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Multi objective optimization for DC-DC power converter with EMC consideration

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Abstract

This research project proposes a comprehensive multi-objective optimization approach for DC-DC power converters, emphasizing the resolution of Electromagnetic Compatibility (EMC) challenges. The methodology includes the application of the Design of Experiments (DOE) method alongside traditional objectives such as efficiency, analysis of EMI emissions under optimized conditions, and PCB implementation. Case studies will evaluate the proposed approach specifically in electric vehicle applications. The anticipated outcomes aim to guide engineers in developing high-performing DC-DC power converters compliant with EMC standards, contributing to advanced design practices aligned with contemporary power electronics priorities.

Resumé

Ce projet de recherche propose une approche d'optimisation multi-objectifs complète pour les convertisseurs DC-DC, en mettant l'accent sur la résolution des défis de compatibilité électromagnétique (CEM). La méthodologie inclut l'application de la méthode de plan d'expériences (DOE) avec des objectifs traditionnels tels que l'efficacité, l'analyse des émissions (EMI) dans des conditions optimisées et la mise en œuvre du PCB. Des études de cas évalueront l'approche proposée spécifiquement dans les applications de véhicules électriques. Les résultats escomptés visent à guider les ingénieurs dans le développement de convertisseurs DC-DC performants et conformes aux normes CEM, contribuant ainsi à des pratiques de conception avancées alignées avec les priorités contemporaines de l'électronique de puissance.

الملخص

يقترح هذا المشروع البحثي نهج شامل لتحسين متعدد الأهداف لمحولات الطاقة من تيار مستمر إلى تيار مستمر، مع التركيز على حل تحديات التوافق الكهرومغناطيسي. تتضمن المنهجية تطبيق طريقة تصميم التجارب (DOE) مع الأهداف التقليدية مثل الكفاءة، تحليل انبعاثات (EMI) تحت الظروف المحسنة و تنفيذ لوحة الدوائر المطبوعة (PCB). تقيم دراسات الحالة النهج المقترح بشكل خاص في تطبيقات السيارات الكهربائية. تهدف النتائج المتوقعة إلى إرشاد المهندسين في تطوير محولات الطاقة من تيار مستمر إلى تيار مستمر عالية الأداء ومتوافقة مع معايير التوافق الكهرومغناطيسي، مما يساهم في ممارسات تصميم متقدمة تتماشى مع أولويات الإلكترونيات القوية المعاصرة.

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Dedication

To my mother, who tirelessly raised and educated me, this graduation is a testament to your dedication and love. To my sister Ghada, my unwavering supporter throughout my life, your encouragement has meant everything to me. To my brother Moatez belleah , my other half, my unwavering pillar of strength, and my greatest champion. To my beloved younger siblings Mays and Moatasseem, who bring joy and laughter to our family every day, to my beloved father for his unconditional love and support. To Hana, Djihan, Majda, and Soumia, my beloved sisters, you mean the world to me. To Palestine, you are in our thoughts and hearts.

I personally wish to thank my teammate and dear friend Imane

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My heartfelt thanks go to my family for their unwavering support over the years, especially to my mother, father, brothers, as well as to Hamada, Nada, and Hana. May God bless them for their invaluable support throughout this work

To my teammate ouidjdane , I wish to convey my heartfelt gratitude and appreciation

Imane

To all our dear friends with whom we have shared unforgettable moments."

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Abbreviation list

BCM	Boundary Conduction Mode
CCM	Continuous Conduction Mode
CISPR	International Special Committee on Radio Interference
DC-DC	Direct Current
DCM	Discontinuous Conduction Mode
DOE	Design of Experiments
E	Electric field
EMI	Electromagnetic Interference
EMC	Electromagnetic Compatibility
ESR	Internal Resistance
FLC	Fuzzy Logic Control
H	Magnetic field
ICs	Integrated circuits
IEC	International Electrotechnical Commission
IGBT	Insulated Gate Bipolar Transistor
ISO	International Organization for Standardization
MPPT	Maximum Power Point Tracking
MPC	Model Predictive
OVAT	One Variable At a Time
PCB	Printed Circuit Board
PD	Proportional and Derivative controllers
PI	Proportional and integral controllers
PID	Proportional Integral and Derivative controllers
PWM	Pulse width Modulation

Q Predective Quality
R Regression Model
SSM State Space Modeling
SiC Silicon Carbide

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General introduction

The conversion of electrical energy lies at the heart of modern distribution and utilization systems, where DC-DC power converters play a crucial role. These devices enable the efficient and precise conversion of electricity from one form to another, thus facilitating various applications such as renewable energy integration, energy storage systems, and electric vehicles.

