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Abstract

Electromagnetic Interference (EMI) from power converter, particularly DC-DC Converters, has emerged as a critical concern due to their rapid global expansion. The predominant source of EMI in renewable energy systems is the power converter, such as converters, which relies on high-frequency switching devices for energy transformation. These converters generate conducted EMI at both the direct current (DC) interface with power source. To ensure system reliability and prevent disruption to grid operations and connected devices, these emissions must strictly adhere to electromagnetic compatibility (EMC) standards. In this context, developing an electromagnetic interference (EMI) model of the system proves to be a powerful analytical tool, offering detailed insights into the mechanisms of noise generation, propagation, and their effects on various components of the renewable energy system. Moreover, such models are instrumental in formulating effective noise mitigation strategies, including the optimal design of EMI filters.

Keywords: Electromagnetic Interference (EMI), DC-DC Converters, Electromagnetic compatibility (EMC), Conducted EMI

ملخص:

أصبح التداخل الكهرومغناطيسي الناتج عن محولات القدرة، وخاصة محولات التيار المستمر إلى التيار المستمر مصدر قلق متزايد بسبب الانتشار الواسع لأنظمة الطاقة المتجددة. وتُعد محولات القدرة من أهم مصادر التداخل الكهرومغناطيسي نظرًا لاعتمادها على مفاتيح إلكترونية تعمل بترددات عالية لتحويل الطاقة. وينتج عن هذه المحولات تداخل كهرومغناطيسي موصل عند واجهات التيار المستمر والتيار المتناوب، مما قد يؤثر على أداء النظام والأجهزة الإلكترونية المجاورة. ولضمان التشغيل الموثوق والامتثال لمعايير التوافق الكهرومغناطيسي من الضروري فهم هذه الانبعاثات والتحكم فيها. وفي هذا السياق، يمثل تطوير نموذج للتداخل الكهرومغناطيسي أداة تحليلية فعالة لدراسة آليات تولد الضوضاء ومسارات انتشارها وتأثيرها على مكونات النظام المختلفة. كما تساهم هذه النماذج في تصميم وتحسين وسائل الحد من التداخل الكهرومغناطيسي، بما في ذلك تصميم مرشحات التداخل الكهرومغناطيسي، مما يعزز الأداء الكهرومغناطيسي لأنظمة الطاقة المتجددة.

الكلمات المفتاحية: التداخل الكهرومغناطيسي (EMI) ، محولات التيار المستمر إلى التيار المستمر ، التوافق الكهرومغناطيسي (EMC) ، التداخل الكهرومغناطيسي الموصل

Résumé:

Les interférences électromagnétiques (EMI) générées par les convertisseurs de puissance, en particulier les convertisseurs DC-DC, sont devenues une préoccupation majeure en raison de l'adoption croissante des systèmes d'énergies renouvelables. Les convertisseurs de puissance sont considérés comme l'une des principales sources d'EMI puisqu'ils utilisent des dispositifs de commutation à haute fréquence pour la conversion de l'énergie. Ces convertisseurs génèrent des EMI conduites aux interfaces en courant continu (DC) et en courant alternatif (AC), pouvant affecter les performances du système ainsi que les équipements électroniques situés à proximité. Afin d'assurer un fonctionnement fiable et de respecter les normes de Compatibilité Électromagnétique (CEM), il est essentiel de comprendre et de maîtriser ces émissions. Dans ce contexte, le développement d'un modèle d'EMI constitue un outil d'analyse précieux pour étudier les mécanismes de génération du bruit, les chemins de propagation et leurs effets sur les différents composants du système. De plus, ces modèles contribuent à la conception et à l'optimisation de techniques efficaces de réduction des EMI, notamment les filtres EMI, améliorant ainsi les performances électromagnétiques globales des systèmes, d'énergies renouvelables.

Mots-clés: Interférences électromagnétiques (EMI), Convertisseurs DC-DC, Compatibilité électromagnétique (EMC), (EMI) conduite.

DEDICATION

We dedicate this humble work to our parents, in sincere appreciation for their continuous support and efforts throughout our academic journey. May Allah reward them abundantly for all they have done for us.

We also dedicate this work to everyone who supported and encouraged us, even with a kind word, and to those who helped us remain steadfast and committed along this path.

This achievement was not an easy journey, it was filled with challenges that shaped us into stronger and more aware individuals. We hope that this work reflects our sincere efforts and marks a meaningful step toward a better future, God willing.

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List of abbreviations

AFNOR: French Association for Standardization

ANSYS : Analysis System Software

CE : Conformité Européenne

CEN: European Committee for Standardization

CENELEC: European Committee for Electrotechnical Standardization

CISPR: International Special Committee on Radio Interference

CM : Common Mode

CV : Constant Voltage

DC–DC: Direct Current to Direct Current

DM: Differential Mode

EC: European Community

EMC: Electromagnetic Compatibility

EMF: Electromagnetic Field

EMI: Electromagnetic Interference

EN : European Norm

EPC : Equivalent Parallel Capacitance

EPR: Equivalent Parallel Resistance

ESL: Equivalent Series Inductance

ESR: Equivalent Series Resistance

EUT: Equipment Under Test

FCC: Federal Communications Commission

FEA: Finite Element Analysis

GTEM: Gigahertz Transverse Electromagnetic Cell

GTM: General Terminal Modeling

HF: High Frequency

HVDC: High Voltage Direct Current

IEC: International Electrotechnical Commission

IEEE: Institute of Electrical and Electronics Engineers

IGBT: Insulated Gate Bipolar Transistor

ISO: International Organization for Standardization

LF: Low Frequency

LISN: Line Impedance Stabilization Network

LTSpice: Linear Technology Simulation Program with Integrated Circuit Emphasis

MOSFET: Metal Oxide Semiconductor Field Effect Transistor

MPPT: Maximum Power Point Tracking

MTB: Modular Terminal Behavioral

PCB: Printed Circuit Board

PSIM: Power Simulation

PV: Photovoltaic

PWM: Pulse Width Modulation

RE: Radiated Emission

RF: Radio Frequency

RLC : Resistance–Inductance–Capacitance

SiC: Silicon Carbide

SPICE: Simulation Program with Integrated Circuit Emphasis

TLM: Transmission Line Modeling

Introduction

The manufacturing and marketing of electrical equipment is a real challenge. Indeed, electricity, electronics, and power electronics have not traditionally been at the core of manufacturers' expertise. The number of onboard electrical systems, whether low-voltage (sensors, control circuits, electronic control units, etc.) or high-voltage (electric actuators, power electronics, etc.), is continuously increasing.

This trend inevitably leads to an increase in unwanted electromagnetic phenomena and, consequently, a higher risk of system failures. For manufacturers and their suppliers, such a risk is unacceptable and must be assessed at an early stage to determine whether the equipment can be approved for market release. This validation process is governed by compliance with standards and specifications that can collectively be referred to as Electromagnetic Compatibility (EMC) requirements.

Power conversion systems primarily rely on power converters, which are electronic circuits, composed of semiconductor switches, magnetic components such as inductors and transformers, and energy storage elements like capacitors. Among the various types of power converters, DC-DC converters are the most versatile for regulating DC voltage. The commonly used configurations include boost, buck, buck-boost, and flyback converters. Of these, the DC-DC boost converter is the simplest topology for reliably producing a higher output voltage from a given input voltage. It is widely employed in applications such as front-end converters for battery systems, solar photovoltaic (PV) systems, and fuel cells.

The frequent switching actions of semiconductor devices in a boost converter result in significant voltage spikes and increased output voltage ripple. To achieve high power density, these converters are typically operated at elevated switching frequencies. However, continuous high-frequency switching introduces several challenges, including degradation of power quality, harmonic injection, reduced reliability, and electromagnetic interference (EMI). Among these issues, EMI is particularly critical, as it can lead to severe and potentially catastrophic operation of DC-DC boost converters.

EMI modeling in DC-DC converters is essential for accurately analyzing and predicting electromagnetic emissions. Although individual power converters may comply with regulatory emission limits under standard test conditions, their combined operation within a complete

energy conversion system can result in excessive EMI due to interactions among multiple converters and other system components [20]-[26]. These issues are often identified only after installation, making post-deployment EMI mitigation both time-consuming and costly. In many cases, on-site EMI measurements may be impractical or unavailable.

In this context, the work is focused on developing a detailed simulation model of the EMI propagation paths in a DC-DC boost converter. It includes the analysis and characterization of EMI and examines their impact.

To achieve this objective, a work plan consisting of three chapters has been structured as follows:

- The first chapter introduces the fundamental concepts and general principles related to electromagnetic compatibility (EMC), serving as a preliminary introduction to the subject.
- The second chapter provides an overview of the existing literature on EMI in DC-DC converters. It also includes the modeling of the fundamental components.
- The third chapter presents a detailed modeling of a DC-DC boost converter, highlighting the sources and propagation paths of EMI. This analysis is supported by simulation results obtained using LTSpice, which illustrate the behavior of disturbances under various conditions. The chapter also examines the influence of key parameters, such as the switching frequency and different types of MOSFETS, on EMI generation.

Finally, the work will conclude with a general summary and a discussion of potential directions for future research.

Chapter I:

Fundamentals of electromagnetic compatibility (EMC)

I.1 Introduction:

Electromagnetic compatibility (EMC) is the discipline aimed at ensuring the electromagnetic coexistence of devices and systems incorporating electrical and/or electronic components. It focuses on analyzing the mechanisms of disturbance transfer, whether radiated or conducted, between such systems. The objectives of EMC include the development of strategies to minimize emitted disturbances and improve the immunity of systems to external Electromagnetic Interference (EMI).

This chapter begins with an introduction to the fundamental challenges related to EMC. In the second section, we examine the relevant standards and measurement techniques used to evaluate EMC performance. Finally, the chapter concludes by presenting practical solutions and mitigation strategies aimed at reducing electromagnetic disturbances.

I.2 Definition of Electromagnetic Compatibility (EMC):

EMC is the ability of a device, equipment, or system to operate satisfactorily within its electromagnetic environment without itself generating electromagnetic disturbances that are intolerable to other equipment, devices, or systems (definition of the International Electrotechnical Commission) [1].

I.3 Fundamental Principles of EMC:

- Electrical and electronic devices must not cause harmful interference to other devices, whether during normal operation or in the event of misuse or foreseeable malfunction.
- Devices must have adequate immunity to external electromagnetic disturbances to ensure reliable performance.
- Products sold within the European Union must comply with EMC regulations under the European Community (EC) directives and carry the CE marking, indicating the manufacturer's and distributor's responsibility for compliance.
- To meet these requirements, devices must pass standardized EMC tests and measurements, such as those defined by the CISPR 22/EN 55022 standard (International Special Committee on Radio Interference) [2].

I.4 Electromagnetic Interference (EMI):

Electromagnetic interference (EMI) refers to the transmission of disruptive electromagnetic energy from one electronic device to another, either through radiated or conducted paths, or both. Suppression of EMI involves reducing or eliminating this unwanted energy, often through methods such as shielding and filtering.

The nature of EMI whether primarily radiated or conducted depends on the type of coupling or propagation path involved. In practice, conduction is almost always accompanied by some radiation, and vice versa. Radiated interference occurs when a component predominantly emits energy that travels through space to reach a receptor. The source of this radiated interference can either be part of the same system as the receptor or an entirely separate, electrically isolated unit.

Conducted interference, on the other hand, arises when the source is electrically connected to the receptor via power or signal cables, transferring interference along these connections. It typically affects the system's main power supply and can often be mitigated using filters. Reducing conducted emissions frequently also lowers related radiated emissions. However, when radiated interference dominates, it can impact any signal path inside or outside the system, making it considerably more challenging to shield effectively [3].

I.5 Classification of Electromagnetic Interference (EMI):

I.5.1 Conducted EMI and Noise Propagation Paths Conducted coupling

occurs when electromagnetic disturbances are transmitted directly through physical connections, such as cables linking sensors, control units, power supplies, grounding systems, and reference grounds. This type of coupling is generally classified into two modes:

I.5.1.1 Common Mode (CM)

Common mode (CM) current flows in the same direction along all the conductors of a cable bundle and returns to ground through parasitic capacitances. This current is distributed across the connected wires, maintaining the same direction in each conductor, as illustrated in Figure I.1

I.5.1.2 Differential Mode (DM)

The current in differential mode (or series mode) flows along one conductor, passes through the device, which can cause malfunctions and returns via a second conductor. This closed-loop path forms the basis for signal or power transmission, as illustrated in Figure I.1.

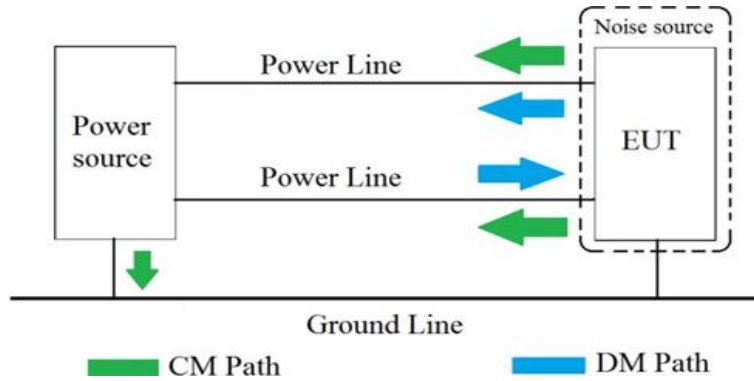


Figure I.1. CM and DM noise paths.

Conducted EMI can propagate through a coupling channel given by metallic planes used for the equipment ground connection or through a coupling channel generated from the equipment power supply.

Regarding the emissions that propagate through the supply network, it is necessary to distinguish between internal network noise sources and external noise sources. For example, among the first, there are both impulsive and non-impulsive over voltages, whereas lightning phenomenon and switching transients, due to electronic converters used for the network voltage regulation, are external noise sources [4].

I.5.2 Radiated Emission

Radiated coupling refers to the interaction between an electromagnetic wave and physical structures such as wires, cables, or openings in a shield. These radiated disturbances can then couple to nearby components and circuits through conduction. This mode of coupling requires distinguishing between near-field and far-field radiation zones [4]. When the source of the disturbance is located at a sufficient distance from the victim, the interaction occurs mainly through radiation, commonly referred to as “field-to-wire” or “field-to-loop” coupling.

When the source is in the immediate vicinity of the victim, coupling occurs primarily through crosstalk, which can be either capacitive or inductive in nature. In this near-field region, the radiated electromagnetic field consists of two components a magnetic field (H) and an electric field (E) which interact by continuously exchanging energy and mutually regenerating as they propagate through space.

