaden our understanding of the concept of electromagnetic compatibility (EMC) and electromagnetic coupling techniques.

Furthermore, we define the fundamental aspects of electromagnetic compatibility (EMC), how to identify these phenomena and how to classify disturbances. It can be said that EMC is a concept of harmony that facilitates the coexistence of systems or equipment; therefore, EMC is a functional objective.

We have indeed observed that, for a clear understanding of EMC phenomena, the propagation path is of great importance to the subject. We therefore propose, in the next chapter, a detailed study of electromagnetic coupling.

Chapter 2

Sources of Disturbances and Coupling Techniques in EMC

2.1 Introduction

Electrical and/or electronic systems are not isolated from their environment. Electromagnetic energy can therefore unintentionally cross their boundaries, either entering or escaping them. Indeed, electrical or electronic equipment can fall victim to the electromagnetic environment in which it operates. The system's operation is then disrupted.

Every device is subject to various electromagnetic disturbances, and every electrical device generates them. These disturbances are generated in many ways; they are mainly sudden variations in electrical quantities, such as voltage or current.

Electromagnetic interference is the disruption of a system by another circuit or external phenomenon. This chapter presents the main sources of disturbance and the different modes of coupling. We also provide an overview of the mechanism by which disturbances are transmitted. Subsequently, EMC protection techniques are explained.

2.2 Examples of EMC-

- 1) The use of mobile phones can interfere with the proper functioning of certain devices, which is why they are strictly prohibited in hospitals, petrol stations and aeroplanes.
- 2) A modern car contains over a kilometre of electrical wiring; it acts as an antenna that emits and picks up EM waves.

2.3 The main sources of electromagnetic interference

Electromagnetic interference: these are electromagnetic phenomena capable of causing malfunctions in a device, apparatus or system. Such interference may take the form of electromagnetic noise, an unwanted signal or a change in the propagation medium. By examining the electromagnetic environment of an electronic device, we will see that there are various sources of interference from different origins. Disturbances of natural origin and sources of disturbance due to human activity. When analysing an electromagnetic disturbance, we find that the problem encompasses three elements, as shown in Figure 2.1 [7, 35, 39].

- 1) **Source:** Disturber characterised by its emission,
- 2) **Victim:** Disturbed element characterised by its immunity or susceptibility,

3) **Coupling:** Propagation medium or coupling path.

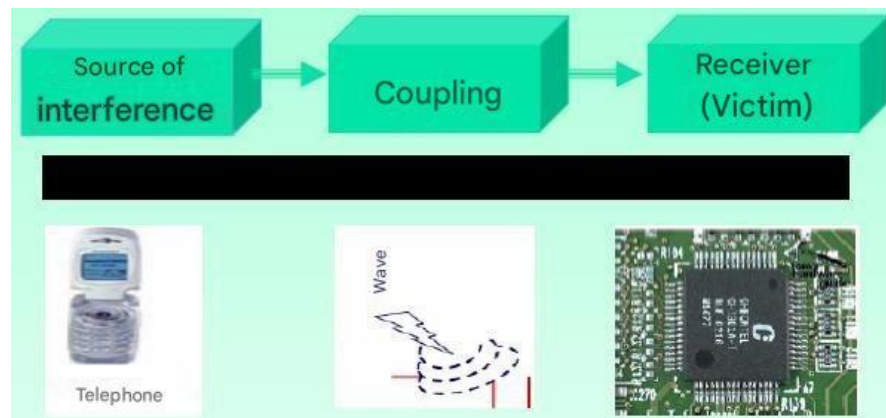


Figure 2.1: Electromagnetic disturbance.

2.4 Sources

Any device that emits an electromagnetic disturbance, whether by conduction or radiation, is classified as a source. Among the main causes of disturbances are the distribution of electrical energy, radio waves, electrostatic discharges and lightning.

When considering the electromagnetic environment of a system, we will see that there are various sources of interference of different origins.

Disturbances of natural origin (lightning, electrostatic discharge, solar activity, cosmic sources, etc.); however, the majority of sources are man-made.

These are also referred to as industrial noise (artificial noise). Among these sources, some are:

- ✓ **Intentional:** radio transmitters, mobile phones, microwave ovens, induction cookers, , arc furnaces, arc welding, discharge lamps.
- ✓ **Unintentional:** ignition systems for internal combustion engines, all systems for switching an electrical signal on and off, discharge lamps, control and power electronics, protection electronics, power equipment, high-power commutator motors, starting of all types of high-power electric motors.

Rather than classifying them according to their origin, it is more appropriate to examine their temporal and frequency behavior. This is what determines their impact.

We shall mention a few major sources of disturbance: continuous disturbances and intermittent disturbances.

2.4.1 Permanent

By definition, a permanent source emits disturbances for as long as the device containing that source is in operation.

2.4.2 Intermittent sources of

An intermittent source emits disturbances only sporadically, often unpredictably, at intervals ranging from a few seconds to several days. Table 2.1 [35, 37, 38] summarises the various sources of noise.

Table 2.1: The various sources of noise.

Sources	Examples
Permanent sources (fixed frequency)	-Radio transmitters -Radars -Noise from electric motors -Fixed and mobile communications -Computers, monitors, printers -Rectifiers
Transient sources (wide frequency band)	- Lightning -Nuclear pulse of storm origin -Faults in power lines - Power cuts -Electrostatic discharge (circuit breakers)
Permanent sources (wide frequency band)	-Electronic systems - Microprocessors

The main disturbance phenomena considered by EMC are [1, 10, 17]:

- Magnetic and electric fields,
- Harmonics,
- Voltage fluctuations,
- Brief power cuts and voltage dips,
- Three-phase voltage imbalances,
- electrostatic discharges and lightning strikes,
- Signal transmission over networks,
- Power supply frequency variations,

- DC components on AC networks,
- Surge voltages and currents and high-frequency disturbances.

2.5 Mechanism of disturbance transmission

Identifying the mode of disturbance transmission is essential for a proper analysis of EMC phenomena.

In the classic diagram shown in Figure 2.2 [19, 24] (sources, paths and victims), in EMC analysis, disturbance generators, or sources, act upon a victim via propagation paths. EMC modelling therefore consists of representing these three components as accurately as possible.

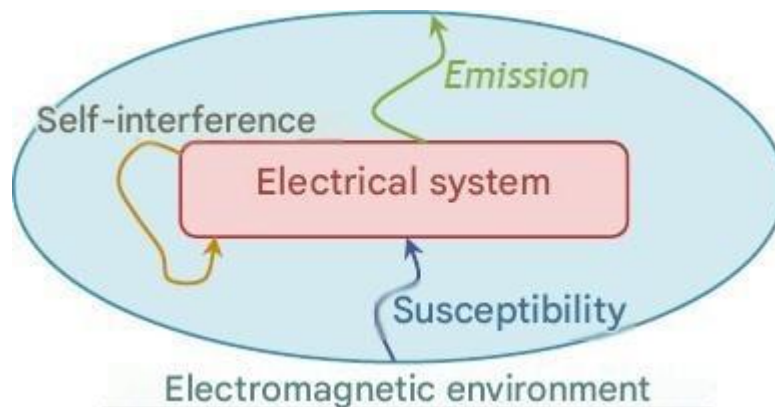


Figure 2.2: Representation of the three EMC components.

2.5.1 Coupling of disturbances ()

Coupling (the propagation path) refers to the connection, passage or transmission of electromagnetic disturbances from the source to the victim, i.e. the process by which the energy from the disturbance reaches the victim.

Disturbances are coupled in two ways: either by conduction or by radiation [1, 4, 7, 31].

a) Conducted disturbances: signal transmission via a conductor uses conductive materials as a medium.

b) Radiated disturbances: are transmitted by an electromagnetic wave (electric field, magnetic field, electromagnetic field) and use dielectric media as a medium.

In the first case, the disturbances occur either in common-mode (CM) or differential-mode (DM). In the second case, the disturbances are radiated either in far-field coupling mode or near-field coupling mode.

2.5.1.1 Differential mode ()

Useful signals are generally transmitted in differential mode (denoted DM), also known as serial mode (symmetrical mode). The current propagates along one of the conductors, passes through the device, and returns to the source via another conductor, as shown in Figure 2.3 [4,7].

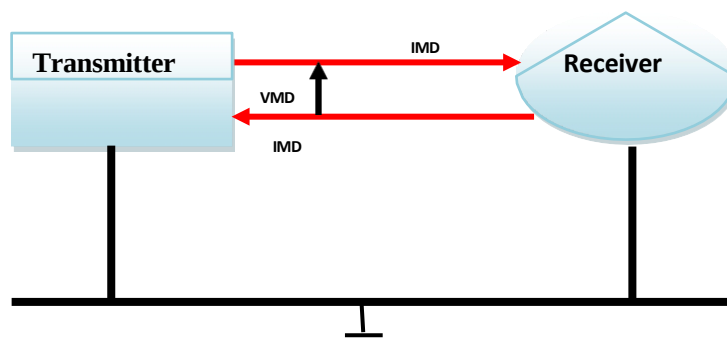


Figure 2.3: Transmission of disturbances in differential mode.

2.5.1.2 Common-mode

Common-mode (denoted CM) is rarely used for useful signals; it often corresponds to a spurious mode. It is also known as parallel mode (asymmetric mode). The current flows in the same direction through all conductors and returns via earth, as shown in Figure 2.4 [4, 7, 22].

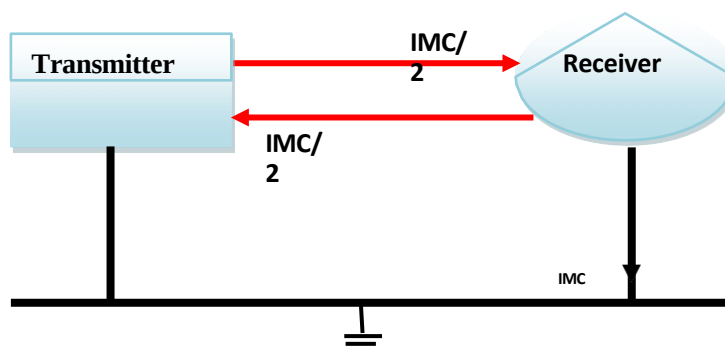


Figure 2.4: Transmission of common-mode disturbances.

Common-mode voltages develop between the connecting wires and the potential reference: device earths, PE equipotential bonding conductor.

2.5.1.3 Radiated disturbances in the near- e field

Near-field coupling, as the name suggests, is the type of coupling that occurs when the radiation source and the affected device are very close together and exchange energy, with the effect being measured in the immediate vicinity of the source

It is clear that as the energy emitted by the source disperses into a volume that increases continuously with the distance D from the source, the amplitudes of the electric field E and magnetic field H decrease as this distance D increases [7,11,32–36] (Figure 2.5). The diagram is based on the variation of the wave impedance as a function of the distance separating the radiation source from the point at which the radiated field is characterised. The wave impedance is defined

by the ratio of the magnitude of the electric field to the magnitude of the magnetic field ($Z = \frac{E}{H}$).