However, the development of efficient and reliable power converters faces significant challenges, particularly concerning Electromagnetic Compatibility (EMC). EMC is essential for ensuring the proper functioning of electronic systems by minimizing undesirable electromagnetic interferences that may disrupt the operation of surrounding devices.

In this context, this research project proposes an innovative methodology based on the application of the Design of Experiments (DOE) method alongside traditional objectives such as efficiency, analysis of EMI emissions under optimized conditions, and PCB implementation. Through case studies, this approach will be evaluated specifically in electric vehicle applications.

The anticipated outcomes of this project aim to provide engineers with tools and guidelines for designing high-performing DC-DC power converters compliant with EMC standards, thereby contributing to the advancement of design practices in the field of power electronics.

To achieve our goal, the manuscript is organized into four chapters. The first chapter provides an overview of power converters. The second chapter focuses on EMC considerations. The third chapter is dedicated to the optimization process. The final chapter investigates the EMC analysis and PCB implementation.

Part 01:

Our final project studies

Chapter 1

DC-DC converters: Principles, Types, and Applications

1.1 Introduction

DC-DC converters are essential components in modern electronics, enabling efficient power management across a wide range of applications. This chapter delves into the operation of DC-DC converters, their diverse topologies, and the associated switch control techniques. It highlights their significance across various domains and underscores recent advancements in control methodologies aimed at enhancing their performance and reliability.

1.2 Converters DC-DC

A DC-DC converter is an electronic circuit that facilitates the conversion of direct current from one voltage level to another based on the requirements. This electric power converter is capable of operating at a wide range of power levels from very low power, such as in the case of batteries, to very large power, such as in the case of large-scale high voltage power transmission systems [1].

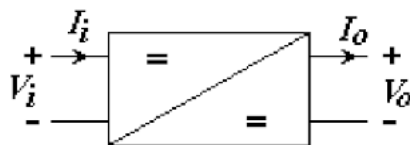


Figure 1: DC-DC Converter symbol

1.3 Operating principle

The operating principle of a DC-DC converter involves the temporary storage of energy in inductive or capacitive components, followed by its release at a different voltage level. This process is facilitated by electronic switches, typically transistors, which are controlled by control circuits [2]

the operating modes in a power converter include Continuous Conduction Mode (CCM), Boundary Conduction Mode (BCM), and Discontinuous Conduction Mode (DCM). In our

power converter work, we primarily utilize Continuous Conduction Mode (CCM) due to its stable operation and smoother waveforms for both current and voltage.

1.4 Types of DC-DC converters

1.4.1 Buck converter

The buck converter, also known as a step-down converter, is widely used in power electronics to reduce a high input voltage to a lower output voltage. This technology is essential in many applications, where certain components require a lower voltage to operate properly.

Its simplicity of design is one of its main advantages, allowing for efficient voltage conversion with a minimal number of components [3].

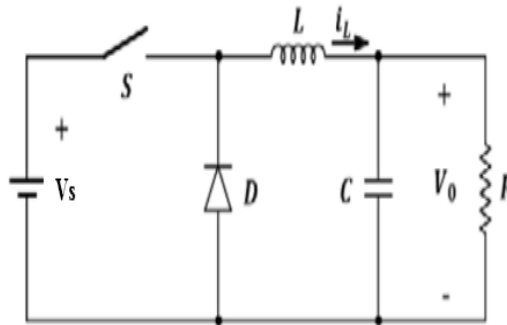


Figure 2 : The Buck Converter Circuit Diagram

The buck converter regulates energy transfer from input to output using switches, an inductor, and a capacitor. It utilizes a high-side MOSFET and a low-side diode to control current flow through the inductor. Adjusting the high-side switch's duty cycle regulates the output voltage proportionally to the input. Energy is stored in the inductor's magnetic field during the high-side switch's on-time and transferred to the output during its off-time [3].