I.5.2.1 Near Field

If the disturbing source has a low impedance, it produces a relatively high current compared to the voltage, creating a dominant magnetic field near the conductor. Conversely, if the source has a high impedance, it generates a relatively low current and a higher voltage, resulting in a stronger electric field near the source.

I.5.2.2 Far Field

As the distance from the source increases, the initial imbalance between the electric and magnetic fields gradually decreases due to continuous energy exchange, eventually leading to a balance in which both fields carry equal amounts of energy a characteristic of far-field propagation.

I.6 Sources and Origins of EMI:

An EMI source refers to any device that transmits, distributes, processes, or uses electrical energy in a way that produces conducted or radiated signals capable of degrading equipment performance. Figure I.2 illustrates the taxonomy of various electromagnetic interference sources, and a brief explanation of each category is provided below [1].

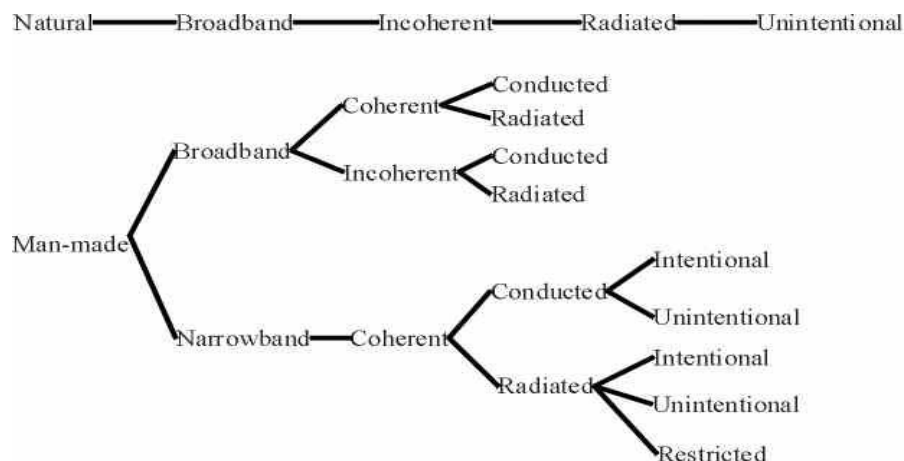


Figure I.2. Taxonomy of EMI Sources [13].

I.6.1 Natural sources and Man-made EMI sources

EMIs can be of natural or anthropogenic origin. Natural sources include terrestrial phenomena such as lightning, as well as extraterrestrial sources like solar noise. Human-made disturbances, on the other hand, can be classified as intentional or unintentional, depending on their origin and purpose.

I.6.2 Broadband sources and narrowband sources

Classifying interference sources based on their bandwidth provides valuable insight into the potential severity of their impact on the affected systems. For wideband sources, where the

interference bandwidth exceeds that of the affected device, the level of disruption largely depends on the bandwidth characteristics of the victim system.

In contrast, narrowband sources, whose emission bandwidth is narrower than that of the victim system, can transmit their entire interference spectrum to the victim, potentially causing more targeted and sustained interference.

I.6.3 Intentional and unintentional sources

This classification distinguishes between intentional and unintentional sources of electromagnetic disturbances. Devices specifically designed to emit electromagnetic waves, such as radiocommunication systems, radars, and other similar technologies, are classified as intentional sources [13].

I.6.4 Sources of EMI in power electronics

The operation of static converters contributes significantly to electromagnetic pollution due to their fast switching and high signal amplitudes. Fast switching is used to minimize switching losses, which occur when voltage and current overlap in power electronic switches. Typical switching gradients can range from 100 to 1,000 A/ μ s for current (di/dt) and from 5 to 50 kV/ μ s for voltage (dv/dt). In addition, high switching frequencies, ranging from 100 Hz to 1 MHz, further exacerbate electromagnetic emissions.

Due to its high-speed switching, a static converter generates abrupt voltage and current variations that cause electromagnetic disturbances. These disturbances propagate unintentionally within the circuit and into the surrounding environment. Superimposed on useful signals, they can disrupt the normal operation of the system as well as nearby electronic devices. Consequently, any system can act as a source (emitter) or a receiver (sensitive device) of electromagnetic interference, giving rise to the fundamental concepts of EMC: emission and susceptibility [1].

I.7 Electromagnetic Compatibility (EMC) Standards:

EMC encompasses two key aspects: regulatory compliance to prevent environmental electromagnetic pollution and ensure human safety, and adherence to manufacturer-defined criteria to guarantee product reliability and customer satisfaction. To achieve these objectives, various regulatory and standardization bodies enforce EMC requirements by applying specific standards tailored to different operational environments. A standard constitutes a structured set of rules, specifications, and methodologies that manufacturers can reference during the design and

testing of their products. The main standardization bodies responsible for EMC are shown in Figure I.3.

The different standardization bodies are:

- At the global level, the general standardization body is ISO, while for the electrical sector, it is the International Electrotechnical Commission (IEC), established in 1904. The IEEE (Institute of Electrical and Electronics Engineers) defines international technical standards, particularly in the field of networks.
- At the European level, the general standardization body is CEN (European Committee for Standardization), and for electricity, it is CENELEC (European Committee for Electrotechnical Standardization). In France, the equivalents of these organizations are AFNOR (French Association for Standardization) at the general level, CEF (French Electrotechnical Committee) corresponding to IEC, and UTE (Technical Union for Electricity) corresponding to CENELEC.

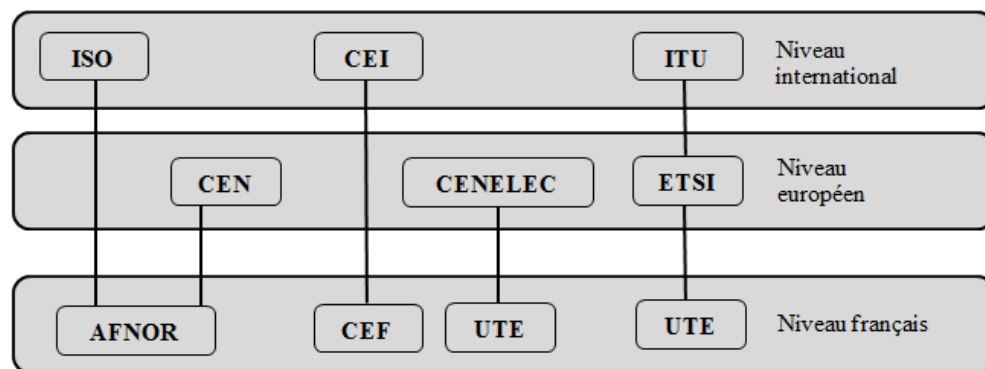


Figure I.3. Different Standardization Bodies.

The International Electrotechnical Commission (IEC) created a special committee, the **International Special Committee on Radio Interference (CISPR)**, to develop EMC standards. CISPR publications are generally used by various countries as a reference document for establishing their own standards. It should be noted that in the United States, EMC regulations for commercial products are defined by the **Federal Communications Commission (FCC)** [2] [13].

I.8 EMI measurement techniques:

EMI testing can be conducted either as compliance testing, which strictly adheres to the procedures outlined in authorized standards, or as pre-compliance testing, which involves

developing new in-house techniques. All pre-compliance test setups should closely replicate the compliance test environment in terms of hardware, software, and methodology. EMI typically involves three key components: the emitter/source, which generates unwanted interference; the receiver/susceptor, which responds to the interference; and the coupling channel, which transmits the interference from the source to the receiver.[4]

If the coupling channel is **conductive**, the resulting EMI is classified as **conducted emission**. If the coupling channel is **radiative**, it results in **radiated emission**. These components may belong to different systems, causing **intersystem EMI**, or to different subsystems within a larger system, causing **intrasystem EMI**. Based on these distinctions, EMI measurements and tests are categorized as illustrated in Fig. I.4.

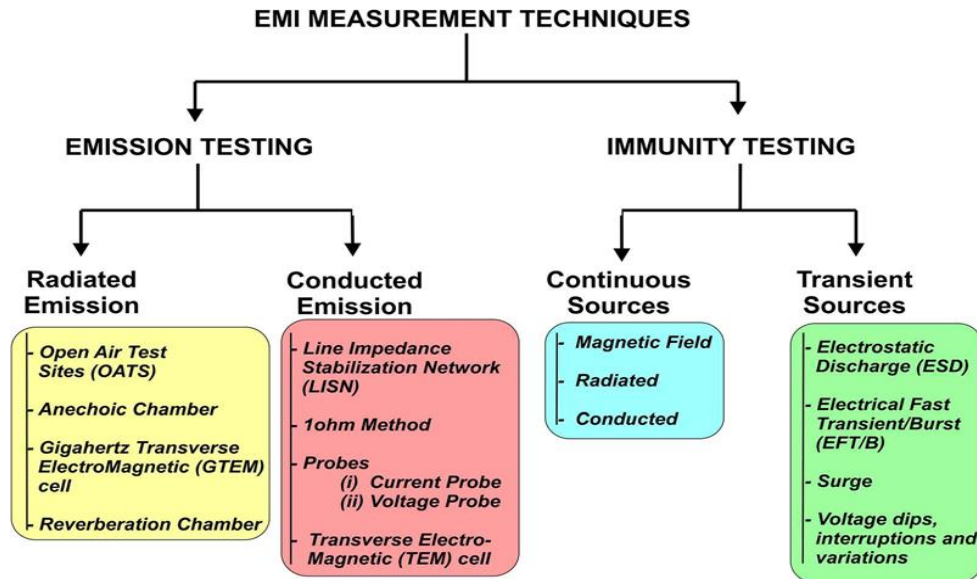


Figure I.4. EMI measurement techniques.

I.8.1 Emission Testing

In these tests, the **emitter** is the **equipment under test (EUT)**. As noted, emission testing can target either **radiated** or **conducted emissions**. The following subsections describe various test setups used to assess EMI arising from these unwanted emissions.

I.8.1.1 Radiated Emission Testing

A conventional setup for **radiated emission (RE) EMI testing** is illustrated in Fig. I.5. Standard radiated emission tests are typically performed over the frequency range of **30 MHz to 1 GHz**, corresponding to wavelengths of **10 m to 0.3 m**, respectively [5].

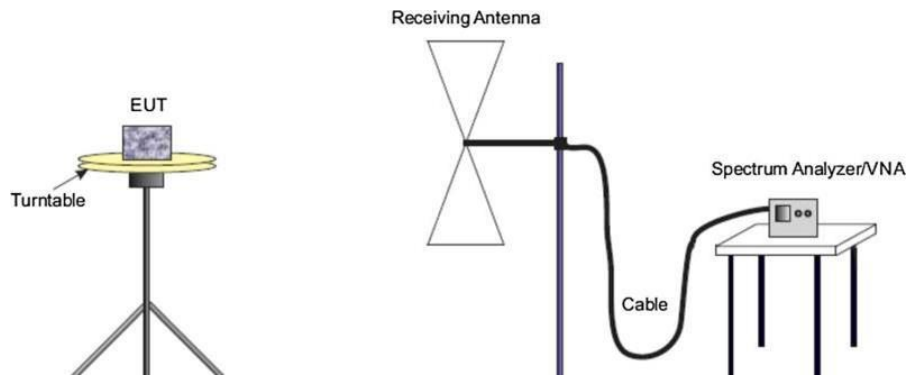


Figure I.5. Radiated emission test set-up.

However, for smaller prototypes, these measurements are carried out in specialized chambers such as anechoic chambers, reverberation chambers, or gigahertz transverse electromagnetic (GTEM) cells. Some typical examples of these chambers are illustrated in I.6.[6].

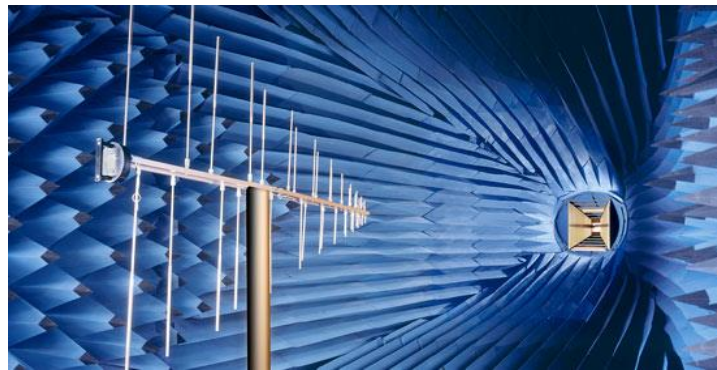


Figure I.6. Anechoic Chamber.

Anechoic Chamber: The walls and floor of an anechoic chamber are fully or partially covered with microwave absorbers (in the case of a semi-anechoic chamber) to minimize unwanted interference that could affect electromagnetic measurements [6].

I.8.1.2 Conducted Emission Testing

Conducted emission testing is performed to evaluate the noise generated by sudden changes in voltage or current within the equipment's circuitry, which is then emitted through the power lead to connected peripheral or load devices. Such unwanted noise can seriously affect the performance of these devices and may even cause equipment malfunction [7]. Common methods for conducted emission testing include:

1. Line Impedance Stabilization Network (LISN)
2. 1Ω method
3. Probes

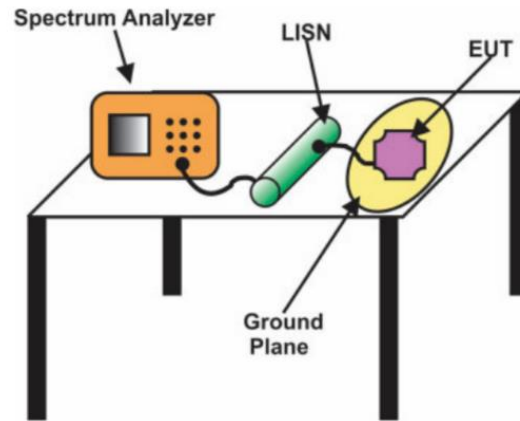


Figure I.7. Measurement setup for conducted EMI testing using a Line Impedance Stabilization Network (LISN) [8].

When placed between the EUT and the power source, a Line Impedance Stabilization Network (LISN) eliminates noise caused by variations in the AC power source impedance. The LISN provides stable impedance at a single frequency to the EUT, allowing noise voltage to be measured according to CISPR 25 (2010). Its RF port is connected to a measurement receiver, which records the noise voltage. A typical setup for conducted emission testing using an LISN is shown in Fig. 7. This method is accurate up to 100 MHz and is therefore not suitable for high-frequency circuits [8].