Indeed, for a distance less than $\frac{\lambda}{2\pi}$ from the source (λ is the wavelength of

propagation), the electric and magnetic fields have ‘independent’ components. They can be considered quasi-stationary and exhibit a rapid decay of the

amplitudes (in $\frac{1}{D^2}$ or $\frac{1}{D^3}$).

In the case where the wave impedance ($Z = \frac{E}{H}$) is less than the characteristic impedance

of free space ($Z_0 = 377 \Omega$), we refer to a low-impedance field (the dominant magnetic field).

Typically, these are fields generated by a current source. In the case

where the wave impedance is greater than the impedance z_0 , we refer to a high-impedance field (the dominant electric field).

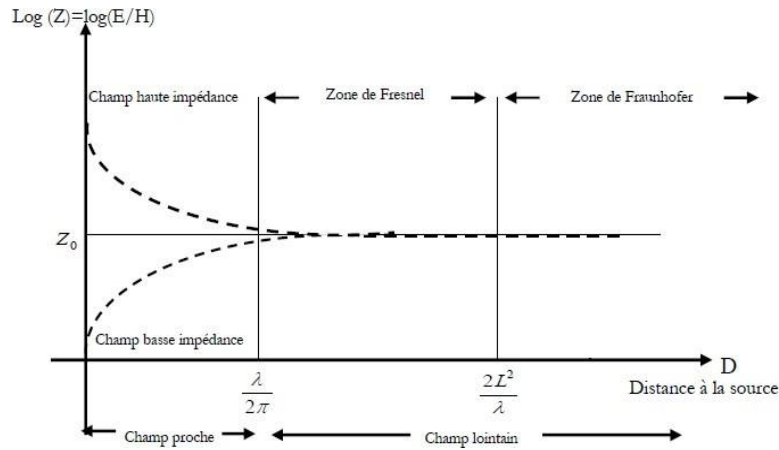


Figure 2.5: Field impedance diagram.

2.5.1.4 Radiated disturbances in the far-field

As we can see in Figure 2.5 above, as we move away from the source, the process of energy exchange between the two fields cancels out this initial difference, until an energy equilibrium is reached between the two fields. We thus have:

$$\xi_0 \frac{E^2}{2} = \mu_0 \frac{H^2}{2} \quad (2.1)$$

The ratio of the amplitudes of the electric and magnetic components of the electromagnetic field is constant, as shown in Figure 2.5.

$$E / H = (\xi_0 / \mu_0)^{1/2} = 377\Omega \quad (2.2)$$

Where:

$\xi_0 = (1 / 36\pi \cdot 10^9) \text{ F.m}^{-1}$, $\mu_0 = 4\pi \cdot 10^{-7} \text{ H.m}^{-1}$ are, respectively, the permittivity and permeability of free space.

The ratio given in equation (2.2) is called the characteristic impedance (z_c) of the propagation medium.

The Fresnel zone lies between $D = \frac{\lambda}{2\pi}$ to $\frac{2L^2}{\lambda}$, where the impedance Z corresponds

almost exactly to z_0 . The radiation pattern depends on the distance D .

For $D \succ \frac{2L^2}{\lambda}$, this is the Fraunhofer zone; the fields are coupled and form a transverse electromagnetic (TEM) wave, i.e. the fields are orthogonal

to each other and also to the direction of propagation. The radiation pattern is independent of distance and the fields decay as $(1/D)$.

2.6 -coupling modes

Couplings are the modes of action of electromagnetic interference (EMI) on the affected equipment. From the diagram in Figure 2.6, we can clearly see that for coupling to occur, at least two pieces of equipment must be present: one that generates spurious signals (the source, the aggressor), and another that is affected by the interference (the victim).

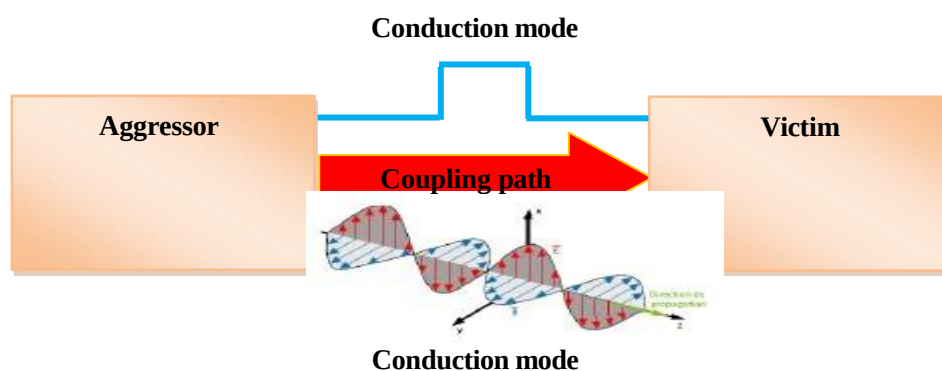


Figure 2.6: Illustration of an EMC problem

In fact, we distinguish between the following five coupling modes [1-5,7]:

- ✓ common-impedance coupling,
- ✓ inductive crosstalk coupling,
- ✓ capacitive crosstalk coupling,
- ✓ wire-to-wire coupling,
- ✓ loop field coupling.

The first is conductive coupling (through a resistor or inductor), and the last four are electromagnetic field radiation couplings.

2.6.1 Common- -impedance coupling

Common impedance coupling (or common element or galvanic coupling) As the name suggests, this coupling results from the presence of an impedance common to two or more circuits. It occurs when a current flows between two subsystems of an electrical system through

common impedances formed by connections between the two subsystems. This common impedance may be the earth connection, the earth network, the

power distribution network, or the return conductor for multiple signals in the same low-current link. It is important to note that common-impedance coupling occurs when two loops share a section of conductor whose impedance cannot be neglected.

Figure 2.7 shows an example of common-impedance coupling

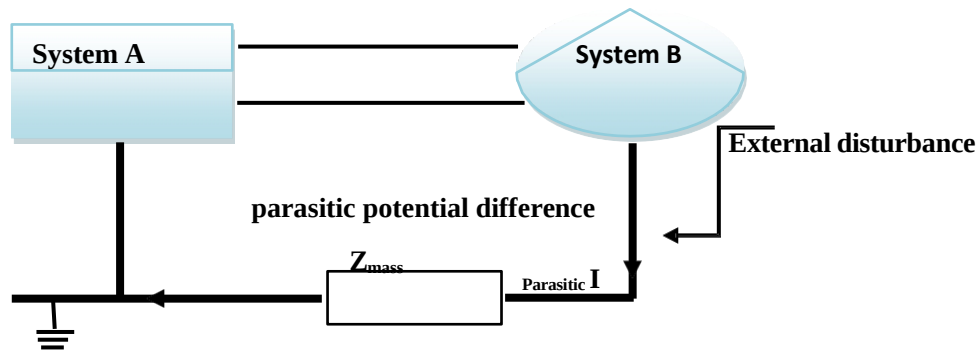


Figure 2.7: Common-impedance coupling (common-mode).

The figure shows an example of two devices connected to the 230V mains supply: a source of interference that generates parasitic voltages on the mains supply, and a victim device that uses the mains supply and simultaneously picks up this parasitic voltage.

To improve EMC, the following methods may be used [1, 7, 11]:

- Avoid common sections,
- Connect the grounds at a single point,
- Reduce impedances, for example by widening the traces.

2.6.2 -field coupling

Near-field coupling, as the name suggests, is the type of coupling that occurs when the radiation source and the affected component are very close together and exchange energy. In this type of coupling, we often speak of mutual disturbance or interference. This results in two cases of near-field coupling:

- ✓ Inductive crosstalk coupling:
- ✓ Capacitive crosstalk coupling or electric field coupling

2.6.2.1 Inductive crosstalk coupling

It should also be noted that any varying current flowing through a conductor will create a magnetic field around it. The resulting flux variation will create parasitic induced voltages in the loops formed by the conductive cables adjacent to the interfering cable.

Inductive crosstalk coupling [4,5]: corresponds to an electromagnetic disturbance produced by the varying magnetic field radiated by a circuit (source) which will disturb another neighbouring circuit (victim) behaving as a loop. Inductive crosstalk is characterised by the effect of a varying parasitic voltage across the victim.

An illustration of this near-field coupling mode is shown in Figure 2.8.

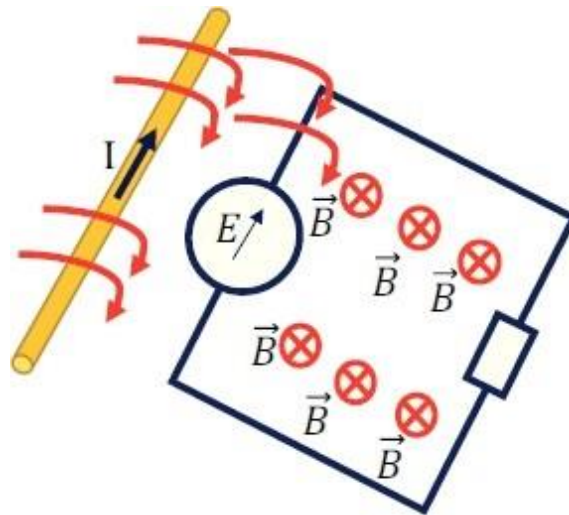


Figure 2.8: Coupling via inductive crosstalk.

Techniques for improving EMC (remedies) can be classified as follows [1,4]:

- ✓ Limit currents (sources of disturbance), limit current variations in conductors (the dI/dt component).
- ✓ Reduce mutual interference between wires by separating the interfering conductors from the sensitive conductors: wire power and control wires separately, ensure a good distribution of conductors within ribbon cables whilst increasing the number of 0 V conductors.
- ✓ Minimise the value of the induced voltage; the induced currents in the affected conductor are lower if the impedance of the loop formed by that conductor is high; increase the terminating impedance of the connections.

2.6.2.2 Crosstalk coupling -capacitive

There is always a parasitic capacitance between two closely spaced conductors at varying potentials.

Capacitive crosstalk coupling is created by a voltage variation between two facing conductors. The parasitic capacitance formed by the two conductors will present a low impedance at high frequency to this potential difference (d.d.p.) and allow a parasitic current to flow.

Figure 2.9 illustrates the basic principle of capacitive crosstalk.

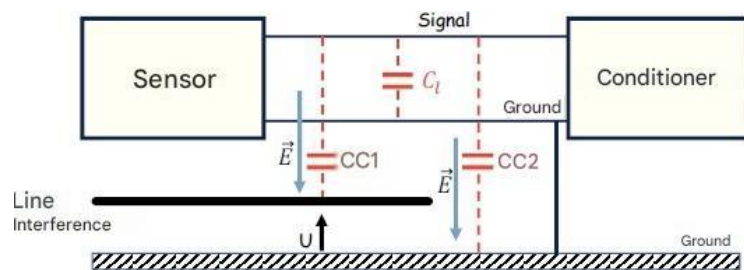


Figure 2.9: Capacitive crosstalk coupling.

Capacitive crosstalk is an electromagnetic disturbance caused primarily by the electric field radiated by a conductor, which interferes with another nearby conductor. The source of the disturbance is coupled to the desired signal via a capacitive link. Under these conditions, another signal—the spurious signal—is superimposed on the desired signal.