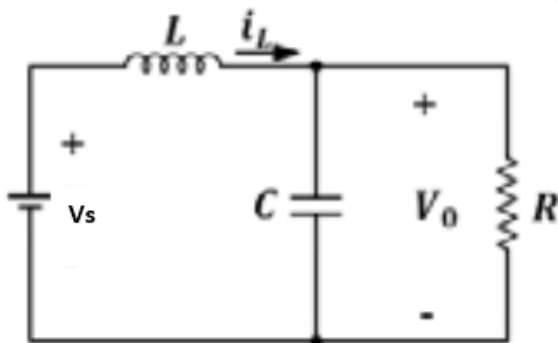


Figure 3: Circuit Diagramm for
Buck converter during Switch ON

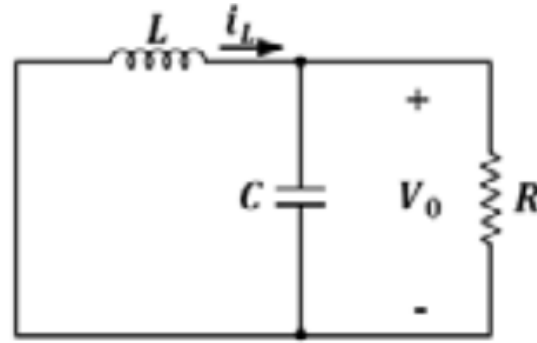


Figure 4: Circuit Diagramm for
Buck converter during switch OFF

The waveforms of current and voltage for a Buck converter are shown in the following figure:

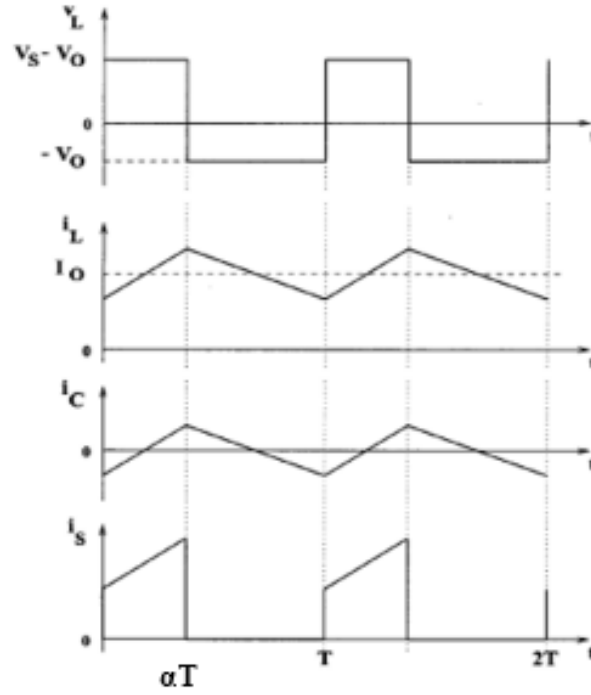


Figure 5: Voltage and current waveforms of Buck converter

We present the following Equations:

$$\begin{cases} v_l = L \cdot \frac{di}{dt} \\ i_c = C \cdot \frac{dvc}{dt} \end{cases}$$

(1)

When the switch is closed ($0 < t < \alpha T$), the state equations are:

$$\begin{cases} v_l = v_s - v_o \\ \frac{di}{dt} = \frac{1}{L}(v_s - v_o) \\ i_c = i_l - \frac{v_o}{R} \\ \frac{dvc}{dt} = \frac{1}{C}(i_l - \frac{v_o}{R}) \end{cases}$$

(2)

When the switch is opened ($\alpha T < t < T$), the state equations are:

$$\begin{cases} v_l = -v_o \\ \frac{di}{dt} = -\frac{1}{L} v_o \\ \frac{dv_c}{dt} = \frac{1}{C} \left(i_l - \frac{v_o}{R} \right) \end{cases}$$