I.8.1.2.1 Operation of the LISN

The LISN is essentially a four-port passive filter composed of inductors, capacitors, and resistors, with the number, configuration, and specific values determined by the standard applicable to the relevant use case. Additionally, the network is equipped with a BNC output for each phase, allowing the voltage drop across a fixed impedance to be observed; this voltage drop serves as a representation of the conducted disturbance.

The general configuration of an LISN is shown in Figure I.8.

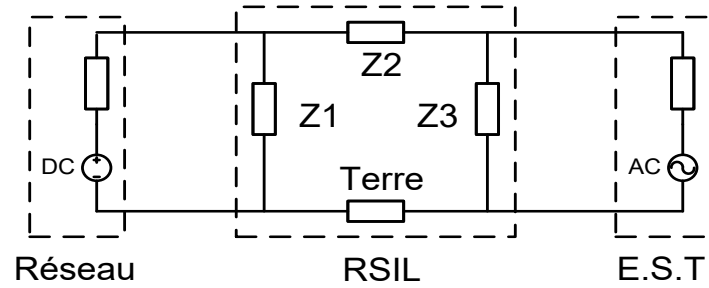


Figure I.8. General topology of an LISN.

The efficiency of the LISN must be maintained over a wide range of frequencies, as it operates in two distinct frequency bands.

- The network frequency f_{network}
- The interference frequency $f_{\text{interference}}$

For these two frequency ranges, the LISN incorporates two corresponding simplified structures, as illustrated in Figures I.9 and I.10.

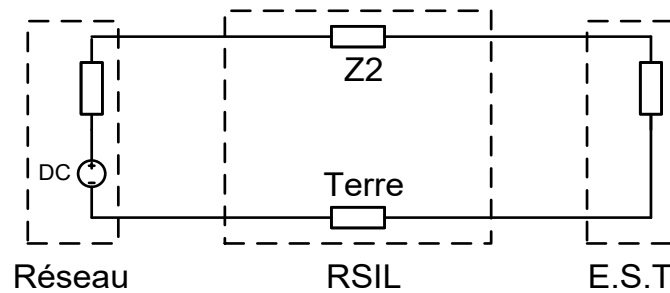


Figure I.9. Simple diagram of the LISN at low frequency (LF).

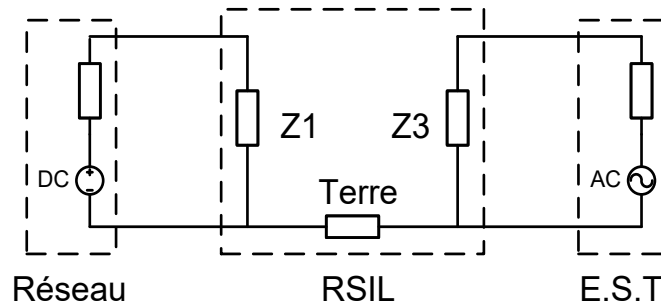


Figure I.10. Diagram of the LISN at high frequency (HF).

Thus, the LISN must simultaneously perform four tasks:

- Ensure that the device under test is supplied with low frequency without significant attenuation (with a voltage drop of less than 5% of the nominal voltage). To achieve this, the network must present a very low impedance Z_2 at the load while maintaining very high impedances Z_1 and Z_3 relative to ground.
- From the perspective of the power network, the LISN must present a high impedance (Z_2) to block, and a low impedance (Z_1) to short-circuit, high-frequency disturbances coming from the network or from other users connected in parallel, thus preventing these disturbances from contaminating or distorting the measurement at Z_3 .
- From the perspective of the device under test (the disturbance generator), the LISN must isolate the generated disturbances from the mains by channeling them into the measurement impedance Z_3 , which serves both as a load for the disturbance generator and as a fixed reference impedance of the power network.
- Maintain a fixed impedance of $50\ \Omega$ between phase and ground, as well as between neutral and ground, to properly manage the high-frequency electromagnetic pulses (EMIs) emitted by the tested equipment [9].

I.8.1.2.2 Analysis of the LISN with respect to measurement

EMI can propagate between two systems in two modes: differential mode (DM) and common mode (CM). Differential mode disturbances are represented by the voltage drop $V_{PG/NG}$ across the characteristic impedance ($50\ \Omega$), resulting from the current I_{DM} circulating in a closed loop between phase and neutral, without significant interaction with parasitic elements between the system and ground. In contrast, common mode disturbances involve a common-mode current circulating in a closed loop formed by the phase, neutral, and ground conductors. [10]

To avoid any confusion regarding the path of common-mode disturbances, it should be noted that the common-mode current flowing through the ground is denoted I_{CM} , with $I_{MC/2}$ flowing through each conductor (phase and neutral).

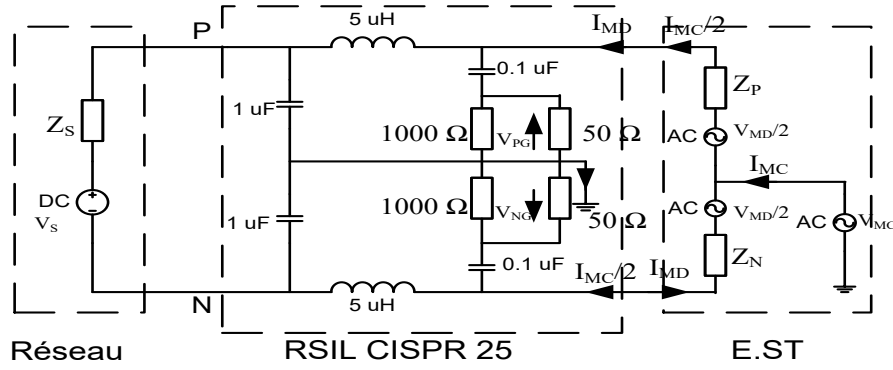


Figure I.11. LISN with respect to DM and CM disturbances.

According to Figure I.11, the phase current I_{PG} and neutral current I_{NG} are defined by the following equations:

$$I_{PG} = \frac{I_{CM}}{2} + I_{DM} \quad (I.1)$$

$$I_{NG} = \frac{I_{CM}}{2} - I_{DM} \quad (I.2)$$

Thus, the voltage drops across the impedances (50Ω) are defined by the following equations:

$$V_{PG} = 25 \cdot I_{CM} + 50 \cdot I_{DM} \quad (I.3)$$

$$V_{NG} = 25 \cdot I_{CM} - 50 \cdot I_{DM} \quad (I.4)$$

V_{PG} : the voltage between phase and ground.

V_{NG} : the voltage between neutral and ground.

The common-mode current is defined as:

$$I_{CM} = I_{PG} + I_{NG} = \frac{V_{PG} + V_{NG}}{50} \quad (0.5)$$

$$V_{CM} = \frac{V_{PG} + V_{NG}}{2} \quad (0.6)$$

The differential-mode current is defined as:

$$I_{DM} = \frac{I_{PG} - I_{NG}}{2} = \frac{V_{PG} - V_{NG}}{100} \quad (I.7)$$

$$V_{DM} = V_{PG} - V_{NG} \quad (0.8)$$

I.9 EMC Protection Techniques:

Improving EMC involves actions on both the source side and the victim side. On the source side, efforts focus on minimizing the emission of electromagnetic disturbances, while on the victim side, measures are taken to protect systems from external interference. Although these approaches may seem distinct, they often rely on interconnected techniques. As previously noted, interference reaches its target through coupling mechanisms; this is the crucial point for intervention. An effective strategy is to use decoupling devices, a concept that predates the formal introduction of electromagnetic compatibility into the technical vocabulary.

I.9.1 Shielding

A shield or electromagnetic screen (Figure I.12) is a conductive enclosure that divides space into two distinct zones: one containing the sources of electromagnetic fields, and the other intended to remain unaffected. The main objective of shielding is twofold: to confine radiated emissions within the shielded enclosure and to prevent the penetration of external electromagnetic radiation into the protected zone [11].

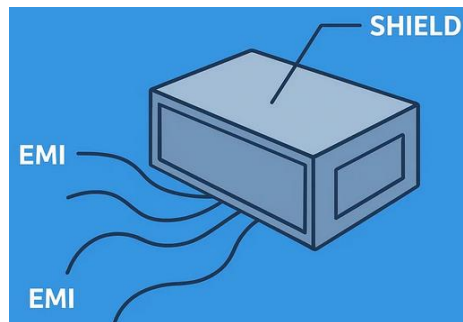


Figure I.12. Electromagnetic shielding.

I.9.2 Filtering

Filters are designed to allow the transmission of desired signals while attenuating or eliminating unwanted components, such as EMIs, from the signal path (Fig. I.13) [12].

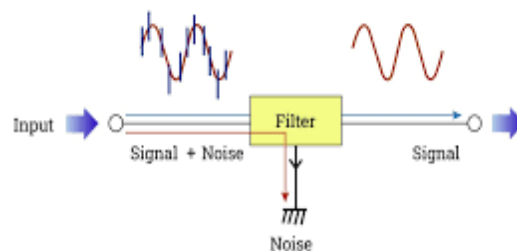


Figure I.13. EMF Filtering.

I.9.3 Twisting

Twisting involves replacing a large loop formed by two parallel conductors with several smaller loops arranged so that opposing magnetic fluxes within adjacent loops cancel each other out pair by pair (Figure I.14). While slight asymmetries between individual loops—even down to micrometer-level differences—can cause residual interference, the overall disturbance is significantly reduced. This technique is particularly effective for reducing low-frequency interference, typically up to 100 kHz, and in some cases, up to 1 MHz [11].

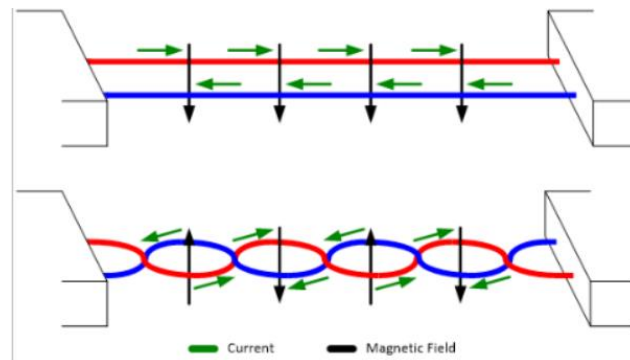


Figure I.14. Magnetic field reduction using the twisting principle.

I.10 Conclusion:

This chapter provides a general overview of electromagnetic compatibility (EMC) by addressing the phenomenon in three main parts. It first establishes that EMC issues are widespread and, in some cases, particularly disruptive. It then examines how electromagnetic disturbances are generated and discusses general strategies for minimizing their impact. Although the discussion has remained at a general level, it has laid the groundwork for understanding the importance of EMC and the need for effective mitigation measures.

In the second part, we explored the fundamental aspects of EMC, focusing on the propagation vectors and the different modes through which electromagnetic disturbances are transmitted. The transmission of EMIs from a source to a victim involves one or more physical mechanisms called coupling, which can occur either through direct radiation or conduction along cables.

In the third part, we examined the impacts and implications of EMC in the field of power electronics. In particular, we discussed EMC testing procedures, applicable standards, and common protection techniques. Energy conversion in power electronics relies on two

complementary processes: switching and energy storage. Switching is carried out using power semiconductors, which enable the rapid transitions essential for effective energy control and regulation.

Chapter II:

Conducted electromagnetic interference (EMI) Modelling for DC– DC Converters

II.1 Introduction:

A comprehensive model is necessary for EMI analysis and prediction. The following sections present modeling techniques for various EMI aspects, with particular emphasis on conducted emissions. This is followed by a review of existing and proposed EMI modeling methods for DC–DC converters.

II.2 Overview of EMI modeling:

The following section provides an overview of the modeling and estimation of conducted EMI noise generated by a DC–DC converter.

II.2.1 Signal integrity and cross-talk

Signal integrity and crosstalk are the primary concerns related to the self-interference aspect of electromagnetic compatibility. Signal integrity involves ensuring that a signal remains undistorted during transmission through interconnects. As clock frequencies and data transfer speeds continue to increase, the impact of interconnect conductors on signal transmission becomes more significant.

EMI issues in printed circuit boards (PCBs) are categorized into areas such as traces, cables, grounding methods, and circuit configuration. In the circuit configuration category, studies focus on switched-mode power supplies and electromagnetically compatible components. In [14–16] review PCB simulation and modeling techniques, with particular attention to modern structures in terms of electromagnetic compatibility and signal integrity.

II.2.2 Conducted EMI modeling techniques

Conducted emission modeling techniques are classified into two main types: behavioral modeling and detailed modeling. Behavioral modeling treats power converters as black boxes using multi-port networks and measurements to predict common-mode (CM) and differential-mode (DM) noise. It is mainly used for system-level analysis. In contrast, detailed modeling focuses on the characteristics of circuit components through device-based approaches and equivalent circuits. Engineers may also combine both methods for more accurate EMI modeling. Figure II.1 presents the classification of conducted EMI modeling methods.

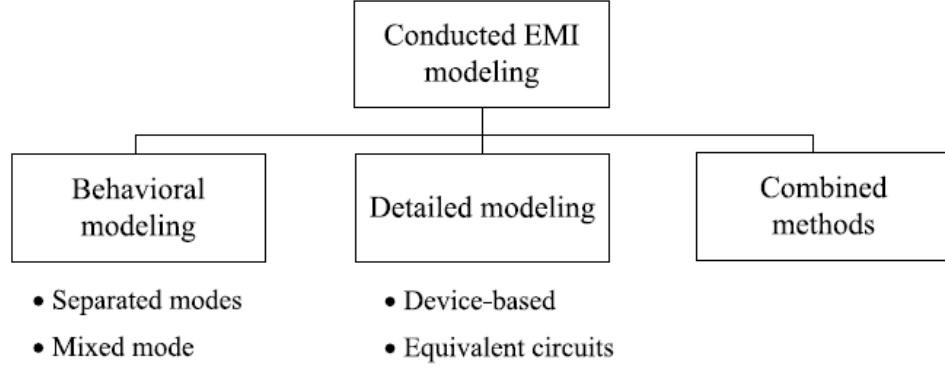


Figure II.1. Classification of conducted EMI modeling techniques.