In this case, the main remedies are [1,7]:

- ✓ Separating the interfering and affected cables, and designing interface circuits with the lowest possible impedance.
- ✓ Minimising the voltages that cause interference, limiting voltage variations across the wires (dV/dt).
- ✓ Minimise the capacitance between wires; parasitic capacitance can be reduced by moving interfering wires away from sensitive wires, and avoid parallel wires.
- ✓ Isolate the conductors from one another

2.6.3 Far- e field coupling

Two types of coupling can be distinguished in the far-field region: these are wire-to-wire coupling, also known as cable-to-cable coupling, and loop-to-loop coupling.

2.6.3.1 Wire-to- field coupling

When a conductor is subjected to a varying electric field, a parasitic electrical signal is generated within that conductor. The varying electric field generates a varying parasitic voltage (of the same frequency) across the conductor, which superimposes on the useful signal. Wire-field coupling is characterised by an increase in the amplitude of the useful signal in the circuit.

Figure

2.10 shows wire-field coupling.

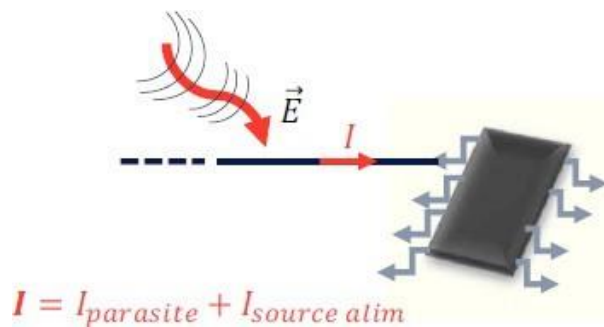


Figure 2.10: Field-to-wire coupling

In this mode of coupling, to improve EMC, the following measures must also be taken [3,8]:

- ✓ Reduce interference fields by using shielding and ground planes
- ✓ 2. Reduce the antenna effect by orienting conductors according to the polarisation of the incident fields, and by reducing the length of sensitive traces.

2.6.3.2 Field-to-loop coupling

This is a type of EM disturbance caused by the effect of a varying magnetic field in a loop. Across the surface of the loop, formed for example by a conductor, a varying magnetic field is

observed. The variations in this field induce an electromotive force. Figure 2.11 shows field-to-loop coupling

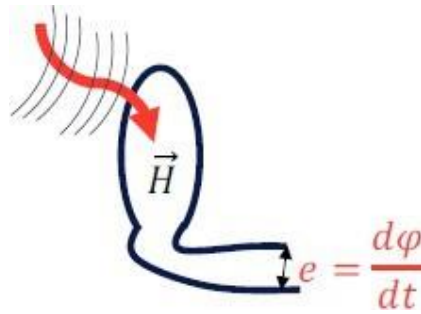


Figure 2.11: Field-loop coupling

In fact, for this type of coupling, the remedies are [31, 35, 37]:

- ✓ Reducing disruptive fields; it is essential to note the difficulty of shielding against low-frequency magnetic fields, as this requires the use of materials with high permeability μ , which are very expensive. At high frequencies, shielding is achieved using conductive materials in which eddy currents that create a field opposing the incident field.
- ✓ Reducing the antenna effect by reducing the surface area of the affected loop or, if possible, by pairing the conductors.

2.7 Conclusion

In this chapter, we have presented the sources of electromagnetic interference as well as the various types of coupling, as ultimately one of the best ways to resolve EMC issues is precisely to minimise these couplings as much as possible.

These couplings are caused either by the effect of an electric/magnetic field radiated by one of the components or by the effect of a parasitic signal coupling that will interfere with another neighbouring component. In the next chapter, we shall therefore examine EMC standards and measurements.

Chapter 3

EMC Standards and Measurements

3.1 Introduction

In recent years, electromagnetic compatibility has become a regulatory requirement with the introduction of numerous national and international standards that set the emission and susceptibility levels which electrical equipment must comply with.

At European Economic Community (EEC) level, regulations are drawn up by the various Technical Committees (TCs) of the European Committee for Electrotechnical Standardisation (CENELEC).

3.2 Definitions and objectives of EMC standards

EMC applies to all sectors of electronics and electricity. It covers all frequencies, from direct current to GHz.

All electronic devices, equipment or systems – for example, in a PC – must be EMC-compliant; the PC itself must be compliant, and in a network comprising several PCs and various electronic devices, the entire system must meet EMC standards.

The main objective of the standards is to characterise as precisely as possible the conducted and radiated measurement environment, the measurement conditions (cable length, antenna distance, height, angle, etc.), and the calibration and adjustment of the measuring instruments used, with the aim of carrying out reproducible and reliable measurements. We therefore distinguish between two main categories of standards: those that define the permissible levels of conducted or radiated emissions, and those that define the electromagnetic susceptibility of equipment, namely its tolerance to electromagnetic disturbances.

3.3 Standards

The requirements regarding the limits of disturbances caused by electrical equipment are set out in EMC standards. These standards are formulated at international level by the International Special Committee on Radio Interference (CISPR).

3.3.1 Definitions

A standard is a collection of rules, descriptions and methodologies that a manufacturer can use as a reference when defining and testing one of its products.

There are three types of EMC standards:

- 1) Fundamental standards,
- 2) Generic standards, setting out the basic limits and methods generally applicable to all equipment,
- 3) Product or product family standards.

Generic standards: These are standards or guides that generally define the requirements relating to EMC (phenomena, tests, etc.). They apply to all products and serve as a reference, particularly for committees tasked with developing specific standards. Fundamental standards will not be harmonised at European level.

Generic standards: These standards define the essential requirements in terms of the level to be achieved for each type of test, drawn from the fundamental standards. In the absence of product or product family standards, they apply to any product installed in a defined environment.

Product or product family standards: These standards define the applicable design requirements, characteristics, test methods and test levels for specific products or product families. Where they exist, these standards take precedence over generic standards.

3.3.2 standardisation bodies

At European Economic Community (EEC) level, regulations are drawn up by the various Technical Committees (TCs) of the European Committee for Electrotechnical Standardisation (CENELEC). European Directive No. 89/336/EEC stipulates that in all EEC member states, equipment capable of generating electromagnetic disturbances or whose operation may be

affected by such disturbances may only be marketed in EEC countries if it complies with EMC specifications. This directive came into force on 28 October 1992. At international level, the International Electrotechnical Commission (IEC) established a special committee, the International Special Committee on Radio Interference (CISPR), to formulate EMC standards. CISPR publications are generally used by different countries as a basis for establishing their own standards.

CISPR: International Special Committee on Radio Interference,

IEC: International Electrotechnical Commission in Geneva,

CENELEC: European Committee for Electrotechnical Standardisation in Brussels

50155

EN50155 is the European standard for railways (rolling stock) and is commonly accepted worldwide.

AC

Alternating current. Single-phase mains (115V in the USA, 230V in Europe) alternates its polarity 60 times a second (USA) or 50 times a second (EU).

Air Dis- charge

A method for testing ESD protection, in which the ESD generator creates a spark, which arcs over to the device under test (DUT).

Antenna Factor

Antenna Factor is the ratio of the incident electromagnetic field to the output voltage from the antenna (gain).

Amplitude Modulation (AM)

A broadcast signal that varies the amplitude of the carrier wave to carry the signal information. It is used by AM broadcast stations and requires an AM receiver. The AM frequency range is 530 to 1710kHz.

ANSI

American National Standards Institute

Balanced Line

Balanced lines are less prone to interference than unbalanced lines. One of the signal wires carries the signal, while the other carries an out-of-phase inverted duplicate. When the signal reaches the destination, the inverted duplicate is flipped and added to the original. Any noise added by interference is also inverted. When combined with the non-inverted noise, the two noise signals cancel each other.

Bandwidth

Bandwidth (BW) is a range of frequencies or information that a circuit can handle or the range of frequencies that a signal contains or occupies. When measuring low-frequency ripple and noise, high-

frequency interference can give false readings; so, for example, the input of oscilloscopes is often restricted to a bandwidth of 20MHz using a special filter: “20 MHz B/W Restricted”.

Bass

The lower end of the music scale: 60-250Hz.

3-Phase

In a three-phase power supply system, three live conductors carry an alternating current of the same frequency and voltage but with a phase difference of one-third the period (120°). The common reference can be earth because if the load is the same on all three phases, the net result will be zero. Therefore, a neutral connection is not required (L1/L2/L3 + PE), compared to single phase, which has only L, N, and PE connections.

62368-1

The replacement for the IEC 60950-1 standard. The standard is Hazard-Based (HB), which means that in addition to the electrical and fire safety tests, an extra risk assessment must be conducted to safeguard against any serious consequences of faults and abuse.

60601-1

The main safety standard that covers medical-grade power supplies. The international (IEC60601-1), North American (AAMI/ANSI 60601-1), and European versions (EN60601-1) of the standard are all very similar but carry separate certificates. The current version is the third edition (3rd Ed.)

60601-1-2

The main EMC standard that covers medical-grade power supplies. The current version is the fourth edition (4th Ed.)

61010-1

The main safety standard that covers measurement, control, and laboratory equipment. This standard has UL, CSA, IEC, and EN versions.

61010-2-201

The safety standard that covers the particular requirements for control equipment. UL 61010-2-201 replaces the popular UL 508 standard.

60355-1

The main safety standard that covers Safety of Household Equipment (often also required by building automation applications). This standard has UL, IEC, and EN versions.

3.3.3 Examples of CISPR publications

CISPR 11-1990 Limits and methods of measurement of electromagnetic disturbance characteristics of industrial, scientific and medical (ISM) at radio frequencies.

CISPR 14-1993 Limits and methods of measurement of radio disturbance emissions from household and similar electrical appliances incorporating motors or thermal devices, from portable electric tools and from similar electrical appliances.

CISPR 16-1993 Specifications for methods and apparatus for the measurement of radio disturbance and immunity to radio disturbance, Part 1: Apparatus for the measurement of radio disturbance and immunity to radio disturbance.

3.4 Examples of EMC standards

Generally speaking, the characterisation of radiated electromagnetic emissions involves measuring the level of the electric field and/or magnetic field generated by a device. It also involves identifying the component causing the most interference (radiation) on a target (e.g. a printed circuit board).

EMC characterisation methods and techniques are the tools and procedures used to characterise the emission and susceptibility of a system or component in radiated or conducted modes.

There are three approaches in the literature for characterising electromagnetic emissions radiated by a circuit or an integrated electronic component [6, 9, 11]:

- ✓ The first involves performing numerical calculations on the component using appropriate simulation software,
- ✓ The second involves carrying out experimental measurements on a real device,
- ✓ The third involves analytically modelling the electromagnetic field radiated by the device under test.