(3)

The duty cycle of the buck converter is defined as:

$$\alpha = \frac{T_{on}}{T}$$

(4)

the output voltage for a buck converter is defined as:

$$v_o = \alpha \cdot v_s$$

(5)

The output capacitance is defined as:

$$C = \frac{1}{8} \cdot \frac{T^2(1-\alpha)}{L \cdot \frac{\Delta v_o}{v_o}}$$

(6)

From the preceding equations, we deduced the following expressions for the ripple current (Δi_L) and ripple voltage (ΔV_o)

$$\begin{cases} \Delta i_L = \frac{\alpha(1-\alpha)v_s}{L \cdot f} \\ \Delta v_o = \frac{\alpha(1-\alpha)v_s}{8 \cdot C \cdot L \cdot f^2} \end{cases}$$

(7)

1.4.2 Boost converter

The boost converter, also referred to as a step-up converter utilized for raising the input voltage to meet the load's voltage requirements. This step-up conversion is executed by storing energy

in the inductor and subsequently releasing it to the load at a higher voltage, ensuring optimal performance across various electrical systems [4].

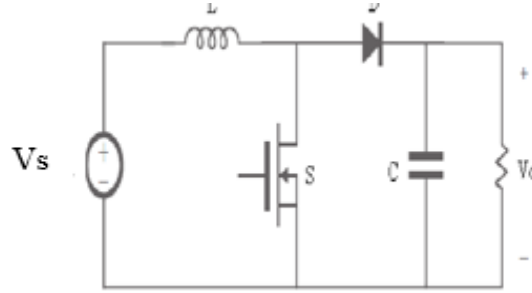


Figure 6: the boost Converter Circuit Diagram

When the switch is turned on, current flows through the inductor, storing magnetic energy. During this phase, the output voltage is blocked by the output diode, thus isolating the load from the source [4].

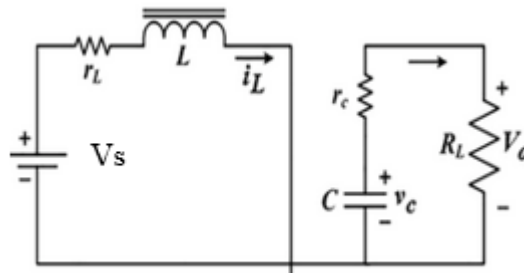


Figure 7: Circuit Diagram for boost converter during Switch ON.

When the switch is turned off, current flows through the output diode, allowing the energy stored in the inductor to be transferred to the load and output capacitor. During this phase, the current in the inductor gradually decreases [4].

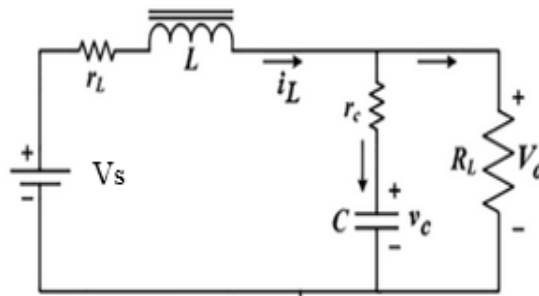


Figure 8: Circuit Diagram for boost converter during Switch OFF

The waveforms of current and voltage for a Boost converter are shown in the following figure:

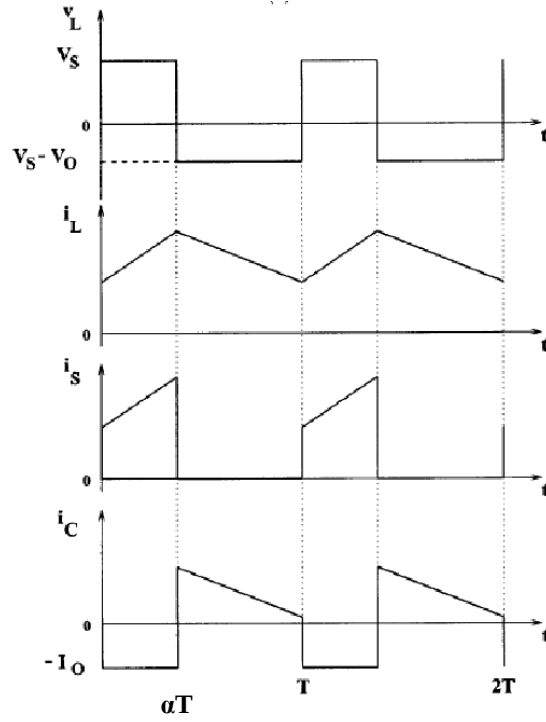


Figure 9: Voltage and current waveforms of the Boost converter

When the switch is closed ($0 < t < \alpha T$), the state equations are:

$$\begin{cases} v_l = v_s \\ \frac{di}{dt} = \frac{1}{L}(v_s) \\ i_c = -\frac{v_o}{R} \\ \frac{dvc}{dt} = \frac{-v_o}{R \cdot C} \end{cases}$$

(8)

When the switch is opened ($\alpha T < t < T$), the state equations are:

$$\begin{cases} v_l = v_s - v_o \\ \frac{di}{dt} = \frac{1}{L}(v_s - v_o) \\ i_c = i_l - \frac{v_o}{R} \\ \frac{dvc}{dt} = \frac{1}{C}(i_l - \frac{v_o}{R}) \end{cases}$$

(9)

the output voltage for a boost converter is defined as:

$$v_o = \frac{1}{1 - \alpha} v_s$$

(10)

The output capacitance is defined as:

$$c = \frac{\alpha \cdot T}{R \cdot \frac{\Delta v_o}{v_o}}$$

(11)

From the preceding equations, we deduced the following expressions for the ripple current (Δi_L) and ripple voltage (ΔV_o)

$$\begin{cases} \Delta i_L = \frac{\alpha \cdot v_s}{L \cdot f} \\ \Delta v_o = \frac{\alpha v_s}{(1 - \alpha) \cdot R \cdot c \cdot f} \end{cases}$$

(12)

1.4.3 Buck-Boost converter

The buck-boost converter, also known as an inverting regulator, serves to adjust the output voltage, which can either be higher or lower than the input voltage. This versatile functionality allows it to efficiently manage power flow in systems where the load's voltage requirements may differ from the input voltage. By alternately storing and releasing energy, it ensures stable output voltage regardless of input variations, enhancing performance in a variety of electrical applications [5].

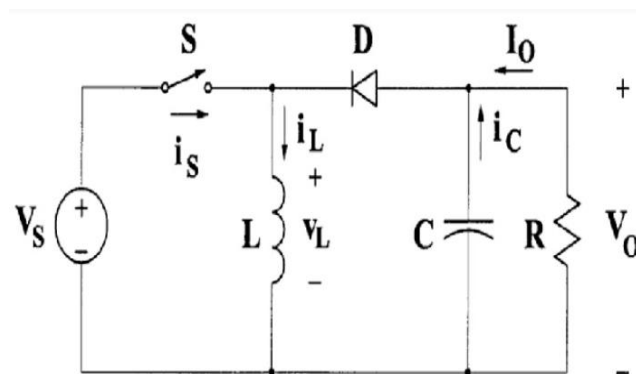


Figure 10: The Buck-Boost Converter Circuit Diagram

When the switch in a buck-boost converter is turned on, current flows from the power source to the inductance, enabling it to store magnetic energy.

When the switch is turned off, the stored magnetic energy in the inductance is released, ensuring the voltage supply to the load via the diode.