II.2.2.1 Behavioral modeling

Reference [17] first proposed the use of an equivalent Thevenin source to represent the EMI behavior of a single IGBT switch. In this model, the IGBT package is treated as the primary noise source, while a two-port impedance network is used to describe the propagation path, as illustrated in Figure II.2. Since the propagation characteristics of DM and CM noise are generally different, they are modeled separately. The impedance matrix of the propagation path is determined experimentally using an impedance analyzer, together with voltage and current measurements.

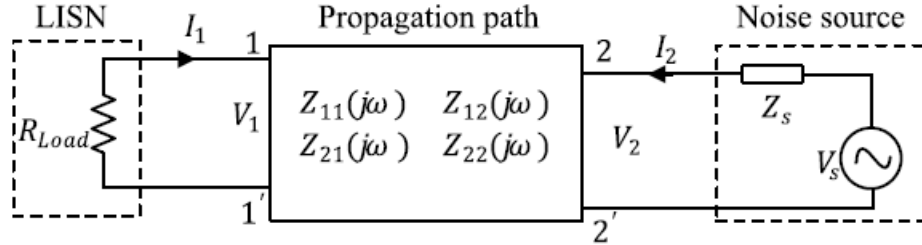


Figure II.2. Thevenin equivalent EMI noise emission model for a single IGBT [17].

The LISN port (V_1 , I_1) is used, and by applying equation (II.1), the values of V_2 and I_2 are determined.

$$\begin{bmatrix} V_1(j\omega) \\ V_2(j\omega) \end{bmatrix} = \begin{bmatrix} Z_{11}(j\omega) & Z_{12}(j\omega) \\ Z_{21}(j\omega) & Z_{22}(j\omega) \end{bmatrix} \begin{bmatrix} I_1(j\omega) \\ I_2(j\omega) \end{bmatrix} \quad (\text{II.1})$$

$$V_2(j\omega) = V_s(j\omega) - Z_s(j\omega)I_2(j\omega) \quad (\text{II.2})$$

Using equation (II.2), the noise source parameters V_s and Z_s in Fig.II.2 can be determined. However, two sets of equations are needed to find the unknowns. The second set is derived by

modifying the impedance network. The resulting system of equations is then solved to obtain the voltage source V_s and the source impedance Z_s .

To address the mode decoupling problem, the terminal model of a single IGBT is extended to phase-leg-based converters, enabling the analysis of a wide range of common converter topologies [18]. An IGBT phase leg is represented using a three-terminal Norton model, as illustrated in Fig. II.3. the propagation path is replaced by a multi-port impedance network, whose matrix size depends on the number of phase legs. For a full-bridge converter consisting of two-phase legs, the impedance network becomes a 6×6 matrix (excluding ground). This modeling approach allows the simultaneous analysis of CM and DM emissions, including mixed-mode emissions.

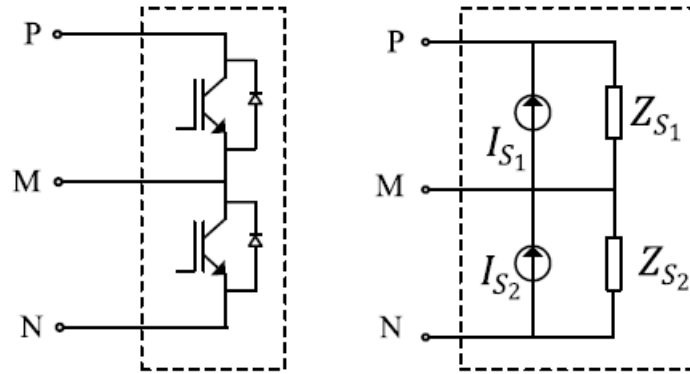


Figure II.3. Norton equivalent EMI noise emission model of an IGBT phase leg [18].

The methods discussed are known as Modular Terminal Behavioral (MTB) modeling, but the “modular” aspect is limited since it only holds under fixed switching and operating conditions. Moreover, increasing terminal count complicates the impedance network and makes measurements more difficult.

To address these issues, General Terminal Modeling (GTM) was introduced as a more general, black-box approach for multi-port systems with improved high-frequency accuracy [19]. Unlike MTB, GTM relies only on terminal voltage measurements, avoiding difficult impedance measurements and related noise and parasitic effects.

GTM models any three-terminal system using three impedances and two current sources, requiring five parameters in total as shown in Fig II.4. These are identified using three measurement cases (nominal and two modified impedance conditions), providing six equations to solve the unknowns [20].

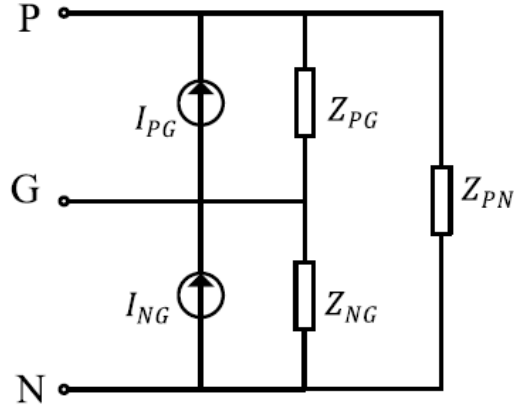


Figure II.4. Generalized three-terminal equivalent circuit [19].

Behavioral methods are simple, quickly derived, and independent of system configuration. However, they also have drawbacks. They require a standard measurement setup for each operating point and do not provide insight into internal component behavior. In addition, parameter identification is necessary, which can be particularly difficult at high frequencies. [21]

II.2.2.2 Detailed modeling

Detailed modeling techniques use a device-level, physics-based approach that includes all parasitic elements [21–26]. They are highly versatile for EMI analysis, offering good scalability and adaptability since component lumped models can be reused across different configurations. This also enables effective parametric studies. However, the method requires detailed physics-based models that are not always available, and the resulting lumped circuits can become complex, demanding significant computational resources. As a result, this approach is best suited for addressing EMI issues during the design phase.

Although simplified lumped-circuit models can predict common-mode (CM) and differential-mode (DM) noise, they are often time-consuming, particularly for parametric studies. In contrast, frequency-domain analysis offers a much faster approach.

II.3 Modeling for DC–DC Converters:

The following section presents modeling techniques for the main components of a DC–DC converter system.

II.3.1 Parasitic components

In power converters, the high dv/dt caused by fast switching devices generates CM and DM conducted emissions through system parasitic elements. Understanding the mechanisms of CM

and DM noise generation and propagation is essential for accurate conducted-noise analysis and prediction.

Switching waveforms with fast rise and fall times generate CM currents through the system's stray capacitors to ground. The dominant stray capacitances include those between the DC–DC converter enclosure and ground, cable shielding and ground, and the switching device and grounded heat sink. In addition, stray inductances in the DC bus bar, connecting wires, leads, and the DC-link capacitor impedance play a significant role in both CM and DM noise generation [21].

Inductors and capacitors exhibit parasitic characteristics that become significant at high frequencies. The equivalent circuit of a capacitor (Fig. II.4.b) includes an equivalent series inductance (ESL) and an equivalent series resistance (ESR), which arises from the capacitor leads and electrode plates. For inductors, the equivalent parallel capacitance (EPC) is caused by capacitances between windings, turns, and the core, while the equivalent parallel resistance (EPR) results from the coil resistance, as illustrated in Fig. II.5.a [27].

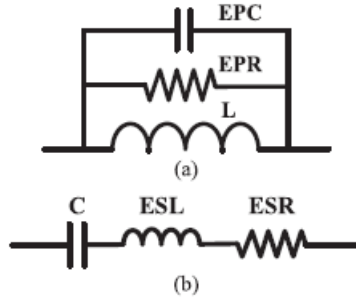


Figure II.5. High frequency equivalent models: (a) Real inductor, (b) Real capacitor.

II.3.2 Switching devices

Switching devices are the main source of noise in power converters because each switching event generates sharp pulses that create CM and differential-mode DM currents. Accurate modeling of these devices is therefore essential for EMI analysis. Commercial simulation tools use detailed nonlinear models, including physics-based models such as Hefner's IGBT model, to capture switching behavior [28]. Similar physics-based models have also been developed for IGBTs [29] – [33] and power MOSFETs [34] – [36]. Common simulation platforms include SPICE-based tools, PSIM, and ANSYS Simplorer, with model parameters obtained from measurements and device datasheets [37], [38].

Power switching devices can be implemented as either modules or discrete components, depending on the application. For power modules, parasitic inductance must be included in the model to improve accuracy. The stray capacitance between the module and the grounded heatsink is also important for calculating CM conducted noise. Because the insulating layer between the module and heatsink is very thin to enhance thermal performance, this stray capacitance is typically significant. An equivalent circuit of an IGBT phase leg incorporates interconnects and lead inductance as well as stray capacitances is depicted in Fig. II.6.[28].

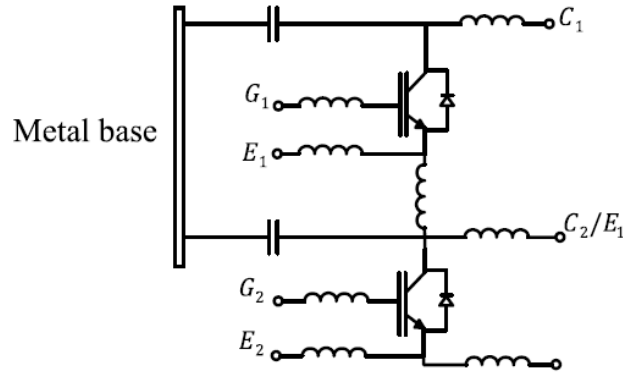


Figure II.6. Equivalent circuits of an IGBT phase leg with stray capacitances and inductances [28].

Accounting for the nonlinear behavior of switching devices improves accuracy but increases model complexity and simulation time. To address this, analytical and simplified approaches have been developed. One method divides the switching period into several time intervals, models the nonlinear stray capacitances of the IGBT in each interval, and solves the corresponding voltage and current equations to reconstruct the overall waveforms. Another approach uses a piecewise-linear IGBT model, as depicted in Fig. II.6 [39]. Where parameters such as on-state resistance are obtained from datasheets and capacitances are measured experimentally. Simplified models also include stray capacitances between the IGBT terminals and the base plate, as well as lumped device capacitances. Additionally, trapezoidal source modeling approximates switching voltage waveforms, significantly reducing simulation time while maintaining acceptable accuracy [40].

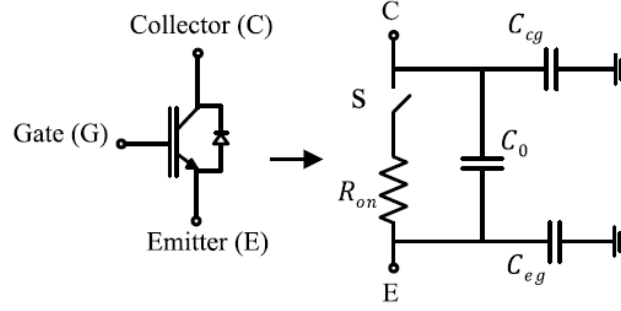


Figure II.7. Piece-wise linear IGBT model [39].

II.3.3 Bus bars

Bus bars are high-current conductors that connect key power converter components such as the DC source, bulk capacitor, and switching devices. A laminated bus is shown in Fig. II.8, consisting of conductive layers separated by insulation, is widely used due to their favorable electrical characteristics [41]. Effective bus bar design aims to minimize stray inductance, which helps reduce voltage overshoot and conducted EMI. This can be achieved by using thin, flat conductors with large surface areas, minimizing holes, and reducing the spacing between conductive layers. Closer conductor spacing also increases interlayer capacitance, which improves high-frequency noise filtering. The high-frequency equivalent circuit of a bus bar can be obtained through finite element analysis (FEA) or direct measurements, with FEA being the more commonly used method [42].

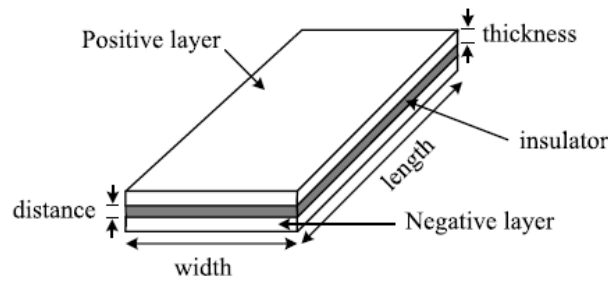


Figure II.8. A simple laminated bus bar.

II.3.4 Cables

Cable modeling techniques include direct impedance measurements, finite element analysis, and analytical calculations, with the choice depending on desired accuracy and available tools. Both lumped and distributed circuit models can be used: distributed models, consisting of

multiple series RLC sections, are better suited for long cables. The number of sections is selected based on cable length, required accuracy, and computational resources [43].

The number of sections used to model a long cable depends on its length, required accuracy, and computational capacity. For example, [44] models a long cable with twenty segments, using series R and L for short-circuit behavior and C for open-circuit characteristics shown in Fig. II.9. Similarly, [45] employs RL and RC ladder networks to represent the cable's distributed impedance.

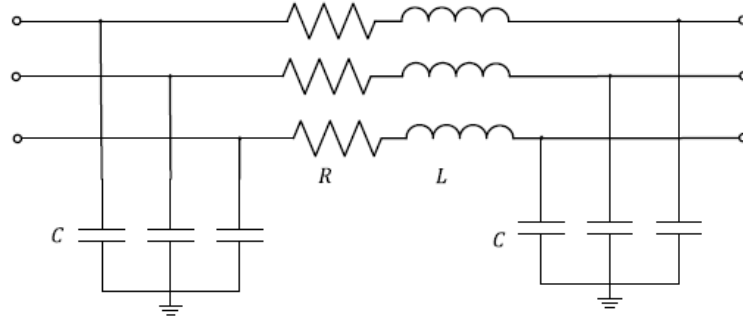


Figure II.9. Per section equivalent circuit for modeling a long cable [44].

II.4 Simulations methodologies:

Regardless of the modeling approach, conducted emissions must meet legal requirements defined in the frequency domain [46]. Simulations can be performed in either the time or frequency domain, which are connected through the Fourier transform. In power electronic systems, switching devices—the primary sources of noise—are typically modeled as square or trapezoidal voltage/current sources. Time-domain and frequency-domain signals are related through the Fourier transform. In power electronic systems, switching devices the main sources of electromagnetic noise are commonly represented by square or trapezoidal voltage/current waveforms.

The voltage or current waveform in the time domain resulting from switching can be approximated by a trapezoidal waveform, as illustrated in Figure II.10.