In this section, we will look at an example of the description of measurement methods for certain standards. Consider standard 55022, which covers an important category of electrical equipment: information processing equipment. This standard is directly derived from CISPR Publication No. 22 and distinguishes between two classes of equipment:

- ✓ Class A equipment, which is intended for use in industrial, commercial or business environments;
- ✓ Class B equipment, which is intended for use in residential premises. Disturbance levels

are given on a logarithmic scale in $dB\mu V$.

$$\text{As follows: } dB\mu V (V) = 20\log\left(\frac{V}{10^{-6}}\right) \quad (3.1)$$

Figure 3.1 [5,7] below shows an example from the EN 55022 standard; here we can see that Class B has significantly stricter limits than Class A. Designers of electrical equipment aim to meet Class B criteria, as this allows them to cover a wider market by reducing the need for filtering measures compared to meeting only Class A requirements.

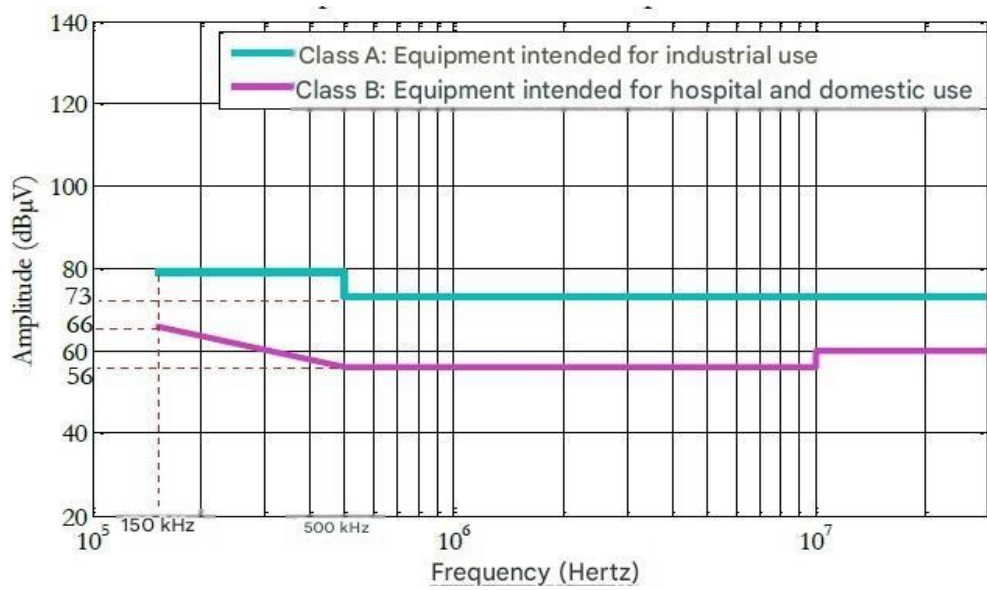


Figure 3.1: Levels of conducted disturbances set by the EN 55022 standard

3.5 EMC- al instrumentation and methods

Compliance with regulations requires measurements and tests, which are themselves defined by standards. The aim is to test equipment for immunity and emissions in both conducted and radiated modes. In this context, a number of instruments or facilities are required, including:

- Environmental test facilities (free-field, Faraday cage, anechoic chamber, mode-mixing chamber, turntables, etc.)
- Measurement equipment (spectrum analyser, RF power meter, RSIL, antennas and field strength meters, etc.).
- Disturbance generators (DES gun, capacitive clamp, RF power amplifier).

Furthermore, a distinction must be made between two types of tests that can be carried out on a product using appropriate equipment [12,21].

a) Type tests: These are tests carried out by the manufacturer to qualify their products prior to marketing

b) On-site tests: These are tests carried out on the equipment in which the product is incorporated. They are conducted under the responsibility of the integrator and are intended to validate an installation, a piece of equipment or a machine.

c) Test methods: The methods and procedures for carrying out these tests are described in detail in the standards.

3.5.1 Line Impedance Stabiliser Network (RSIL)

The Line Impedance Stabilisation Network (LISN) is a filter inserted between the device under test and the power supply network. It serves a dual purpose. It must isolate the network—which may be subject to common-mode and differential-mode disturbances—from the equipment under test. However, at mains frequency, it must exhibit an output-to-input voltage drop of less than 5% of the nominal voltage when carrying the nominal current. This equipment, which is virtually indispensable in EMC testing, ensures the reproducibility of measurements and helps to define, in part, the measurement conditions across the standard frequency range (150 kHz–30 MHz). Several RSIL configurations exist in accordance with the specifications of the standards [7, 23]. Figure 3.2 shows a schematic diagram of a single-phase RSIL.

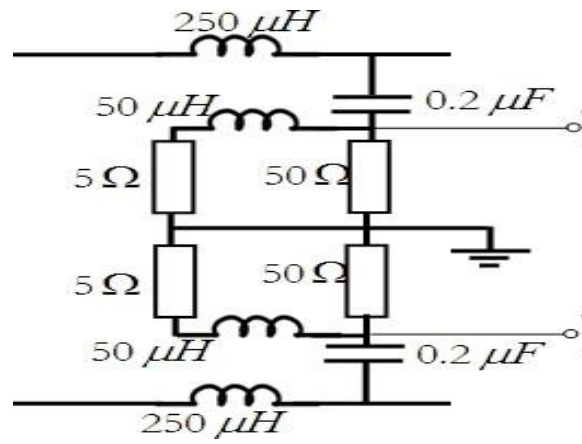


Figure 3.2. Schematic diagram of a single-phase RSIL.

Finally, it must present a constant termination impedance with respect to high-frequency disturbances emitted by the device under test, in both common-mode and differential-mode, and this regardless of the impedance presented by the power network. This impedance is standardised by CISPR. The standard defines the limits of variation for this impedance, measured between an output terminal and earth in the frequency range 10 kHz–100 MHz. This range is divided into three bands (A, B, C). The equivalent circuit for each band is shown in Figure 3.3 [15, 42, 43]. However, there are three approaches

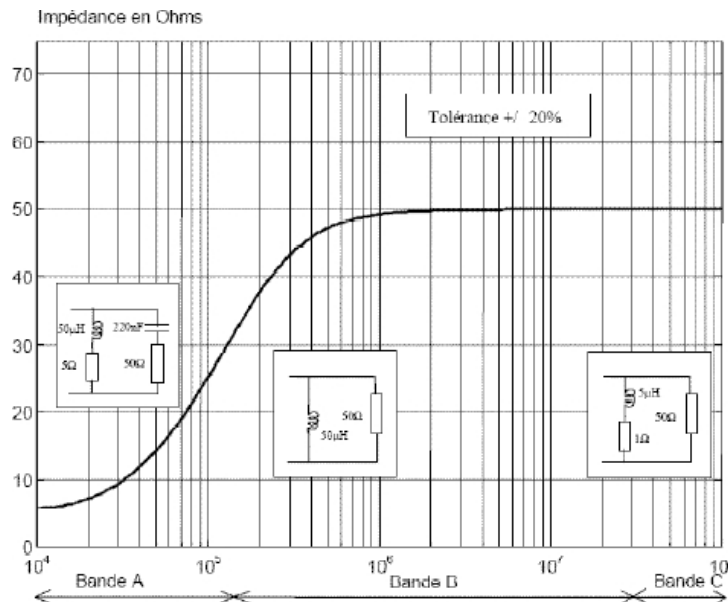


Figure 3.3: Single-phase RSIL impedance from the previous figure.

In the literature, there are several methods and means (measurement equipment) for experimental characterisation, such as: MC/MD splitters, current sensors, isotropic probes,

spectrum analysers, antennas, TEM cells, GTEM cells: High-Frequency variant of the TEM cell.

Most of these methods are standardised by the International Electrotechnical Commission (IEC). In this handout, we focus specifically on the means and methods of emission characterisation to illustrate the mechanisms of conducted emissions in electronic energy conversion structures; the case studied, which we will cite as an example, involves sources of conducted disturbances in power electronics, with these disturbances related to waveform characteristics (switching, synchronisation, etc.), which is the subject of the following section.

3.6 Power electronics and EMC

Electronic energy conversion systems are ideally suited to illustrating the mechanisms of conducted emissions. EMC analysis tends to show that it is necessary to limit rapid variations in electrical quantities (voltage, current) and electromagnetic quantities (fields), whereas switching structures generate abrupt variations, in order to manage the desired energy transfer with minimal losses [10, 12, 14, 16, 38, 41].

In this example, we have proposed an EMC analysis of static power structures, following the classic source-path-victim triad.

As shown in Figure 3.4 [10,12], the diagram reflects the spectral richness of power structures, ranging from harmonics of the mains frequency to the equivalent frequencies of the voltage and current fronts generated by switching.

The switching cell, the basic building block of static converters [10], acts as a generator. Indeed, the switching cell, which is easily identifiable in non-isolated structures, consists of two switches, whether controlled or not. It is the site of high voltage and current gradients. The idealised waveforms, as shown in Figure 3.5 [10], reflect these abrupt variations.

The switching phases would have little or no impact if there were no coupling between the switches and their immediate surroundings. One of the most detrimental forms of coupling is defined by the parasitic capacitance linking the potential of the heat sink—which is generally earthed—to the varying potential of the transistors in the cell.

The example of power MOSFETs shown in Figure 3.6 [10], in a TO220 package, is characteristic because the metal backplate of these devices is at the drain potential of the component. The thickness and permittivity of the insulating film (e.g. Mylar, $\epsilon_r = 2.5$) between this metal substrate and the heat sink then determine this parasitic capacitance, which provides significant common-mode coupling.

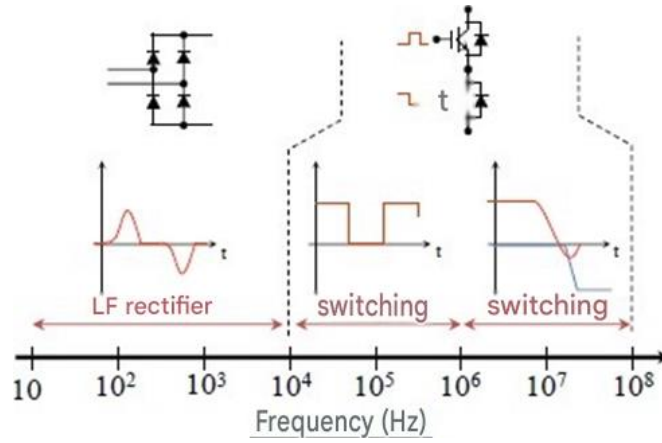


Figure 3.4: Typical spectral range associated with power electronic structures.

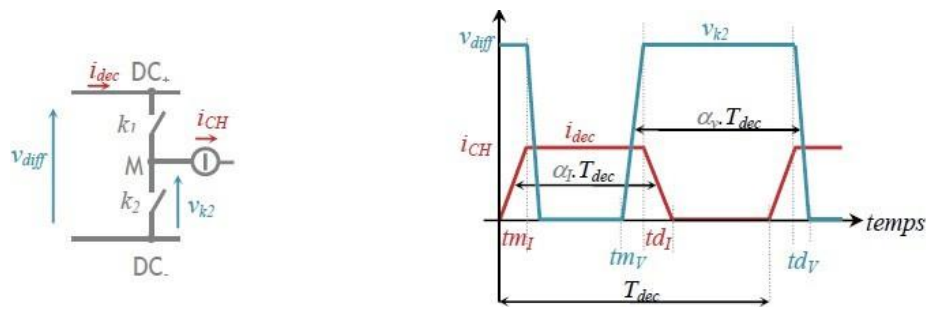


Figure 3.5: Switching cell and associated theoretical waveforms.