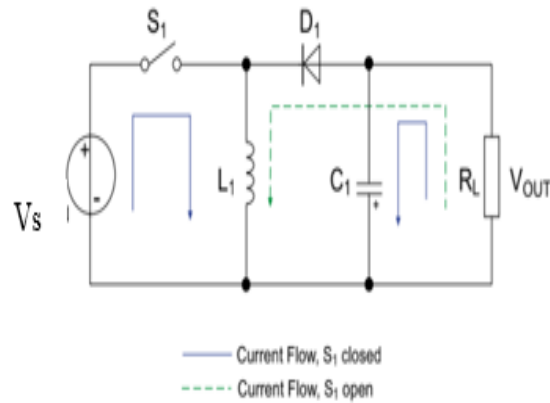


Figure 11: Circuit Diagram for Buck-Boost converter During Switching

The waveforms of current and voltage for a Buck- Boost converter are shown in the following figure:

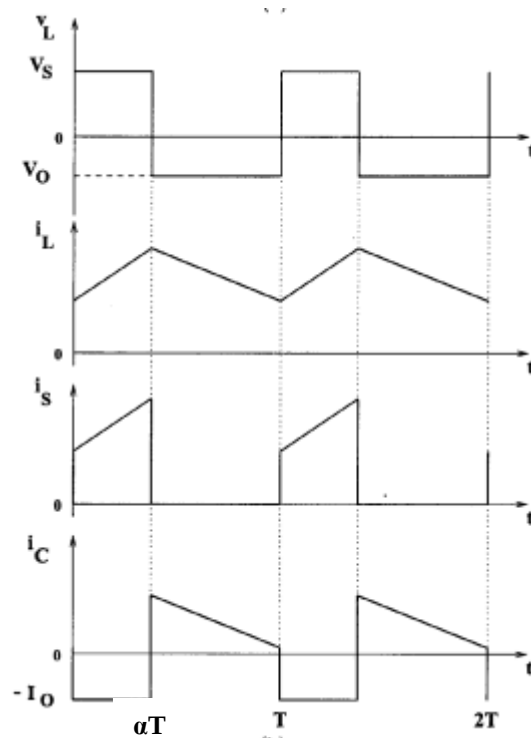


Figure 12: Voltage and current waveforms of Buck-Boost converter

When the switch is opened ($\alpha T < t < T$), the state equations are:

$$\begin{cases} v_l = v_s \\ \frac{di}{dt} = \frac{1}{L}(v_s) \\ i_c = -\frac{v_o}{R} \\ \frac{dv_c}{dt} = \frac{-v_o}{R.C} \end{cases}$$

(13)

When the switch is opened ($\alpha T < t < T$), the state equations are:

$$\begin{cases} v_l = -v_o \\ \frac{di}{dt} = \frac{1}{L}(v_o) \\ i_c = i_l - \frac{v_o}{R} \\ \frac{dv_c}{dt} = \frac{1}{C}(i_l - \frac{v_o}{R}) \end{cases}$$

(14)

the output voltage for a Buck -Boost converter is defined as:

$$v_o = -\frac{\alpha}{1-\alpha} v_s$$

(15)

The output capacitance is defined as:

$$C = \frac{\alpha.T}{\frac{\Delta v_o}{v_o}.R}$$

(16)

From the preceding equations, we deduced the following expressions for the ripple current (Δi_L) and ripple voltage (ΔV_o)

$$\begin{cases} \Delta i_L = \frac{\alpha.v_s}{L.f} \\ \Delta v_o = \frac{\alpha^2 v_s}{(1-\alpha).R.c.f} \end{cases}$$

(17)

1.5 Control Techniques in DC-DC Topologies

The evolution of control technique has significantly improved the performance of these DC-DC converters in terms of energy efficiency, stability, and regulation precision. Among these techniques, we find:

1.5.1 Pulse width Modulation (PWM) Control

is a technique used in DC-DC converters to adjust the voltage or current supplied to a load to a desired target value. This method involves varying the duty cycle at a fixed frequency. One of the main advantages of PWM is that the switching frequency remains constant, allowing electronic designers to effectively filter out the acoustic and electromagnetic noise generated [6].