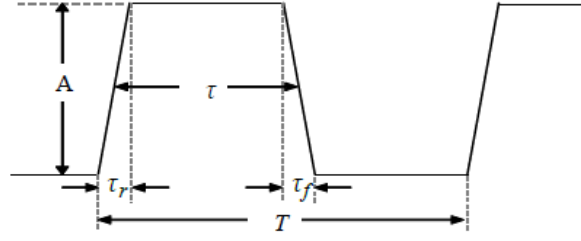


Figure II.10. Trapezoidal waveform in the time domain.

The waveform has amplitude A , a period T , and a conduction time denoted by τ . The rise time and fall time, both finite, are represented by τ_r and τ_f , respectively. Assuming $\tau_f = \tau_r$, the frequency spectrum of the waveform is given as follows [46]:

$$x(t) = A \frac{\tau}{T} + 2A \frac{\tau}{T} \sum_{n=1}^{\infty} \left[\frac{\sin(\pi f \tau)}{\pi f \tau} \right] \left[\frac{\sin(\pi f \tau_r)}{\pi f \tau_r} \right] \cos[2\pi f t - \pi f(\tau - \tau_r)] \quad (0.3)$$

Where $f = n/T$ is the frequency.

The amplitude spectrum of the trapezoidal waveform is shown in Figure II.11. As illustrated, the spectrum's asymptote has three slopes. The first cutoff frequency, located at $1/(\pi\tau)$, indicates that the higher the conduction time or duty cycles of the waveform, the lower the cutoff frequency. The -20 dB/decade slope is due to the first sine component in equation (II.1), which represents the harmonic response of the pulse width. Similarly, the -40 dB/decade slope is attributed to the second sine, representing the harmonic response of the rise/fall time. The second cutoff frequency, located at $1/(\pi\tau_r)$, shows that slower rise/fall times cause additional attenuation of higher-order harmonics. However, faster rise/fall times are preferred in power converters to reduce losses, which, in turn, increase the disturbance spectrum.

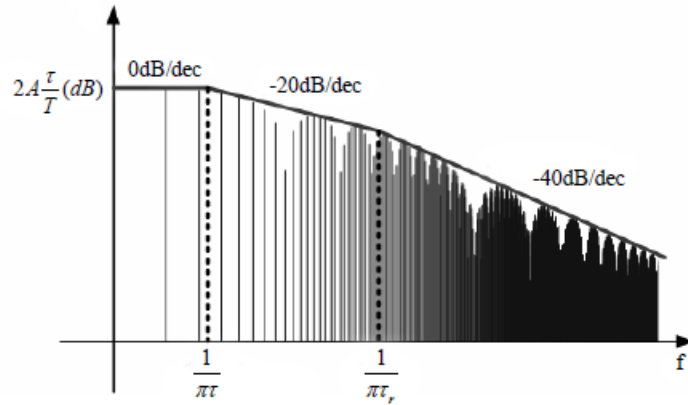


Figure II.11. Frequency spectrum of a trapezoidal waveform.

Time-domain analysis combined with Fourier transform is effective for EMI prediction, as it can account for system non-linearities using physics-based component models. However, analyzing conducted emissions at high frequencies requires very small time steps, increasing computational demands [47]. Time-domain analysis is time-consuming due to system complexity, small time steps, and the need to reach steady state. In contrast, frequency-domain analysis reduces computational effort and serves as a useful design tool, but it requires a good understanding of noise generation and propagation.

Measurement-based behavioral EMI models are mainly analyzed in the frequency domain, where CM and DM emissions are treated separately using equivalent circuits derived from noise sources and propagation paths as shown in Fig II.12. Model accuracy depends on mode decoupling, which is strongly influenced by converter balance. Unbalanced converters, such as buck converters, can generate mixed-mode (quasi-CM) noise due to unequal ground impedances and parasitic paths like heatsink capacitance.

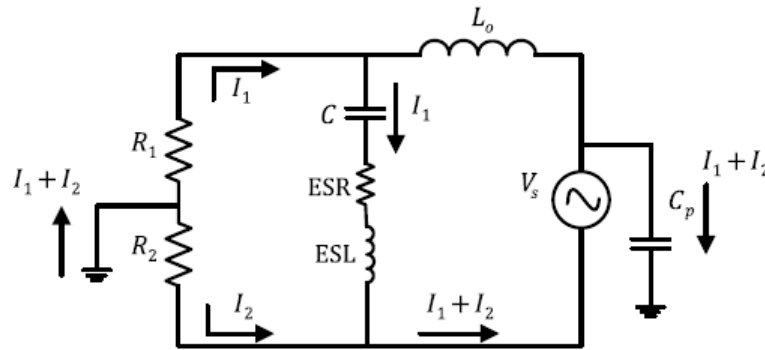


Figure II.12. CM current paths in a buck converter.

II.5 Conclusion:

This chapter reviews electromagnetic interference in DC-DC converters, highlighting affected locations, converter types, and typical conducted emission frequencies. Proper evaluation requires understanding the modeling and analysis of converter components, parasitics, switching devices, bus bars, and cables.

Chapter III:

Simulation Results and Analysis

III.1 Introduction:

Static converters with switching power processes generate and emit high-frequency electromagnetic interference (EMI). This interference can interfere with useful signals and cause malfunctions in a number of other electronic devices and systems, including industrial controls, communication systems, and medical, military, and vehicular applications. In power electronics, EMI propagates by conduction along the lines connecting power equipment. This chapter will present the characteristics and origins of EMI in DC-DC converters, as well as its propagation paths.

III.2 The LTSpice software:

LTSpice is mixed-signal simulation software (analog and/or digital) based on the SPICE language (Simulation Program with Integrated Circuit Emphasis). It runs on personal computers, which is why the first letters “LT” appear in its name. The name is thus an acronym: **LTSpice** stands for **L**inear **T**echnology Simulation Program with **I**ntegrated **C**ircuit **E**mphasis.

The original company MicroSim, the inventor of the SPICE product, was acquired by OrCAD. The latter developed a schematic interface to make it possible to draw an electrical circuit within the Windows environment.

In fact, OrCAD provides a set of tools called Capture CIS, which allows electrical circuit analysis to be performed using a personal computer. This new software replaces LTSpice, which was previously used for electrical circuit simulation. The company OrCAD was later acquired by Cadence Design Systems.

Due to its simulation power and the richness of its library of electronic components, we used this software for modeling solar cells and simulating a solar panel by combining several models of the created cells. Likewise, we used this software for the characterization of EMI generated by a DC/DC converter and propagated toward the power supply.

LTSpice can be used for simulation in two different ways: by drawing the desired circuit or by representing it in the form of code. In this project, we used circuit-based simulation. In Figure (III.1), we show the LTSpice Capture window. This is the home page, where we can create and simulate our project [34].

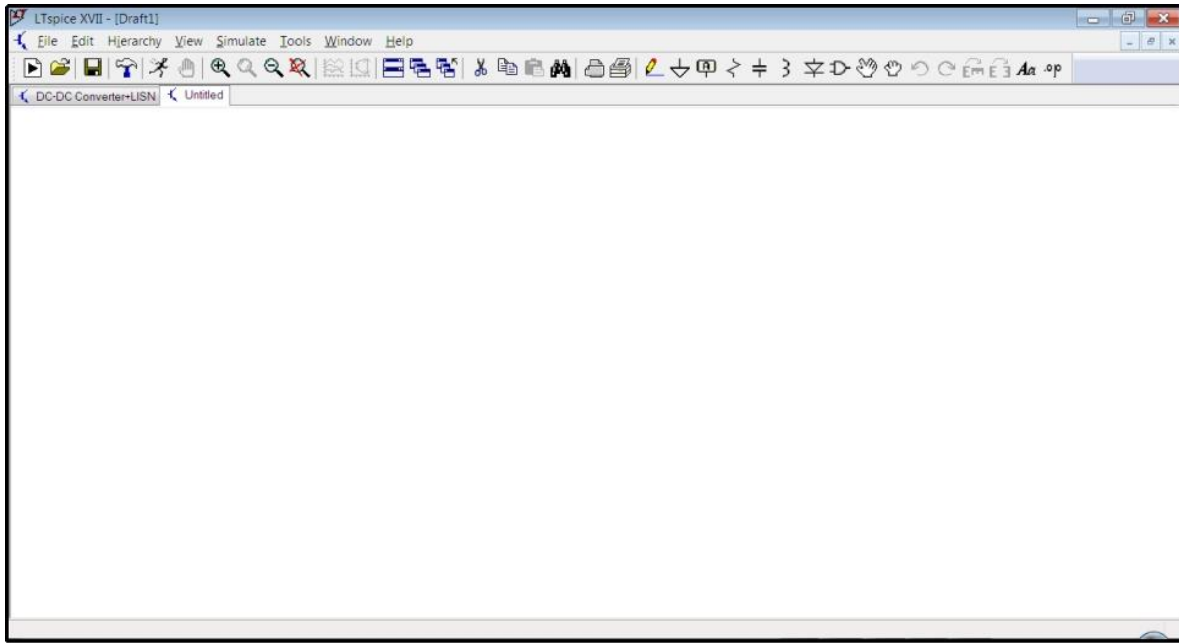


Figure III.1. Demonstration window of LTSpice XVII [34].

III.3 Simulation of a Boost Converter Using LTSpice Software:

A boost converter is a DC-DC converter widely used in PV inverters, designed to increase the input voltage to the required level. As illustrated in Figure III.8, its basic structure consists of an inductor, a switching device, and a diode. The switching element, typically a MOSFET or an IGBT, is controlled by a Constant Voltage (CV) Maximum Power Point Tracking (MPPT) system, as shown in Figure III.7. This discussion focuses on the use of a MOSFET as the switching device. During operation, the MOSFET alternates between the conducting and non-conducting states, causing fluctuations in the inductor current. This switching action stores energy in the inductor's magnetic field when the MOSFET is turned on and then releases it through the diode when the MOSFET is turned off, thereby increasing the output voltage.

In a boost converter, the switching device is the primary source of electromagnetic interference (EMI). Each switching transition generates high-voltage and high-current pulses, which in turn induce CM and DM currents along the propagation path. Therefore, accurate modeling of the switching device is essential for effective EMI analysis. Commercially available circuit simulation tools enable detailed modeling of these devices by accounting for their nonlinear switching characteristics.

For accurate modeling of a boost converter, it is essential to consider the parasitic inductance

inherent in the module configuration. In addition, the parasitic capacitance between the module and the heat sink plays a significant role in the generation and propagation of conducted common-mode noise, making it a critical parameter in EMI analysis.

III.3.1 Modeling of a Boost Converter

Figure III.8 shows the equivalent circuit of a boost converter with a duty cycle of 0.5 and a switching frequency of 35 kHz, incorporating the interconnection and bypass inductances as well as the parasitic capacitances. These parasitic components, which significantly influence high-frequency behavior, are generally determined through experimental measurements and are summarized in Table III.1.

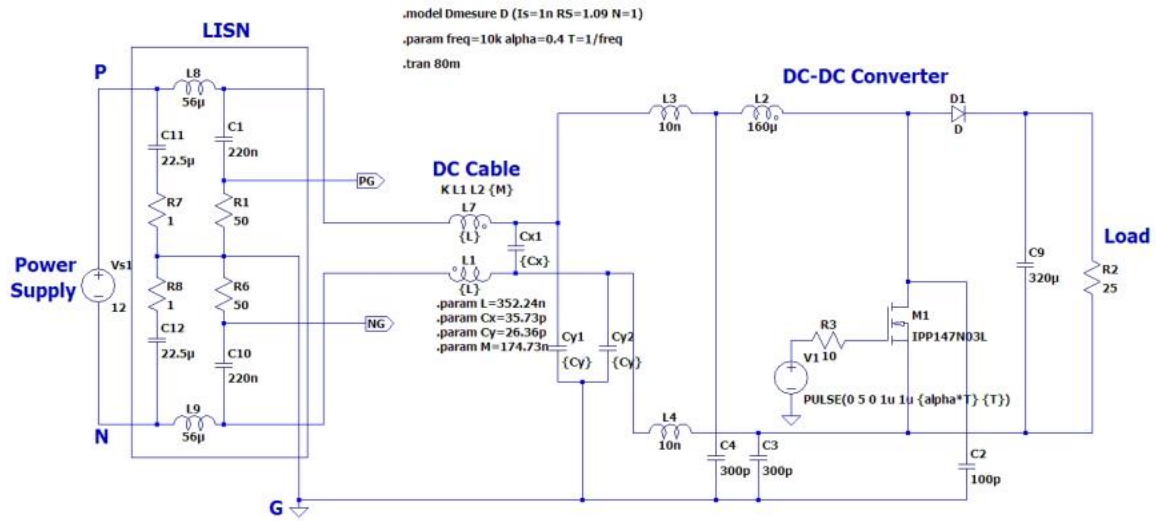


Figure III.2. Equivalent circuit of the boost converter connected to a LISN.

Table III.1. Parasitic Elements of the Converter.

Components	Value	Components	Value
C _{NG}	145.08pF	C _{LG}	145.08pF
L _N	71.49nH	L _L	71.49nH
C _{in}	100μF	C _{dc}	100μF
ESL _{in}	158.31nH	ESL _{dc}	158.31nH
ESR _{in}	200m Ω	ESR _{dc}	200m Ω
L _b	20mH	EPC _{Lb}	288 pF
EPR _{Lb}	150 kΩ	ESR _{Lb}	48 mΩ

In the context of conducted emissions, DC cables are often modeled as multiconductor

transmission lines. However, depending on the cable length and the frequency range under study, they can also be approximated as lumped inductive elements.

The DC cables used in the Converter are shielded twisted pairs, composed of multiconductor conductors with an outer diameter of 2.95 mm and an inner diameter of 2.25 mm. The cable modeling, illustrated in Figure III.3, is based on transmission line theory, where the cables are represented by short segments, each 1 meter long. The electrical parameters of these segments were determined experimentally through impedance measurements using an impedance analyzer, with the corresponding values provided in Table III.2.

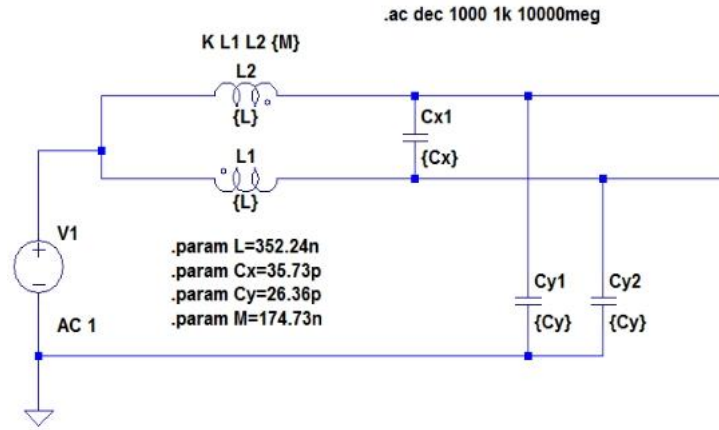


Figure III.3. DC Cable Model.