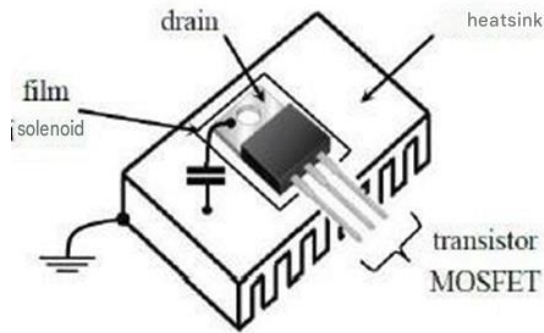


Figure 3.6: Capacitive coupling between transistor and heat sink.

3.6.1 Analysis of a switching cell in common-

To estimate conducted emissions, we adopt a specific representation in which the switching switches are replaced by localised generators [1, 10, 12], whose generated voltages and currents propagate via various common-mode and/or differential-mode paths.

Study of the generic diagram of a non-isolated structure with a switching cell, shown in Figure 3.7.

The input stage is deliberately left undefined; we are only interested in the operation of the switching cell and the common-mode voltage it generates. To simplify the analysis and determine the equivalent common-mode generator, a number of assumptions are necessary [10, 12, 14, 28, 29, 30]:

- The differential and common-mode are completely decoupled; there is no conversion from one to the other,
- The main common-mode coupling is defined solely by a common-mode impedance z_{CM} between the midpoint of the switching cell and earth (the converter load does not provide a simpler propagation path for the common-mode current),
- The voltages v_1 and v_2 between the DC bus and earth are defined indirectly by the input stage of the structure; they are related to the topology of this part of the system.

As shown in the general diagram in Figure 3.7, the currents and voltages denoted (i_{k1}, i_{k2}) and (v_{k1}, v_{k2}) describe the electrical state of the two switches regardless of their technology (diode, transistor). This deliberately idealised representation allows for a simple and accessible formulation of the equations [10, 25, 26, 27].

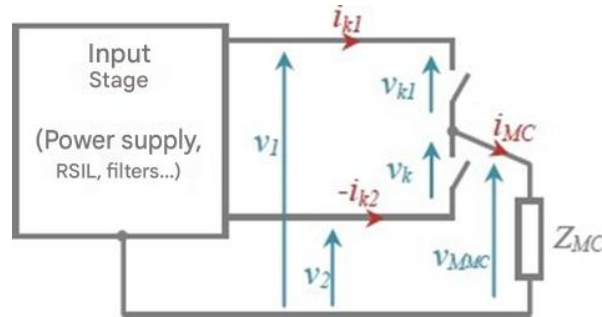


Figure 3.7: Common-mode switching cell.

The first step is to express the voltage between the midpoint of the cell, whose potential varies significantly, and earth in terms of the other voltages in the cell. This expression for the voltage between the midpoint of the cell during MOSFET switching is given by equation (3.2):

$$v_{M_{MC}} = \frac{v_1 + v_2}{2} + \frac{v_{k1} + v_{k2}}{2} \quad (3.2)$$

The various cut-off voltages present across the switches are defined by the differential-mode voltage v_{diff} . By definition, this corresponds to the DC bus voltage, but measured across the cell terminals. Accurately determining this voltage is not straightforward, as it depends on the voltage drops associated with the parasitic currents flowing through the impedances of the power bus. This interaction, generally described as second-order, cannot be accounted for using the simplified model proposed in this resource; only a model employing an iterative solution can take it into account.

$$v_{M_{MC}} = \frac{v_1 + v_2}{2} + \frac{2 \cdot v_{k2} - v_{diff}}{2} \quad (3.3)$$

Where $v_{diff} = v_1 - v_2$ (3.4)
e:

We also know that v_{k2} is defined in terms of the control strategy of the structure represented by the modulation function f_{sw} , as indicated by equation (3.5), and the voltage across the two switches v_{diff} , as shown by equation (3.6).

$$f_{sw} = \begin{cases} 1 & \text{For } k1 \text{ closed, } k2 \text{ open} \\ 0 & \text{For } k1 \text{ open, } k2 \text{ closed} \end{cases} \quad (3.5)$$

$$v_{k2} = f_{sw} \cdot v_{diff} \quad (3.6)$$

The common-mode current i_{MC} , which can be easily expressed in terms of the admittance relative to **ZMC**, denoted Y_{MC} , as shown in equation (3.7), results from the contribution of two specific voltages: the first represents, by definition, the common-mode voltage of the DC bus

closest to the cell, and the second clearly reflects the switching operation as it depends directly on the switching control law.

$$i_{MC} = Y_{MC} \left(\frac{v_1 + v_2 - f_{MC} \cdot v_{diff}}{2} \right) \quad (3.7)$$

Following a similar approach, analysis of the currents on the DC bus upstream of the cell reveals a current flowing in differential mode (Figure 3.8).

For this, the assumption of decoupling this mode is still necessary and implies that only differential-mode currents exist.

Given that:

$$i_{DM} = \frac{i_1 - i_2}{2} \quad (3.8)$$

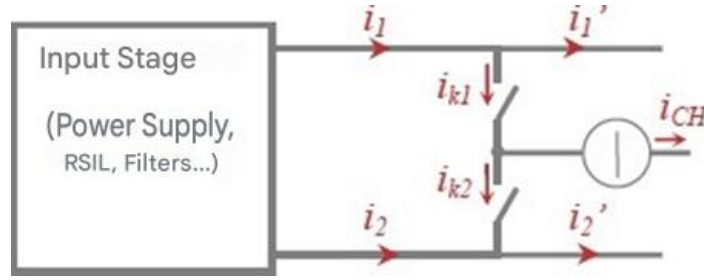


Figure 3.8: Switching cell in differential mode.

Applying equation (3.8), the current i_{MD} is given by equation (3.9).

$$i_{MD} = \frac{1}{2} \frac{I' - i'}{2} + \frac{i_{k1} + i_{k2}}{2} \quad (3.9)$$

The currents in the switches are naturally complementary and are expressed in terms of the current i_{CH} . The expression for the current i_{MD} is therefore written in terms of i_{CH} as: the expression

of the equation:

$$i_{MD} = \frac{1}{2} \frac{I' - i'}{2} + \frac{2i_{k1} + i_{CH}}{2} \quad (3.10)$$

This demonstration allows us to draw conclusions similar to those for the differential-mode current flowing on the DC bus, in the same way as for the common-mode voltage.

It is characterised by the contribution of two terms: one represents the differential-mode current downstream of the cell, and the second is defined by the switched current, as it is expressed in terms of the current through a switch. To simplify this expression and arrive at a relationship that is ultimately obvious, we note that the term downstream of the cell can also be written in terms of the load current i_{CH} , as shown in equation (3.11).

Equation (3.10) is considerably simplified by equation (3.12).

$$I'_1 + \frac{i'}{2} = -i_{CH} \quad (3.11)$$

$$i_{MD} = \frac{i'}{2} + I_{K1} \quad (3.12)$$

The current in the switch is directly related to the load current i_{CH} via the modulation function f_{SW} .

Equation (3.13) finally gives the relationship between the desired current and the load current chopping:

$$i_{MD} = \frac{i'}{2} + f_{SW} i_{CH} \quad (3.13)$$

3.6.2 Modelling of a switching- cell*

As shown by the main expressions (3.7) and (3.13), the study of conducted emissions from a structure in which the switching cell is clearly defined can be approached in a relatively straightforward manner. Ultimately, this involves establishing an equivalent linear circuit in which the switches no longer appear. These are simply replaced by localised sources, allowing the currents i_{MD} and i_{MC} to be verified in this circuit.

Equation (3.7) is relatively straightforward to interpret and translate into an equivalent circuit, as shown in Figure (3.9). By applying the difference between the common-mode voltage upstream of the cell and the voltage produced by an equivalent generator substituting for the cell across the terminals of Y_{MC} , the current i_{MC} is generated. Although this equivalent circuit is extremely simple, it requires the rest of the structure to be modelled in common-mode as well and does not allow for the differential mode to be easily integrated. To resolve this issue, the equation giving the common-mode current must be rewritten, as shown in equation (3.14).

$$i_{v_{MC}} = Y_{MC} + Y_{MC} v - 2 \cdot Y_{MC} v \quad (3.14)$$

$$Y_{MC} = \frac{1}{2} + \frac{1}{2} - \frac{1}{2} g_{MC}$$

$$\text{Where: } v_{g_{MC}} = f_{MC} \cdot v_{diff}$$

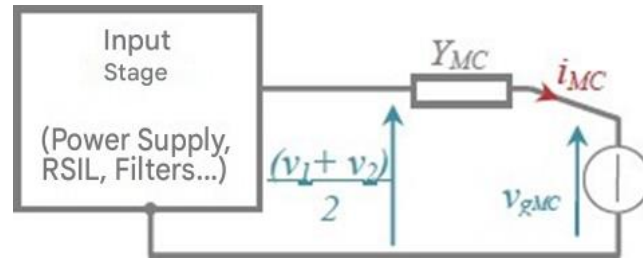


Figure 3.9: Common-mode equivalent circuit.

The equivalent circuit resulting from this notation again shows the DC bus and the rest of the structure unchanged, as illustrated in Figure 3.10.

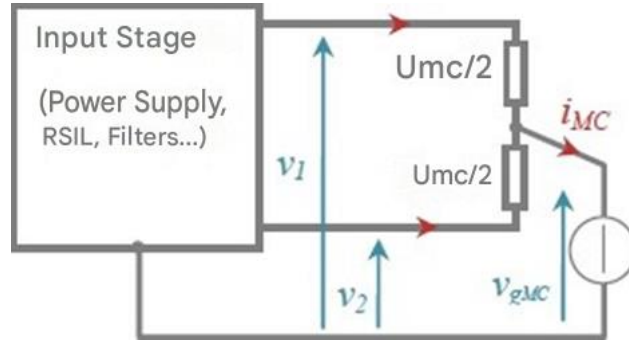


Figure 3.10: Equivalent circuit in distributed common-mode mode.

The definition chosen for the modulation function implies that switch k_1 is controlled and that the load is looped back via k_2 .

The current i^i is, by definition, zero. The interpretation of equation (3.12) relating to the differential-mode current becomes even simpler since the equivalent differential-mode source is equal to the switched load current according to equation (3.15).

$$i_{gMC} = i_{MC} \quad (3.15)$$

The superposition of the two modes, made possible by the assumption that the disturbance sources are decoupled, yields the equivalent EMC circuit diagram of the switching cell shown in Figure (3.11).

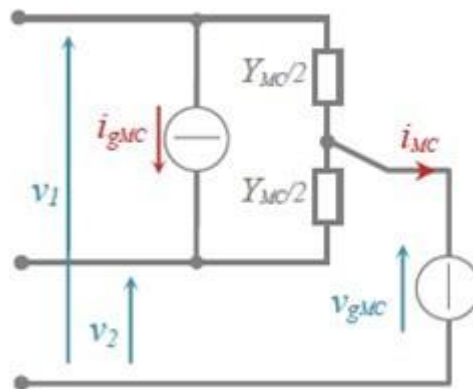


Figure 3.11: Equivalent model of the switching cell.