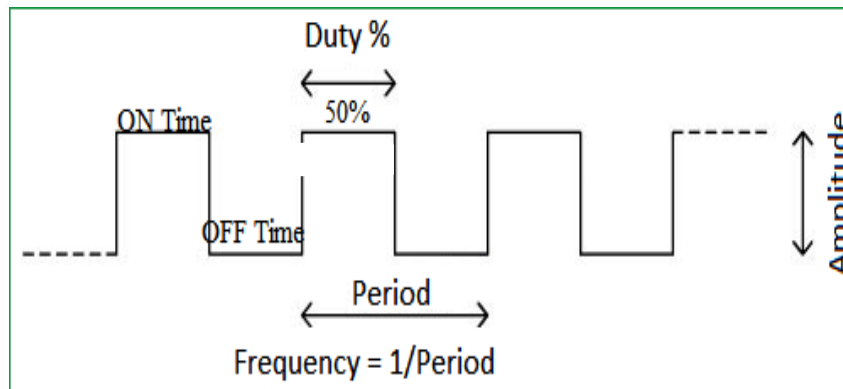


Figure 13: Pulse width modulation

1.5.2 The MPPT (Maximum Power Point Tracking)

is a technique aimed at maximizing the energy production of sources such as solar panels or wind turbines. Its principle involves continuously adjusting the operating conditions to find and maintain the maximum power point (MPP), even in changing environmental conditions. By perfectly adapting the energy source to the load [7].

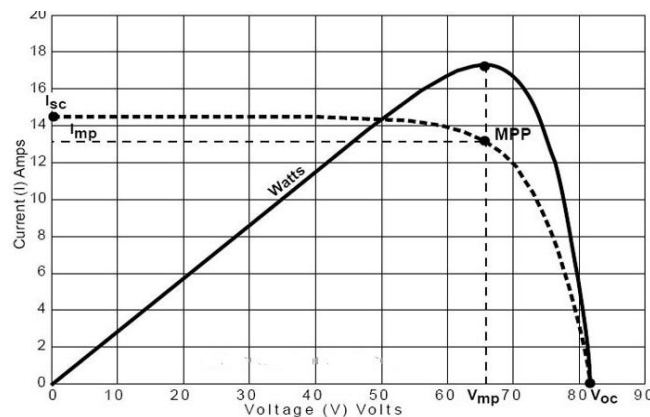


Figure 14: MPPT Curve

1.5.3 PID Control

The PID controller ,or PID regulator is conventional and effective technique that take the feedback signal from the output and control the duty cycle of the switch to achieve the required voltage gain. This controller uses three different terms to adjust the system output based on the error between the desired setpoint and the actual output value of the system :

- Proportional and integral controllers (PI)
- Proportional and Derivative controllers (PD)
- Proportional Integral and Derivative controllers (PID) [8].

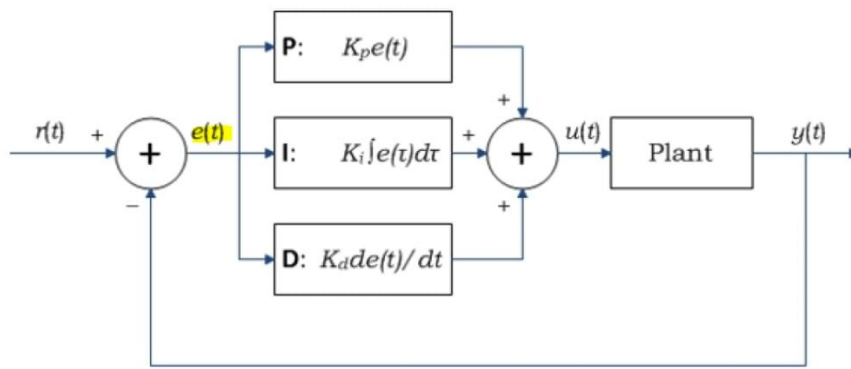


Figure 15: block diagram of a PID control system

1.5.4 Fuzzy Logic (FLC) Control

Fuzzy Logic Control (FLC) is a non-traditional method that emulates human thinking, devoid of the need for precise mathematical models. It interprets system signals into linguistic expressions, compares them against predefined rules, and transforms them into control signal [9].