Table III.2. Identified Parameters of the Cables.

Components	Value
L [nH/m]	352.24
M [nH/m]	174.67
C _x [pF/m]	35.73
C _y [pF/m]	29.39

To ensure accurate measurement and effective attenuation of these disturbances, a LISN is used. The LISN configuration, as specified in the EN 55022 Class B standard, together with the values of its components, is illustrated in Figure III.4 and detailed in Table III.3.

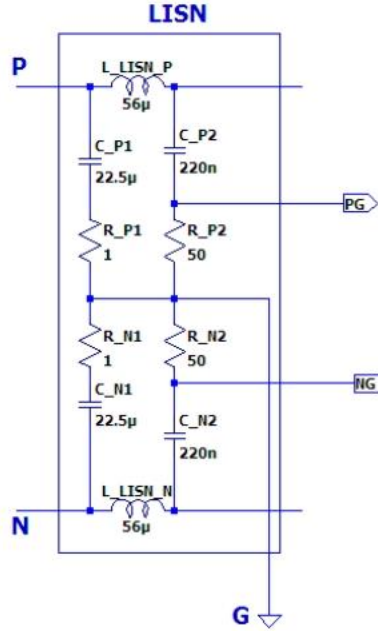


Figure III.4. Diagram of the LISN.

Table III.3. Electrical Parameters of the LISN.

Components	Value
L_{LISN_P} , L_{LISN_N}	56μH
C_{P1} , C_{N1}	22.5μF
C_{P_2} , C_{N_2}	220 nF
R_{P1} , R_{N1}	1 Ω
R_{P2} , R_{N2}	50 Ω

III.4 EMI Measurements:

To investigate the EMI generated by this type of converter, we simulated a Boost converter in **LTSpice**, whose schematic diagram is shown in Figure (III.5). In this study, we used an **IPP147N03L** MOSFET. The MOSFET is driven by a square-wave signal with a fixed duty cycle of **0.4** and a switching frequency of **10 kHz**.

Figure III.6 shows the voltage across the load, as well as the conducted electromagnetic disturbances measured across the equivalent resistance of the RSIL, resulting from the operation of the boost converter.

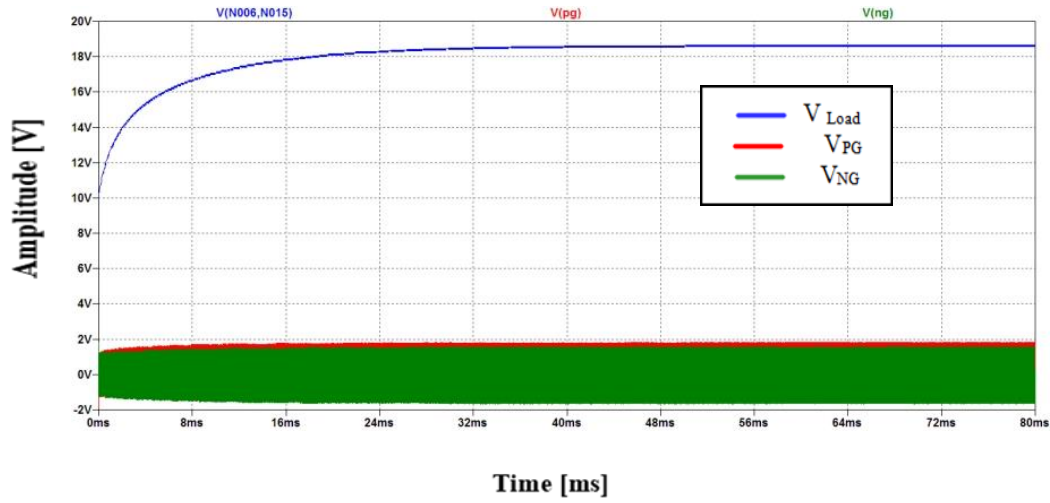


Figure III.5. Time variations of the load voltage and the voltages measured across the LISN terminals.

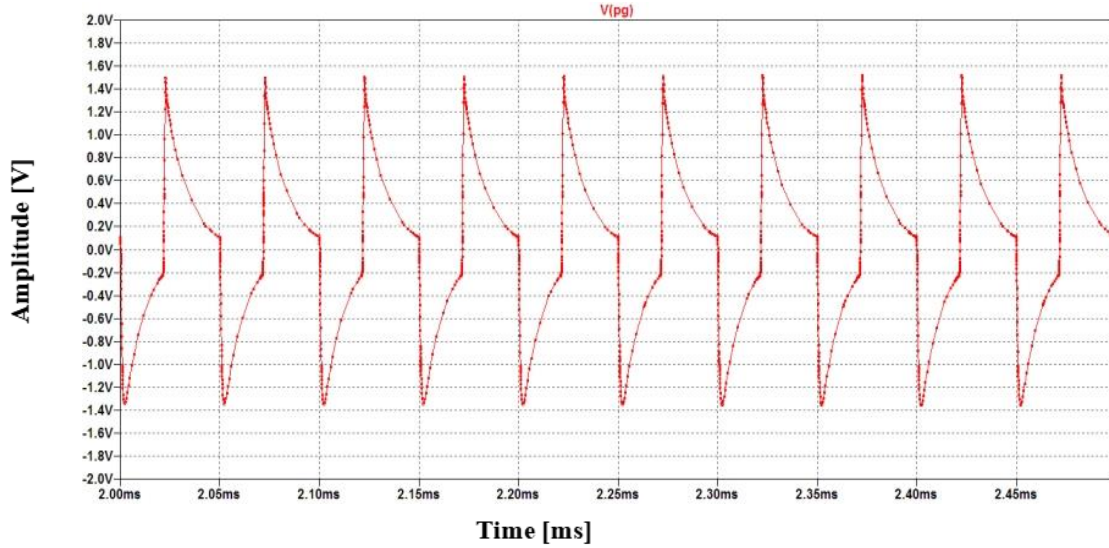


Figure III.6. Zoom on the voltage V_{PG} .

By zooming in on the switching time interval, as illustrated in Figure III.6, a periodic oscillatory phenomenon can be observed. This high-frequency oscillation results from the abrupt switching transitions of the MOSFETs, combined with the influence of the connection inductances and the passive components of the converter. The oscillation has a frequency of approximately 20 kHz and reaches a maximum amplitude exceeding 1.5 V.

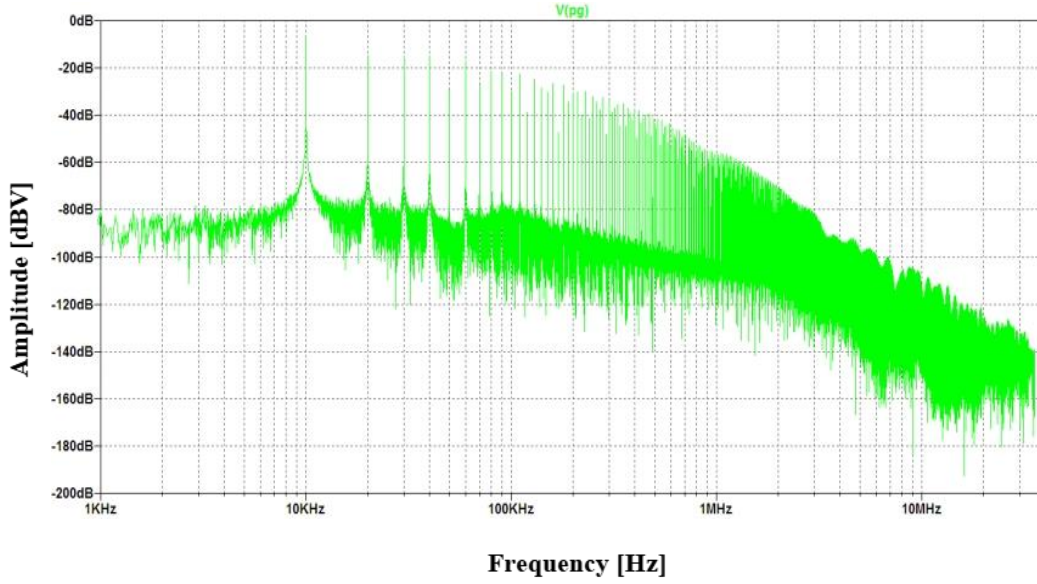


Figure III.7. Spectrum of the conducted EMI measured across the V_{PG} .

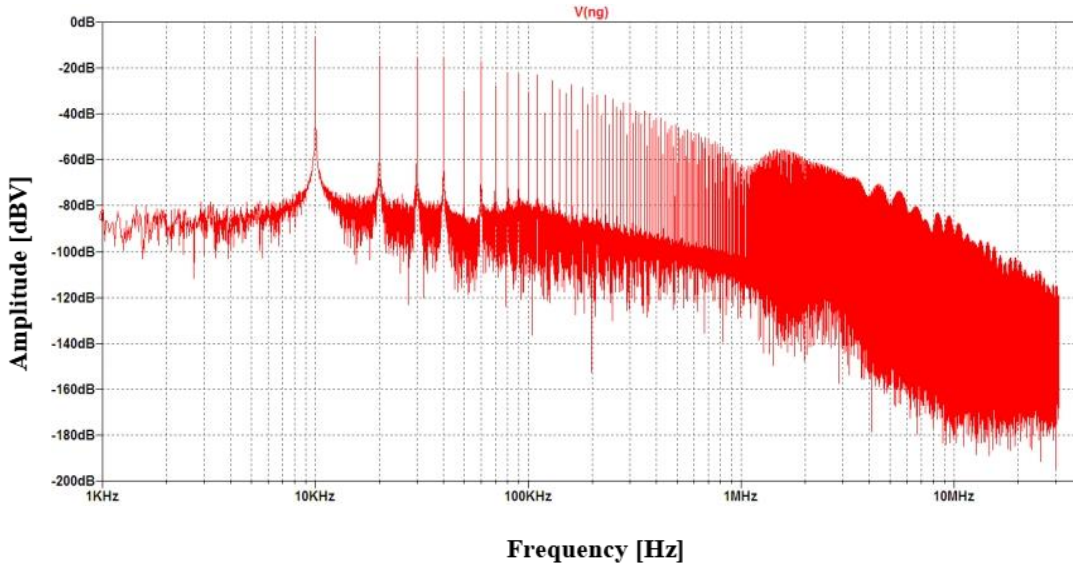


Figure III.8. Spectrum of the conducted EMI measured across the V_{NG} .

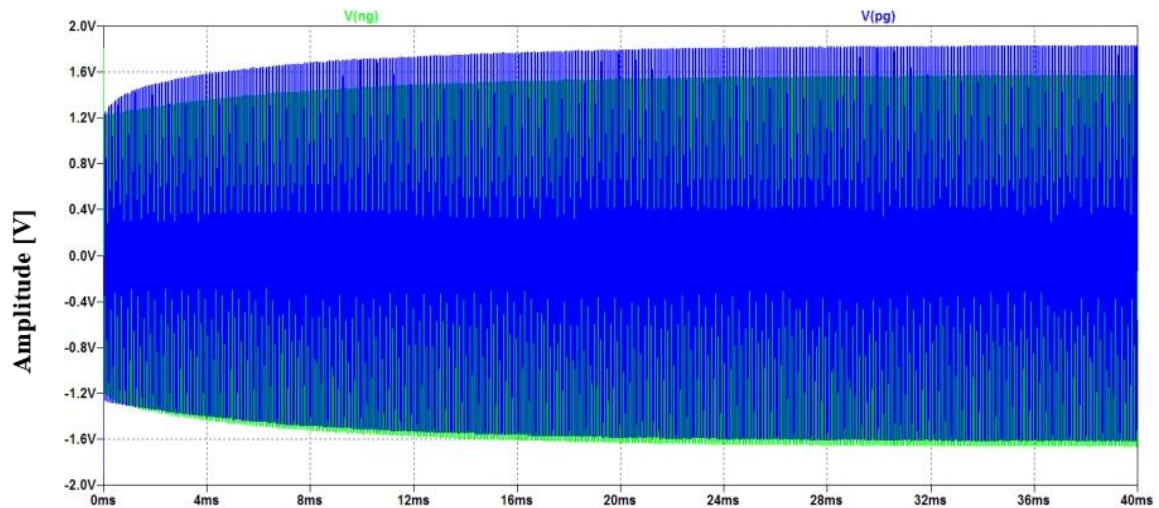
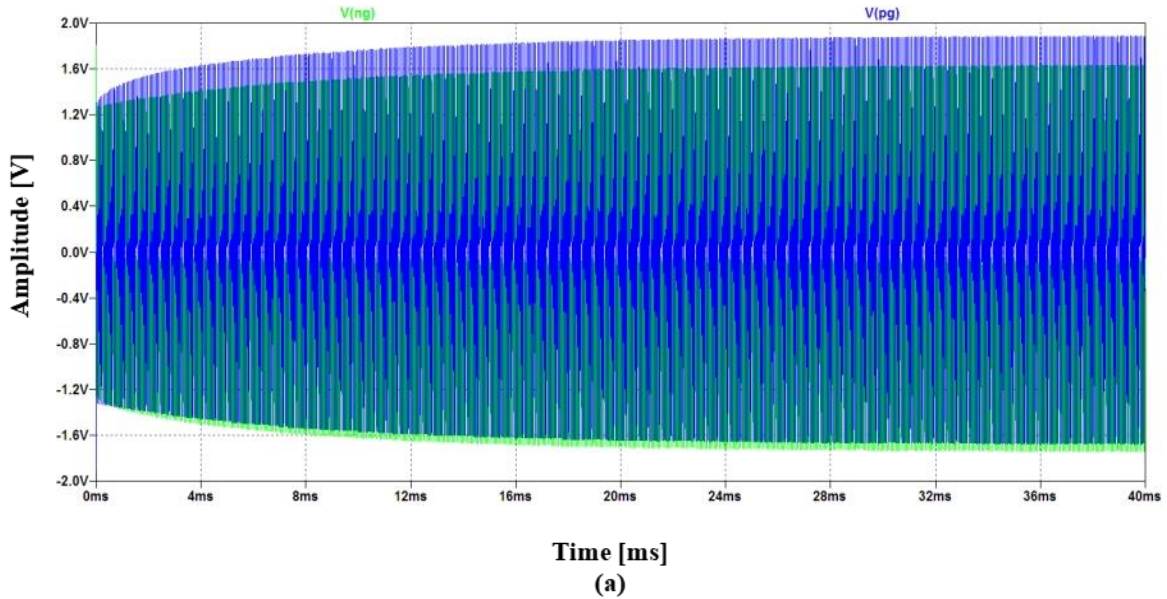
Figures III.7 and III.8 show the frequency-domain spectra of the conducted EMI measured across the V_{PG} and V_{NG} terminals corresponding to the boost converter. In the range from 1 kHz to 35 kHz, significant disturbance peaks are observed, with amplitudes ranging from 8 dB to -60 dB. Beyond 35 kHz, extending up to 10 MHz, the spectrum maintains high noise levels, with amplitudes between -30 dB and -100 dB, indicating persistent high-frequency electromagnetic disturbances caused by inverter switching transients and parasitic circuit effects.