3.7 Conclusion

In this chapter, we have provided a review of the various European and international standards required for the marketing of electrical equipment, as well as the EMC tests and test methods applied within the framework of standardised measurements.

We then outlined, in general terms, that the characterisation of radiated electromagnetic emissions consists of measuring the level of the electric and/or magnetic field generated by a device.

Electronic power conversion systems are ideally suited to illustrating the mechanisms of conducted emissions and providing the building blocks for modelling these phenomena. We have also carried out, as part of this example analysis (power electronics and EMC), an assessment of the electromagnetic compatibility of electronic power converters as a key challenge, given that these devices are incorporated into the majority of electrical systems.

EMC performance must be anticipated and considered from the design phase onwards. The details of EMC protection techniques and methods for reducing electromagnetic interference are covered in the following chapter.

Chapter 4

**EMC protection techniques and reduction of
EM disturbances**

4.1 Introduction

With a view to improving EMC. It is worth noting that techniques for improving electromagnetic compatibility (types of measures) are used to ensure EMC improvement, such as:

- **Reducing external sources:** to reduce electromagnetic emissions, we can minimise disturbances caused by electrostatic discharges by increasing the humidity in the premises and using an antistatic floor.
- **Increasing susceptibility:** to increase immunity to electromagnetic interference, the electronic system can be hardened by selecting components that are less sensitive to disturbances (different technology families: TTL, CMOS).
- **Reducing couplings:** to attenuate the coupling paths between sources and targets; for a given external source, the level of disturbance received by a piece of equipment depends on the couplings, i.e. the propagation path between the source and the target.

We can distinguish between two methods: the first involves acting directly on the source of the interference, and the second involves modifying the propagation path of the interference.

In this chapter, we present the various most widely used improvement and protection techniques in EMC. Indeed, the majority of the techniques used are based primarily on EMC-oriented circuit design strategies (boards, electrical/electronic systems), the addition of filtering components (decoupling, shielding) and validation through measurement and simulation methods.

4.2 General al considerations

EMC issues arise only when these three elements—source, coupling and victim—are present, as shown in Figure 4.3 [1, 12, 15, 18, 39].

As it is not always possible to reduce disturbances. Indeed, one cannot intervene on external equipment because the costs of improvements are very high, meaning there is no return on investment; similarly, on the victim side, it is not always possible to distinguish useful signals from disturbances. It is therefore necessary to focus on reducing coupling by acting on the **(disturber-victim) coupling**.

There are generally four possible methods [39,41]:

- Proper layout and connection of cables and components
- Proper interconnection of grounds and earthing
- Shielding
- Suppression of voltage spikes and filtering.

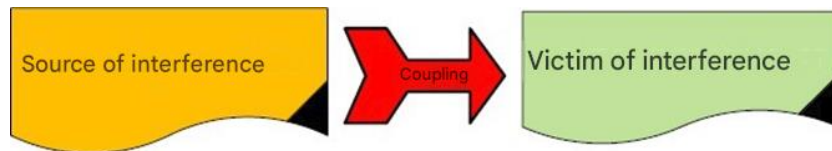


Figure 4.3: Diagram of key EMC factors.

4.3 Definitions

a) Earth: A connection to the earth; the ground of our planet is taken as a conventional potential reference (0V) for certain electrical applications, and its electrical conductivity (which varies greatly) naturally carries, or is used by humans to carry, certain electrical currents. Its symbol is:



Note: Any current flowing through the earth enters it and will exit it to return to its source. Among the applications of connecting installations to earth [28, 29, 39]:

- Distribution in the ground (electrode) of direct lightning currents (atmospheric-to-ground electrostatic discharge).
- Circulation in the ground of currents induced by lightning between two points on an overhead distribution line.
- In a neutral system configuration, the section of earth between the distribution network's earth connection and that of the installation carries the (low) leakage or fault currents produced by the installation.
- The earths of installations are also connected to earth (earth/soil equipotentiality relative to earths and metal structures) to ensure the protection of people (and animals) against electrical risks associated with indirect contact.

b) Earths: This refers to the system's conductive metal casing, or any conductive part of an appliance, equipment or installation that is accessible to the touch and is not live during normal operation, but may become so in the event of a fault. The symbol is as follows:



Examples of earths:

- metal building structures (framework, pipework, etc.), machine frames,
- metal cabinets, unpainted cabinet back panels,
- metal cable trays,
- transformer casing, PLC enclosure, etc.,
- green-yellow (PE - PEN) earth connection wires.

c) Common: The 0-volt reference of a circuit (e.g. amplifier), clearly distinct from earth in floating circuits (i.e. those with no connection to earth), often mistakenly referred to as earth when it is connected to earth. In EMC, the common and earth of a circuit must be implemented separately, even if they are connected at a single point

Its symbol:



GND

d) Ferrite: These are high-frequency (HF) common-mode filters (Figure 4.1). Ferrite consists of materials with high magnetic permeability (μ_r).

Ferrite operates on two principles:

- ✓ common-mode inductance
- ✓ Joule loss absorption (heating) induced by common-mode (HF) disturbances.

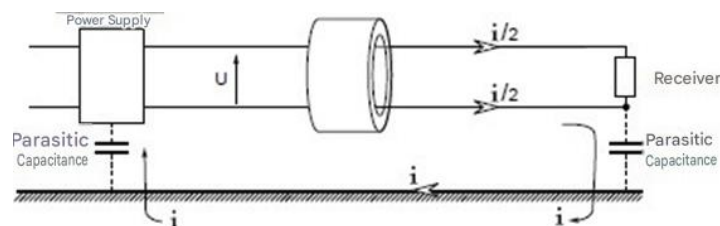


Figure 4.1: Common-mode disturbance current.

These two principles result in a common-mode impedance whose effectiveness depends on its ratio relative to the impedance of the circuit to be protected.

4.4 Layout of components and wiring

The level of electromagnetic compatibility (EMC) in equipment is linked to couplings

between circuits, these couplings being themselves directly dependent on the impedances between these circuits. The conductors used and their installation are therefore crucial to the electromagnetic behaviour of the installation.

4.4.1 Study of the cabling layout

During this stage, it is often necessary to re-examine, in detail, the initial layout proposals. A good cabling layout is based on a few principles and a great deal of careful thought [7, 39, 40]:

- 1) Avoid shared sections between signals of different types, to prevent common-impedance coupling.
- 2) Keep the cabling as short as possible, giving priority to signals that must be kept apart: those most likely to cause interference, as opposed to those most sensitive to it.
- 3) Space out the conductors or traces carrying these signals and, where necessary, insert copper-clad areas connected to earth (to prevent capacitive coupling).
- 4) Minimise the loop area of circuits as much as possible, particularly for the highest currents (which are likely to generate an H magnetic field) and for the most sensitive signals.

As shown in Figure 4.2, at 100 kHz, two 1 mm² cables in parallel have lower impedance than a single 35 mm² cable, hence the benefit of meshing

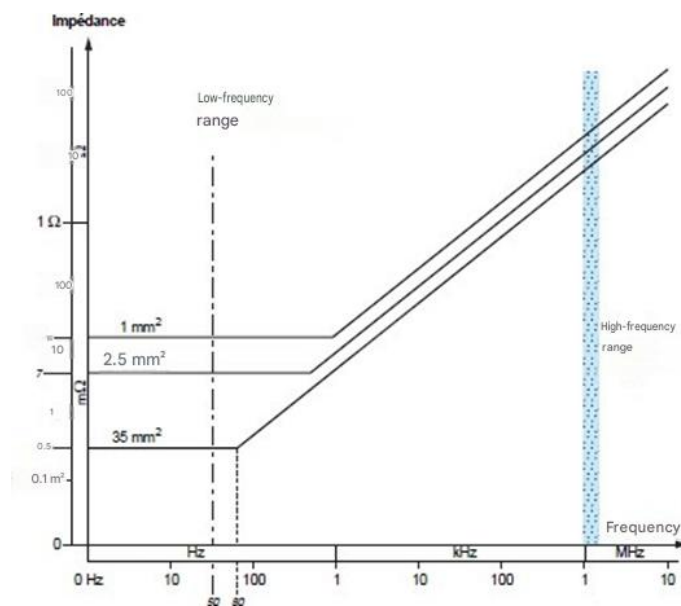


Figure 4.2: Characteristic impedance values (of an electrical conductor of length $L = 1$ m).

4.4.2 Behaviour at low frequency (, LF)

At low frequencies (LF), current flows through the conductor, whereas at high frequencies (HF) the skin effect predominates. Current flows on the surface of the conductor. At low frequencies (LF) (50 Hz – 60 Hz), the cross-sectional area of the wire is the dominant factor

4.4.3 High-frequency (HF) behaviour

At high frequency (HF) ($F > 1$ to 5 MHz)

- ✓ the circumference of the conductor's cross-section is dominant (skin effect)
- ✓ the conductor's cross-sectional area is of little significance
- ✓ the length of the cable is the determining factor

4.4.4 Attenuation effects and high-frequency electrical cables

It is important to note that cables are the weak point of a system from an EMC perspective. It is therefore necessary to reduce emissions or improve immunity at all frequencies.

To reduce the interference picked up by cables, it is necessary to reduce common-mode coupling. It is therefore essential to master attenuation effects, as this is one of the main keys to EMC: effective and cost-effective.

There are three types of common-mode coupling at HF [39]:

- a) Common-impedance coupling, which is limited by grounding loops.
- b) Field-to-cable coupling.
- c) Crosstalk between cables.

Any conductive structure close to the cables provides the following two benefits [39]:

- ✓ Better ground looping. Metal cable trays, metal structures, etc. The ground loop is effective from DC ($f=0$) onwards; it is not a reduction effect as it does not act as a shield. The reduction in common-mode impedance is independent of the distance between the cable and ground.
- ✓ A reduction effect in the strict sense. This effect is cumulative with the previous one. It is achieved by connecting the equipment's earth to conductive structures that are parallel to and close to the cables. This provides a super-shielding effect which, unlike

ground looping, remains effective at high frequencies. It is a virtually cost-free attenuating effect that acts via mutual inductance.

4.4.5 Definition of a reduction-

The reduction effect of a ground structure is defined as the amplitude of the common-mode disturbance (voltage or current) carried by a cable installed far from the grounds, relative to the amplitude on the same cable installed against the conductive structure. For example, a reduction factor of 5 means that a cable receiving a 10V common-mode disturbance (far from the ground) receives only a 2V common-mode disturbance when the cabling is close to the ground network.

Finally, the reduction effect can be modelled by a mutual inductance M between the affected cable and the ground plane.

In addition to the attenuation effect, there is the effect of the ground mesh. A ground strap improves equipotential bonding.

4.5 Shielding

a) Shielding: synonymous with screen, a material designed to reduce the intensity of radiation entering a region.