III.5 Impact of Component Characteristics on EMI:

The resulting EMI are closely related to the type of MOSFET used in the converter, as well as to the converter's switching control characteristics, particularly their time-dependent behavior during switching events. This study aims to determine the extent to which these system parameters influence the EM disturbances.

III.5.1 Impact of Switching frequency

The switching frequency of the DC–DC converter is constrained by the internal limitations of the transistor, meaning that the number of switching cycles tends to vary inversely with the charge-flow dynamics. In this study, the converter switching frequency was set to three distinct values: **15 kHz**, **20 kHz**, and **30 kHz**.



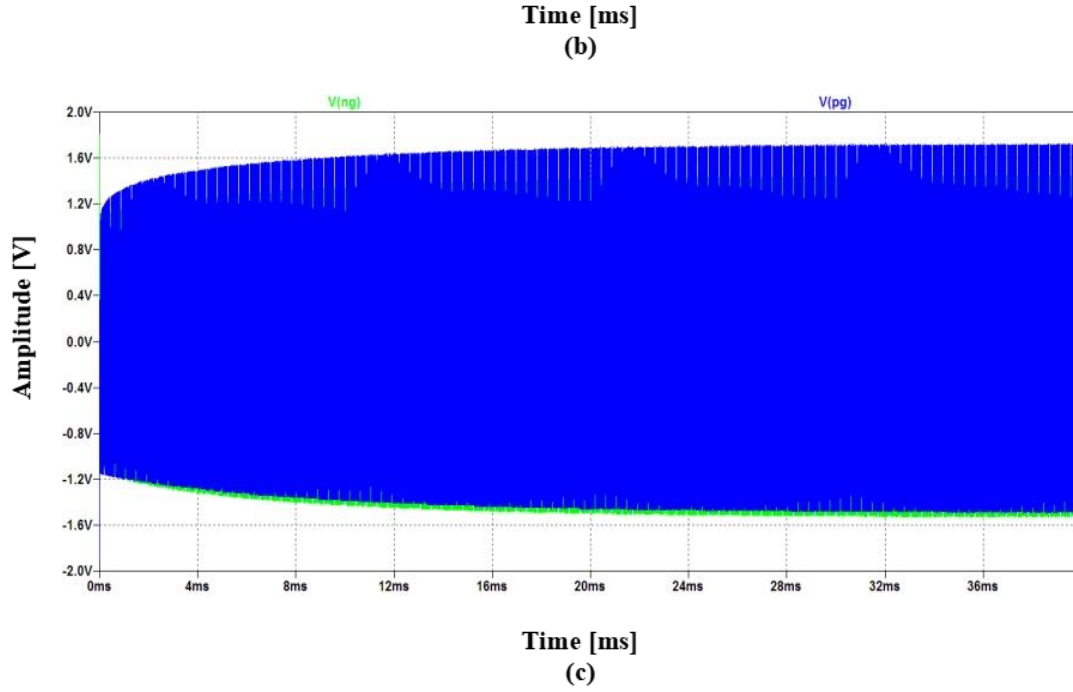
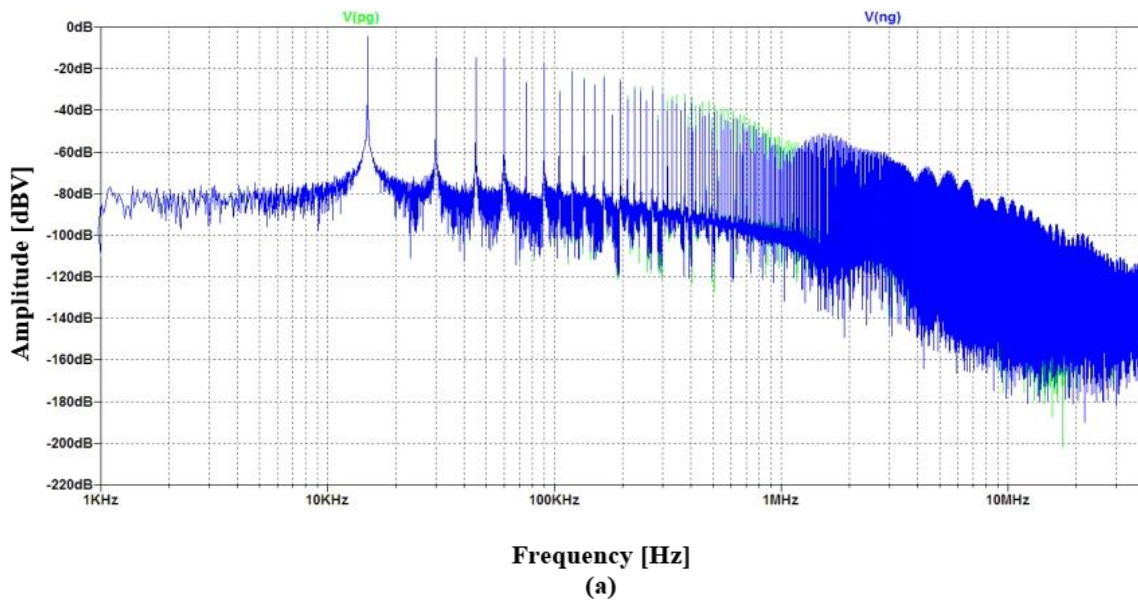


Figure III.9. Temporal variations of the voltage measured as a function of the converter switching frequency: (a) 15 kHz, (b) 20 kHz, and (c) 30 kHz.

The results of the temporal responses of the output signals measured across the RSIL terminals are presented in Figures III.9.a, III.9.b, and III.9.c. They illustrate the amplitude differences at three switching frequencies: $F = 15$ kHz, $F = 20$ kHz and $F = 30$ kHz, corresponding to maximum amplitudes of 19 V, 17 V, and 16.5 V, respectively. As the switching frequency increases, the amplitude of the EMI decreases.



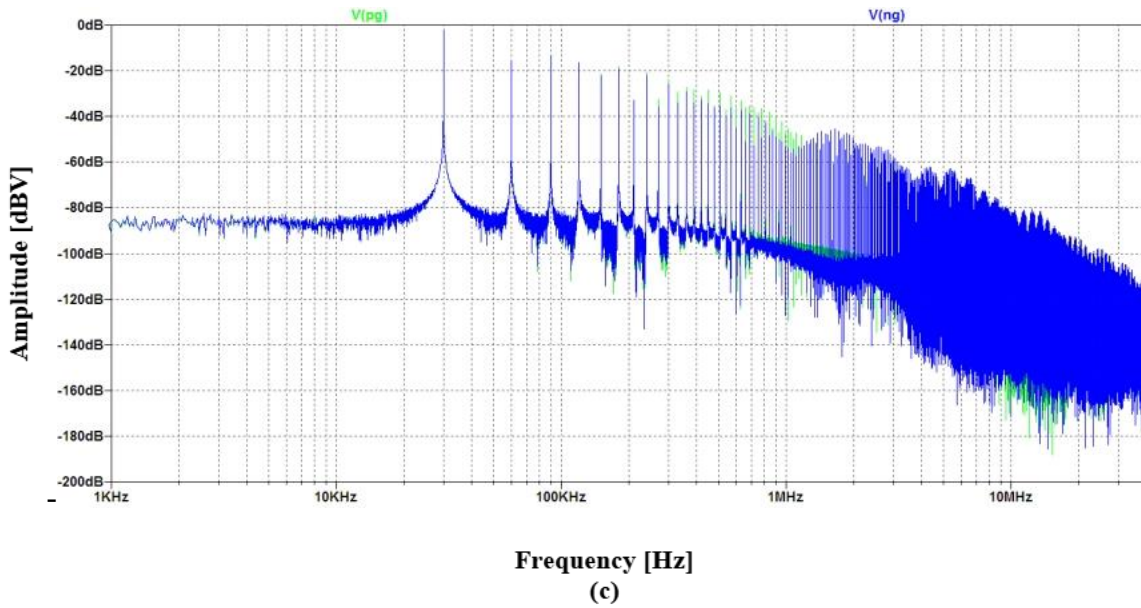
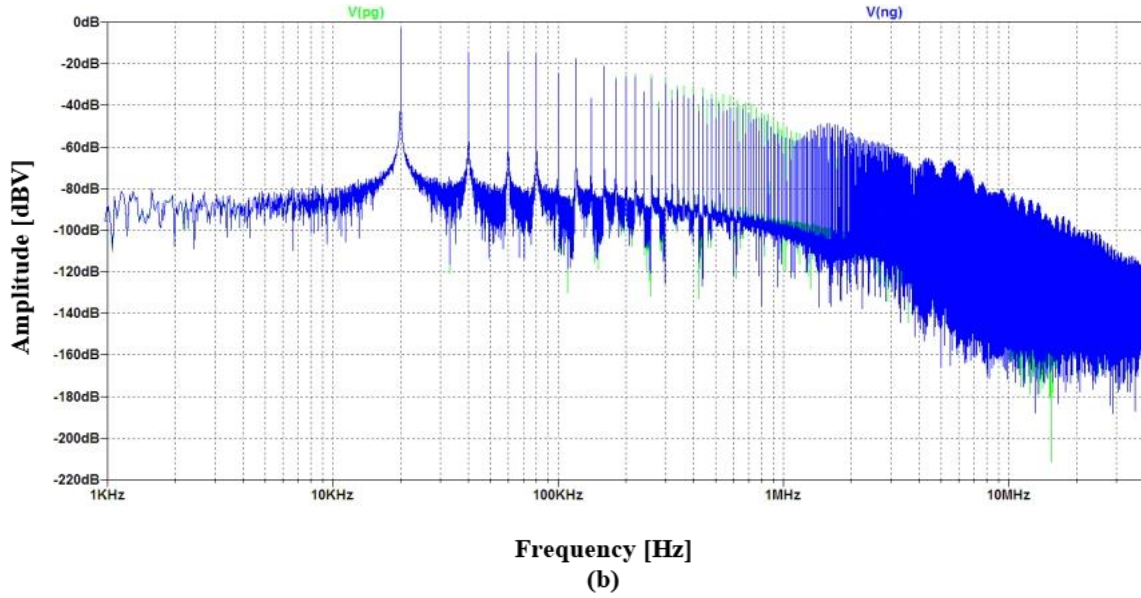


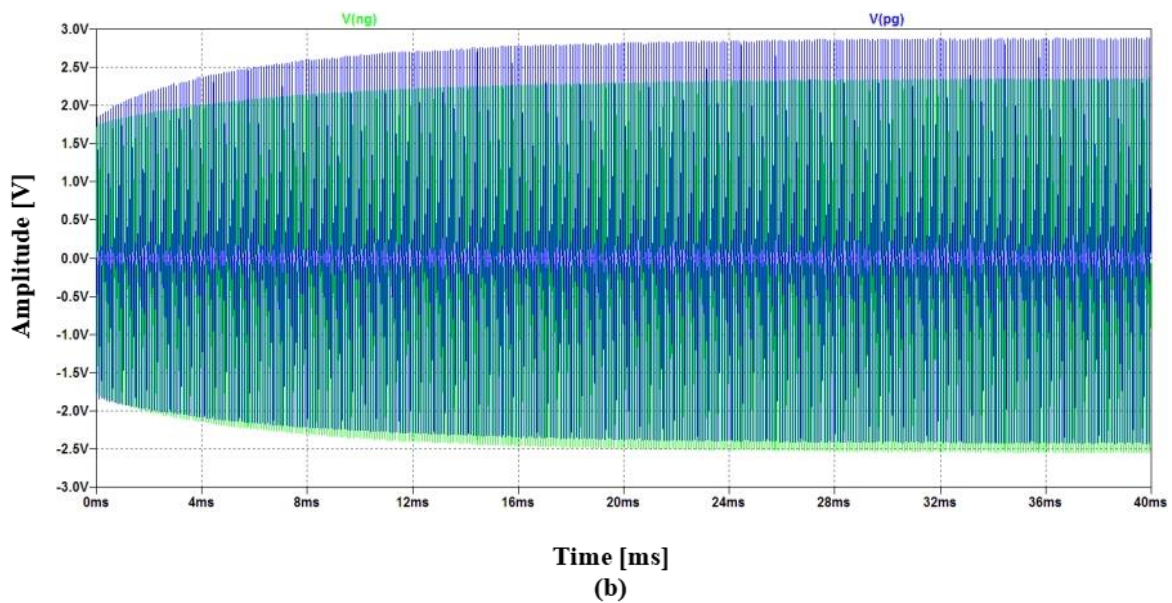
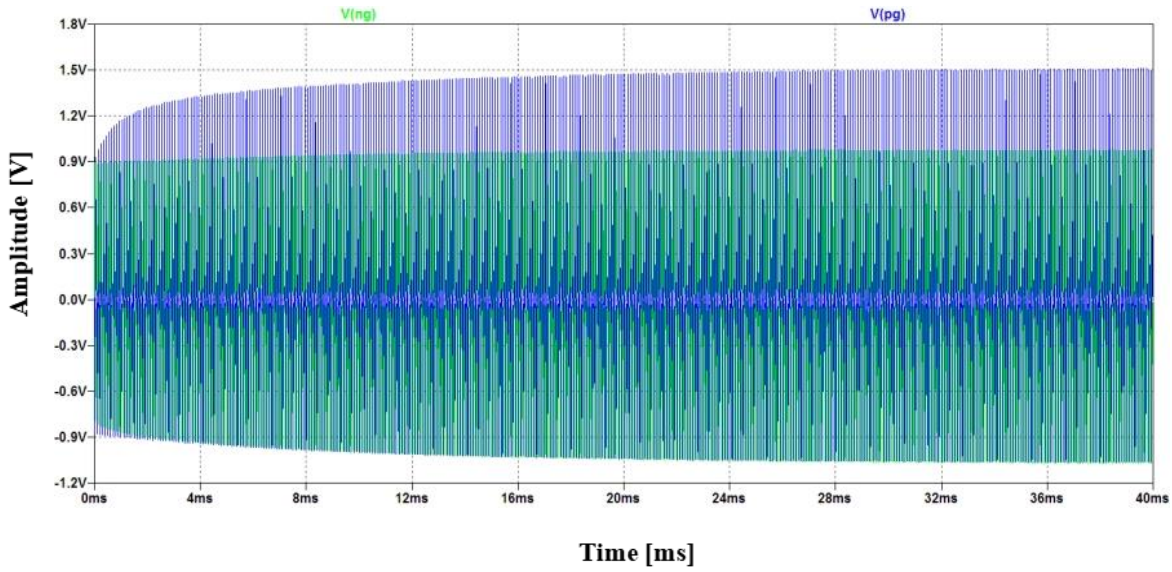
Figure III.10. Spectrum of the conducted EMI measured across the LISN terminals as a function of the converter switching frequency: (a) 15 kHz, (b) 20 kHz, and (c) 30 kHz.