The armour or screen of a cable, whether intended for the transmission of energy or information, can act as shielding.

The purpose of electromagnetic shielding is to protect electronic (or electrical) installations from the harmful effects of certain electromagnetic couplings; consequently, this protection technique is only effective against radiated disturbances [39].

b) Shield: a device used to reduce the penetration of a field into a specific area. This element fulfils several functions [27, 28, 39]:

- ✓ To create an equipotential surface around the insulator,
- ✓ Prevent the effects of external and internal electric fields,
- ✓ Ensure the flow of capacitive current as well as earth fault current (zero-sequence short circuit),

- ✓ To ensure the protection of people and equipment in the event of a puncture. To this end, it is usually made of metal and is continuous (lead tube, mat or braided wire, or strips arranged in a helical pattern).

For vehicle data cables, the screen, more commonly referred to as shielding, consists of strips or mats of copper or aluminium wires, wound to provide shielding against electrical and magnetic interference.

It may be collective, covering all the conductors in the cable, when the disruptive influences are external.

It can be individual, for a certain number of the cable's conductors, to protect them from interference from the other conductors in the same cable.

c) Sheath: an outer covering designed to ensure the cable is watertight.

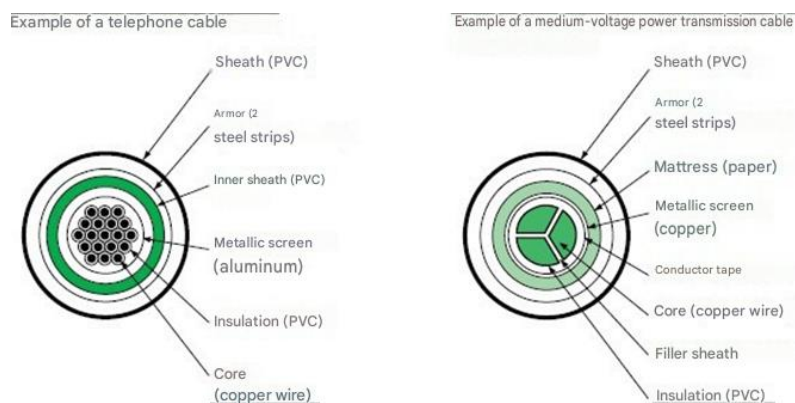


Figure 4.3: Examples of shielding structures [9, 20, 21].

A distinction is made between: magnetic shielding and non-magnetic shielding.

1) Magnetic shielding: this consists of a material capable of providing a path of relatively low reluctance to the lines of force emanating from a magnetic field source (H-field), and of shielding the areas to be protected. This technique can, for example, protect the tube of an oscilloscope from the influence of a power transformer. At low frequencies, protection sometimes requires a noble and expensive material such as mu-metal.

2) Non-magnetic shielding: this consists of a good conductor, such as copper or aluminium. It acts in several ways [7,39]:

- With regard to electric fields (E-fields), it acts like a Faraday cage. It behaves as an electrostatic screen and prevents capacitive coupling between conductors on either side. Depending on the intended application and environment, shielding techniques can be used to:
- Attenuate the electromagnetic field emitted by a device to bring it into compliance with radiated emission standards, as shown in Figure 4.4 (a).
- Attenuate the ambient electromagnetic field received by the device's internal circuits, to ensure compliance with radiated immunity standards, as shown in Figure 4.4 (b).

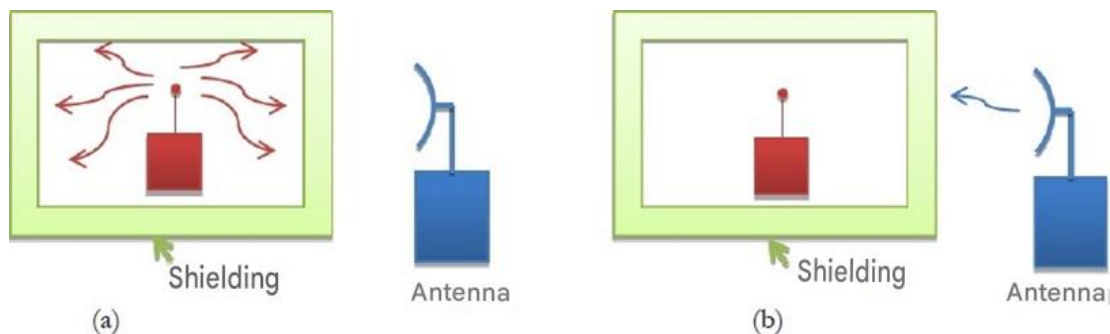


Figure 4.4: Illustration of different types of shielding (a) Prevents emissions from the circuit from radiating outwards (b) Prevents EM fields from entering the circuit

Shielding is therefore the ideal means of eliminating radiation, whether to comply with emission standards, to make the circuit insensitive (total immunity), or to eliminate self- interference between different parts of a system (signal integrity).

4.5.1 Effectiveness of shielding

Shielding effectiveness is defined as: the ratio between the incident field and the field transmitted to the other side, or the ratio between the field without shielding and the field after shielding has been introduced. It is conventionally defined in decibels:

$$\text{Electric field E: } SEE = 20 \log \left(\frac{E_i}{E_t} \right) \quad (4.1)$$

$$\text{Magnetic field H: } SEH = 20 \log \left(\frac{H_i}{H_t} \right) \quad (4.2)$$

In the far field, the two values are identical ($\frac{E}{H} = Z = 377 \Omega$).

In the near field, the definition for the electric field is generally used.

The shielding effectiveness (SE) is positive ($E_i > E_t$); it corresponds to an (insertion insertion attenuation); ideally, it tends towards infinity (no transmitted field).

This definition shows what happens when an EM wave reaches and passes through a shielding wall (assumed to be infinite); it is useful here only for defining the incident (index i) and transmitted (index t) fields.

Generally, effectiveness is measured according to the second definition: measuring (at a specific point) the fields with and without shielding, then calculating the ratio in dB.

The effectiveness of a shield is the combination of the effectiveness of the shielding material (the material used, its thickness, its geometry, and any openings in the shield such as doors, cable entries, display areas and control buttons).

We will first discuss the effectiveness of the material.

4.5.2 Intrinsic efficiency of the material

Intrinsic effectiveness is determined by three factors [7, 9, 37]: attenuation due to reflection at the shield's entrance, absorption within the shield's thickness, and finally the effect of multiple reflections caused by reflection at the shield's exit.

As shown in Figure 4.5

$$S = S_r + S_a + S_m \quad (4.3)$$

Where: S : Intrinsic efficiency

S_r : Attenuation due to reflection

S_a : Absorption within the shielding

S_m : Multiple reflection

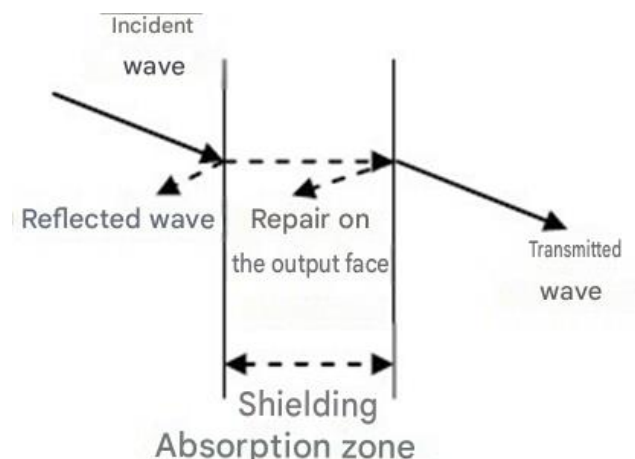


Figure 4.5: Absorption, reflection and transmission of disturbance in shielding.

The material is characterised by its conductivity σ , its permeability μ (generally $\mu = \mu_0$, the permeability of free space) and its permittivity ϵ .

It can be seen that at the interface between media (air–material and then material–air), part of the incident fields is reflected back towards the transmitter and only part is transmitted into the new material.

The overall ratio S_r represents the effect of reflections at the entrance and exit of the shielding. Within the material, the wave is attenuated by dissipation (losses due to conduction and hysteresis) so that it reaches the other side only in an attenuated state. This factor is denoted by S_d .

Finally, the wave reflected at the exit interface returns (attenuating within the material) towards the entrance face, where it undergoes reflection and transmission once again. If the material is thin, we see that multiple reflections between the two faces of the material will cause a slight increase in the transmitted field; therefore, S_m will be negative: the transmitted field is slightly greater than it would be without the multiple reflections.

We can conclude that if we wish to achieve high shielding efficiency, we must use a magnetic material with high relative permeability—which is unfortunately frequency-limited—and also increase the thickness of the magnetic material sufficiently to effectively channel the field lines.

4.5.3 Reflections, reflection coefficients, transmission

At the interface, when a wave passes from a medium with impedance Z_w to a medium with impedance Z_m and then, after passing through, from medium (Z_m) to medium (Z_w)

At the air-material interface, the reflection coefficient ρ (the ratio of the reflected wave to the incident wave) is:

$$\rho = \frac{Z_w - Z_m}{Z_w + Z_m} \quad (4.4)$$

The transmission coefficient, after two interfaces, is therefore calculated as:

$$\frac{E_t}{E_i} = \frac{4Z_w Z_m}{(Z_w + Z_m)^2} \cong$$

$$\Gamma = \frac{Z_w - Z_m}{Z_w + Z_m}$$

$$\Gamma_{\text{If}} = \frac{Z_m - Z_w}{Z_m + Z_w} \quad (4.5)$$

Whether at the interface between two homogeneous media (air and shielding material) or in a transmission cable, the reflection coefficient is calculated using the characteristic impedances of the materials in question.

ρ is the ratio of the reflected field E_r to the incident field E_i . The transmission coefficient transmission $(1 - \rho)$ then represents the ratio between the transmitted field E_t and the incident field E_i on either side of the surface.

What interests us here is the ratio of the transmitted field to the incident field, after two interfaces. We therefore multiply the transmission coefficients of the two successive surfaces:

$$(1 - \rho_1) = 1 - \frac{Z_w - Z_m}{Z_w + Z_m} = 2 \frac{Z_m}{Z_w + Z_m} \quad (4.6)$$

$$(1 - \rho_2) = 1 - \frac{Z_m - Z_w}{Z_m + Z_w} = 2 \frac{Z_w}{Z_m + Z_w}$$

For a cable, the characteristic impedance is the square root of the ratio between its line inductance and its line capacitance (derived from μ and ϵ), but also depends on the cable's dimensions, whereas the second impedance to be considered is the localised impedance loading the cable. However, the phenomena are identical.

4.5.4 Reflections, impedances, wave

In air, Z_w has already been defined as:

$$\checkmark \quad \text{In the far field} \\ Z_w = \eta_0 = 120\pi = 377 \, \Omega \quad (4.7)$$

$$\checkmark \quad \text{In high-impedance near-field (electrical dipole, capacitive coupling)} \\ Z_w = \eta_0 \cdot \frac{\lambda}{2\pi \cdot r} \quad (4.8)$$

$\checkmark$ In low-impedance near-field (magnetic dipole, inductive coupling)

$$Z_w = \eta_0 \cdot \frac{2\pi \cdot r}{\lambda} \quad (4.9)$$

In any material, Z_w is:

$$Z_m = \sqrt{j\omega\mu / \sigma + j\omega\epsilon} \quad (4.10)$$

- For an insulating material: $Z_m \cong \sqrt{\mu / \epsilon}$
- For a conductive material: $Z_m \cong \sqrt{\omega\mu / \sigma}$

Whilst the far-field wave impedance is well known, the formulas given for the near field are only rough approximations.