The frequency-domain responses presented in Figures III.10.a, III.10.b, and III.10.c reveal an increase of approximately 10 dB in conducted EMI. This behavior is attributed to the higher switching frequency, which results in a substantial increase in the voltage transition rate (dv/dt) across the DC–DC converter. The increased dv/dt promotes stronger noise coupling through parasitic capacitances, especially those linking the converter to ground and the heat sink, consequently enhancing the propagation of electromagnetic disturbances throughout the entire

system.

III.5.2 Impact of MOSFET Selection

The selection of a MOSFET significantly affects conducted electromagnetic interference (EMI) in power electronic circuits. In particular, the package type and associated parasitic inductances influence high-frequency noise coupling into power and ground lines. Therefore, selecting a MOSFET requires careful consideration of both switching performance and EMI characteristics to achieve regulatory compliance while maintaining efficiency. In this study, three MOSFET package configurations were evaluated: **Case 1**, IPP147N12N3; **Case 2**, IPU135N08N3; and **Case 3**, STP8NM60.



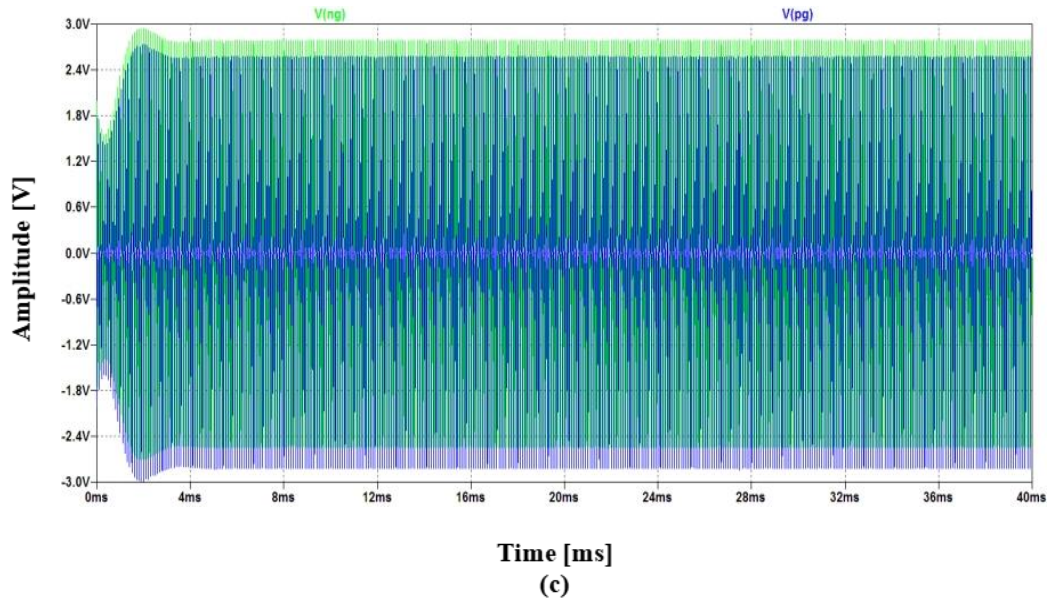
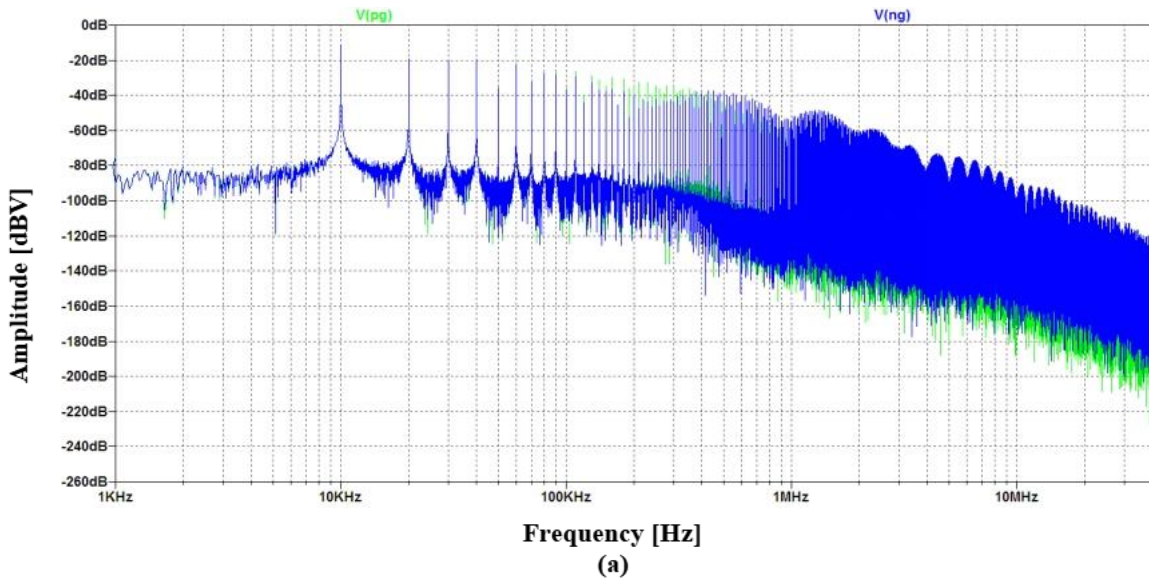
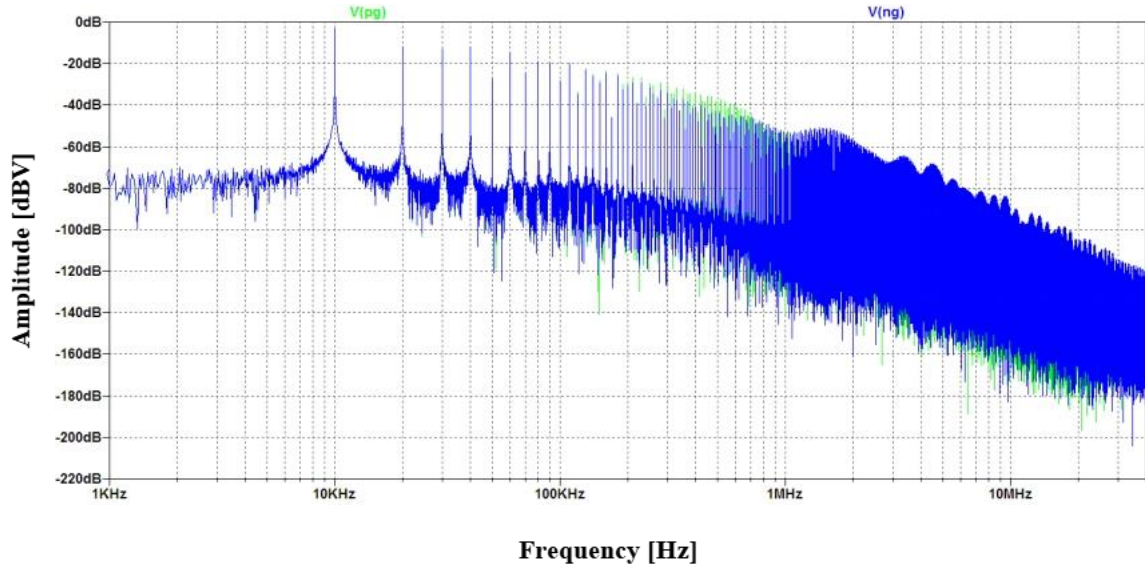


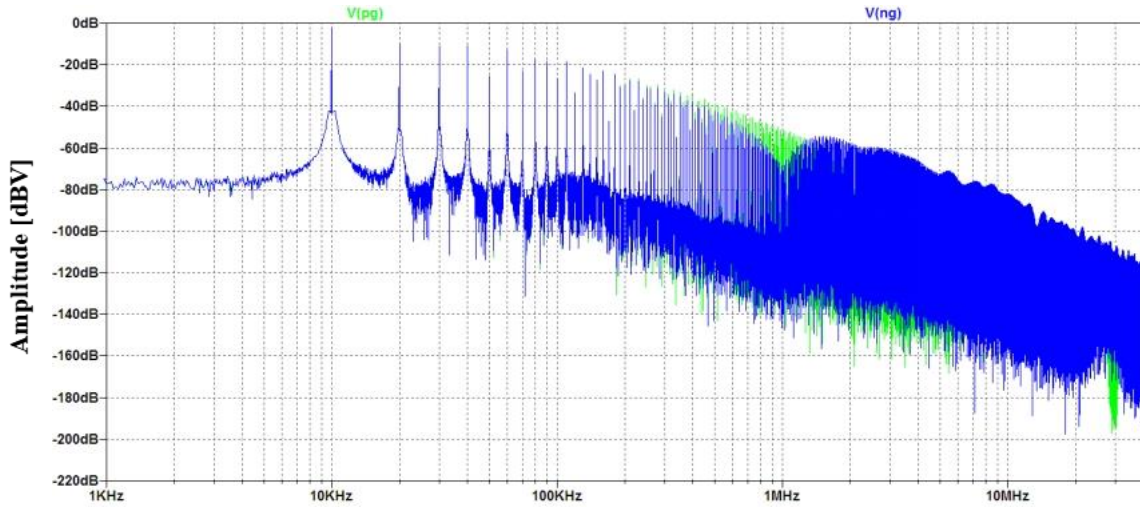
Figure III.11. Temporal variations of the voltage measured for different MOSFET selections: (a) Case 1, (b) Case 2, (c) Case 3.

Figures III.11.a, III.11.b, and III.11.c, which show the measured time-domain response across the RSIL terminals, illustrate the amplitude differences among three MOSFET examples: Case 1, IPP147N12N3; Case 2, IPU135N08N3; and Case 3, STP8NM60, with respective amplitudes of 1.6 V, 2.8 V, and 2.6 V.





(b)



(c)

Figure III.12. Spectrum of the conducted EMI measured across the LISN terminals for different MOSFET selections: (a) Case 1, (b) Case 2, (c) Case 3.

In the frequency domain, Figures III.12.a, III.12.b, and III.12.c show that the spectrum amplitude exhibits significant gains ranging from -8 dB to -38 dB around 150 kHz, and a minor disturbance of approximately -110 dB near 30 MHz for the MOSFET IPP147N12N3. For the MOSFET IPU135N08N3, substantial disturbances with amplitudes between -10 dB and -120 dB are observed in the frequency range from 150 kHz to 30 MHz.

For the MOSFET STP8NM60, the spectrum amplitude shows significant gains from -10 dB to -30 dB around 150 kHz, with a minor disturbance of -120 dB near 30 MHz.

III.6 Conclusion:

In this chapter, the high-frequency electromagnetic behavior of a DC-DC converter is analyzed comprehensively. The developed simulation model incorporates the system's key parasitic elements, including parasitic parameters, the impedance characteristics of DC cables, and the parasitic impedance of the boost converter.

Disturbance voltage spectra were evaluated through simulations, with results strongly influenced by the converter's parasites and different types of MOSFETs, particularly their time-dependent behavior during switching transitions.

Finally, the impact of varying the inverter's switching frequency was examined. Higher switching frequencies led to intensified noise coupling through parasitic capacitances especially those between the converter and ground or the heatsink thereby amplifying the propagation of electromagnetic disturbances throughout the system.

CONCLUSION

Conclusion

The work carried out during this thesis focused on the study of Electromagnetic Interference (EMI) in DC-DC converters used for electrical conversions.

The DC-DC converter employs power semiconductors in switching mode. This operation gives the converter a very high efficiency; however, it also generates numerous electromagnetic disturbances, mainly due to the rapid switching of the semiconductors. These disturbances propagate both toward the converter's power supply and toward the load it serves.

The objective of our study was to develop a model of a DC-DC converter incorporating parasitic components connected to switching devices through DC cables. This model enables an accurate estimation of disturbance sources and facilitates the development of detailed noise emission profiles within the system. It provides comprehensive information for the analysis of EMI and illustrates their behavior under various operating conditions and system configurations.

To achieve this objective, simulation results were analyzed using the LTspice software in order to investigate the electromagnetic disturbances (EMI) generated by a grid-connected DC-DC boost converter. The analysis considered the influence of cable parasitic components and switching characteristics. The results revealed that variations in the parasitic elements of the cables led to an increase in low-frequency peaks within the disturbance spectrum. This effect was particularly pronounced in the medium- and high-frequency ranges, where resonance phenomena caused a downward shift in the peak frequency. Finally, the impact of the switching frequency was evaluated, showing that higher switching frequencies intensified noise coupling through parasitic capacitances, thereby amplifying the propagation of electromagnetic disturbances throughout the system.

In terms of future perspectives, the implications of this thesis should be considered across different time horizons, depending on the evolution of priorities within the field. The following directions are proposed for future research and development as a continuation of the present work:

- Simulate and analyze advanced active EMI filters integrated within converters, assessing their efficiency across wide frequency ranges.
- Study how DC-DC converters influence the stability and EMI levels in microgrids or renewable energy systems.
- Analyze how different types of loads (resistive, inductive, electronic) affect EMI propagation and coupling.
- Implement data-driven optimization of converter design for minimal EMI.

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