In an insulator, σ is negligible, and generally its characteristic impedance is close to that of a vacuum.

Reflection attenuation will therefore be very low. In a conductive material, on the other hand, σ is dominant, reducing the material's impedance to very low values.

The result is significant attenuation due to reflection.

4.5.5 Materials used for shielding-

We have indeed observed that most shielding structures are made from standard (non-magnetic) and conductive materials or from ferromagnetic materials, which are often used for their mechanical properties rather than their ferromagnetic behaviour.

Moreover, it is noteworthy that for most ferromagnetic materials, magnetic permeability decreases with frequency, generally for frequencies exceeding a few tens of kilohertz.

Table 4.1 [7, 9, 39] gives the conductivity values of the most common conductive materials.

Table 1.1: Conductivity of the most common conductive materials

Conductive materials	Conductivity $\sigma \left[\frac{\text{S}}{\text{m}} \right]$
Silver	6.3×10^{-7}
Copper	5.9×10^{-7}
Industrial copper	5.8×10^{-7}
Gold	4.5×10^{-7}
Aluminium	3.8×10^{-7}
Industrial aluminium	3.7×10^{-7}
Wire	4.8×10^{-6}
Phosphor bronze	4×10^{-6}
Nickel-aluminium bronze	2.10^{-6}
Tin	9.2×10^{-6}
Brass	$1.5 \times 10^{-7} - 3 \times 10^{-7}$
Steel	$5 \times 10^{-6} - 10^{-7}$

4.5.6 Effect of holes and

The intrinsic efficiency is generally completely degraded by holes and slits. Their presence distorts the path of the induced currents, so that radiation occurs, depending on the length of the hole and its direction

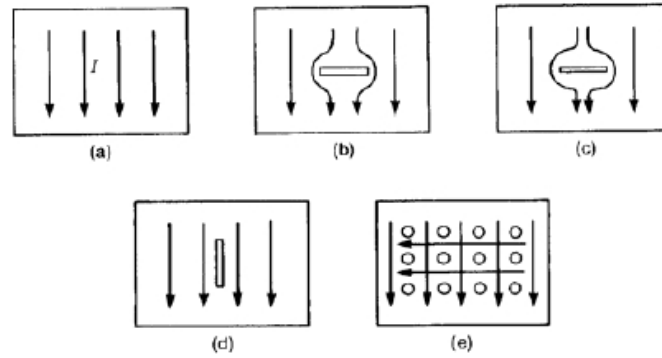


Figure 4.6: Distortion of vertical currents by different slits.

Figure 4.6 (a) to (d) illustrates the distortion of vertical currents by different slits.

In Figure 4.6 (b) and (c), the distortion is virtually the same, almost independent of the width of the slit.

In Figure 4.6 (d), the slit running parallel to the current lines causes almost no distortion.

Similarly, in Figure 4.6 (e), a network of small holes will distort the current lines much less, regardless of their direction, than a single opening of the same total area.

4.5.7 Openings in the shielding

The hole or slot therefore radiates like an antenna of the same dimensions.

It is important to note that this radiation is at its maximum when the length of

the antenna is $D = \frac{\lambda}{2}$.

Where: D is the maximum length of the aperture. Norton then indicates an efficiency of 0 dB.

For: $D = \frac{\lambda}{2}$, he calculates the shielding efficiency as:

$$S = 20 \log \left(\frac{\lambda}{2D} \right) \quad (4.11)$$

Where: α is the aperture index.

We therefore consider that an aperture whose largest dimension is equal to half a wavelength transmits the entire incident field.

In this case, the shielding serves no purpose.

It is only when the size of the aperture is small relative to the wavelength that the transmitted field is attenuated.

Note that the criterion is determined by the largest dimension of the aperture, regardless of the aperture's width. Consequently, joint gaps (cover, adjacent front panels) are the most dangerous.

We observe that for the array of apertures:

If a network of (N) slits is at a pitch $\prec \frac{\lambda}{2}$, then there is an increase proportional to $\sqrt{N}$

The shielding effectiveness is calculated as:

$$S = 20 \log \left(\frac{\lambda}{2D} \right) - 10 \log (N) \quad (4.12)$$

The overall efficiency S_{eff} (material with holes) is then given by the minimum of the intrinsic efficiency and that due to the holes, as:

$$S_{eff} = \min \{ S_i, S(h) \} \quad (4.13)$$

In the presence of an array of apertures, if the pitch in the array is less than $\frac{\lambda}{2}$, then there

no longer any accumulation of the effects of each opening.

If the openings are small enough, a certain degree of effectiveness is maintained. At low frequencies (long wavelengths), the effectiveness matches that of the material used for the shielding. This is expressed by the second formula

As protective measures, it is highly recommended to [19, 20, 37, 38]:

- Reduce the length of the openings by: EMI gaskets, compressed gaskets, contact fingers (bronze-beryllium), repairs using self-adhesive copper or aluminium foil
- Extend the penetration path by: covering sheets, waveguide tubes (ventilation),
- Use special materials such as: conductive glass (display screens), conductive fibre- reinforced plastic, surface metallisation, conductive paint.

4.6 Filtering

To achieve or improve electromagnetic compatibility, another solution that is considered is the insertion of EMC filters.

An EMC filter is characterised by its insertion loss, also known as filter efficiency. By definition, this is the residual level measured after the filter has been installed compared to the level measured without the filter. The insertion loss of a filter depends on the impedances of the upstream and downstream circuits. The function of filters is to allow useful signals to pass through and to suppress the unwanted portion of the transmitted signal.

From a technological perspective, we can distinguish between two types of filters: passive filters and active filters. In this section of the chapter, we have focused on the study of these filters incorporated into static converters.

4.6.1 Passive fil

This technique allows the propagation path of disturbances to be modified in a beneficial way with the aim of disrupting their flow. Filters can be placed upstream (grid side) or downstream of the drive (motor side). This solution can be implemented in the common-mode of the static converter.

a) MC filter upstream of the static converter

As shown in Figure 4.7, the filter is placed opposite the mains [7, 8, 10, 13]; this technique is widely used in new generations of variable speed drives. The combination of high-impedance (inductance) and low-impedance (capacitance) paths allows the disturbance currents to be routed along paths that do not disturb the mains. This type of filter is particularly effective in terms of compliance with standards. Unfortunately, however, it has no effect on motor overvoltages and does not reduce the common-mode currents flowing through the motor.

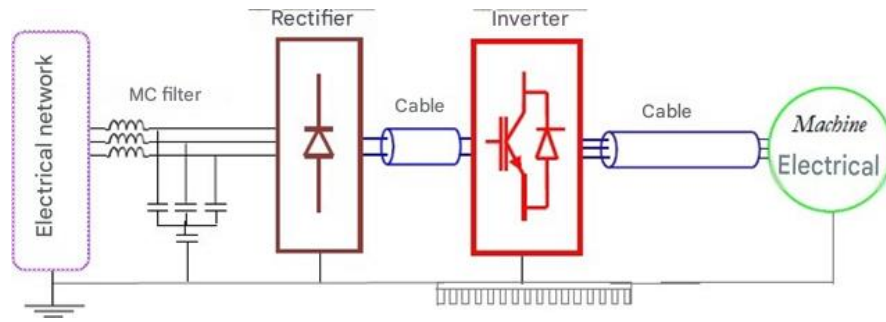


Figure 4.7: Common-mode filter at the rectifier input.

b) CM filter downstream of the static converter

As shown in Figure 4.8, the filter is placed immediately at the output of the inverter [7, 8, 10]; this solution helps to attenuate common-mode voltage variations at the input of the cable-motor assembly. Consequently, the motor's service life is extended by reducing the current in the motor. Radiated emissions from the cables are also attenuated.

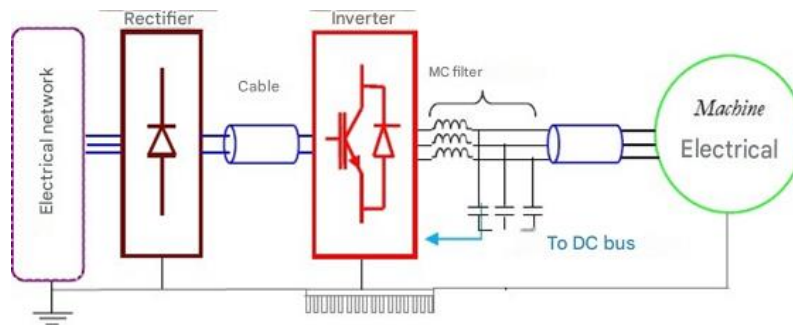


Figure 4.8: Common-mode filter at the inverter output.

4.6.2 Active c e filtering

To reduce electromagnetic disturbances of the common-mode and differential-mode types (most commonly common-mode), an EMC filter appears to be a suitable solution.

One of the active solutions proposed to counteract the common-mode voltage generated by the inverter is the active filter, which involves injecting a voltage opposite to the common-mode voltage, as shown in Figure 4.9 [7,10], using a common-mode transformer. It allows the currents flowing through the cable-machine assembly to be limited up to a few MHz, thereby protecting them.

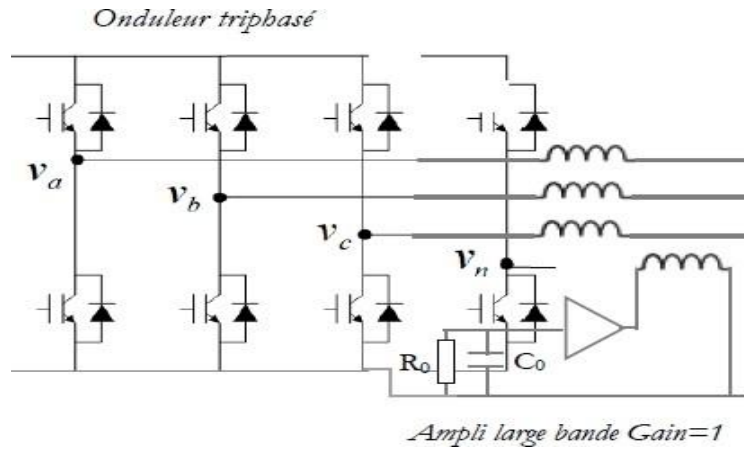


Figure 4.9: Active filtering by injecting common-mode current.

4.7 Conclusion

In this chapter, we have examined the various most common improvement and protection techniques in EMC; we have presented an overview of the main interference reduction techniques currently used in the field of EMC, such as shielding effects, the study of cable layout and their behaviour in (HF) and (LF). Furthermore, we have examined shielding and the use of filters to study the reduction of conducted electromagnetic disturbances in power electronics.

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