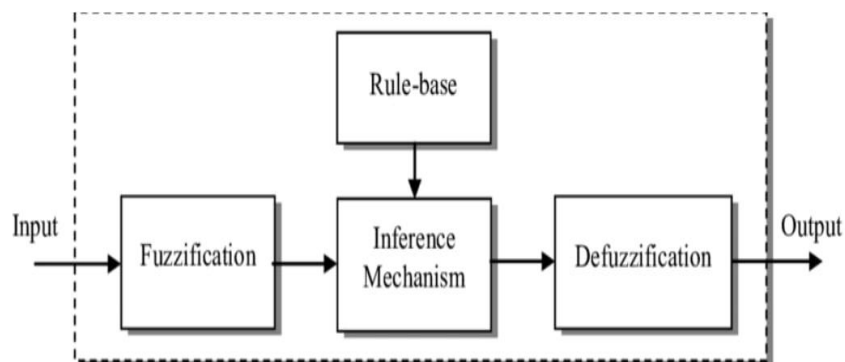


Figure 16 : block diagram of Fuzzy Logic (Control)

1.5.5 Model Predictive (MPC) Control

Model Predictive Control (MPC) is a sophisticated technique that forecasts how a system will behave in the future by leveraging feedback data. It then generates suitable commands to keep the system operating optimally. In the case of DC-DC converters, MPC uses current output signals to predict future states, thereby ensuring uninterrupted operation even in the presence of potential disturbances [9].

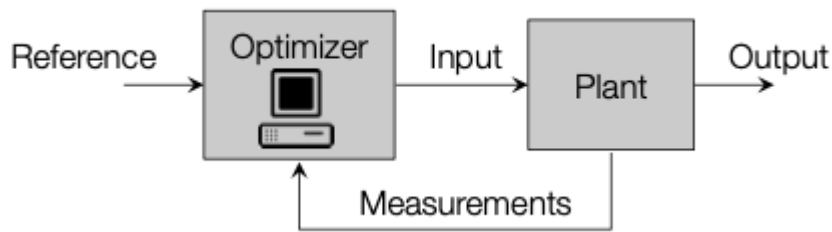


Figure 17: Block diagram of model predictive control

1.5.6 State Space Modeling (SSM) Control

State Space Modeling (SSM) is a mathematical technique employed to accurately depict real-world systems, such as DC-DC converters. By utilizing state equations, it fine-tunes the system's behavior, resulting in enhanced efficiency and precision, particularly apt for applications demanding high levels of accuracy[9].

1.6 Applications of DC-DC Converters

1.6.1 Renewable Energy Systems

DC-DC converters are vital for the efficient integration of renewable energy sources by adapting the variable voltage from solar panels or wind turbines to the charging needs of batteries or electrical appliances. They optimize energy conversion and ensure reliable system operation[10].

1.6.2 Electric Vehicles

DC-DC converters in electric vehicles serve either unidirectional purposes, supplying various loads, or bidirectional functions, facilitating battery charging and regenerative braking. Bidirectional converters typically transfer energy from low to high voltage. To address challenges posed by high voltage/current constraints, solutions like soft switching are employed. These converters play a crucial role in efficiently powering loads at different voltages within electric vehicles, thereby enhancing their reliability and overall efficiency[11].

1.6.3 Embedded Systems

DC/DC converters play a crucial role in adjusting voltages to meet the specific needs of various components. They ensure power stability, even amidst input voltage fluctuations, and guarantee reliable communications by providing precise voltages to communication circuits[2].

1.7 Advancements in DC-DC Power Converter Research

The evolution of research on DC-DC power converters reflects a transition from foundational studies to contemporary multi-objective optimization approaches with a focus on electromagnetic compatibility (EMC). Early research centered on basic converter architectures and control strategies, laying the groundwork for advancements in topology and modulation techniques. Here are some examples of these research studies:

- **Design and Analysis of High Performance DC-DC Converters with SiC Technology:** This revolves around the development and examination of DC-DC converters that leverage Silicon Carbide (SiC) technology to achieve superior performance [12].
- **A Digital Current-Mode Control Technique for DC–DC Converters:** This theme aims to introduce a new digital control method that leverages current-mode operation to enhance DC-DC converters in terms of performance and efficiency [13].
- **DC–DC Converters Dynamic Modeling With State Observer-Based Parameter Estimation:** This theme aims to develop accurate dynamic models for DC-DC converters through parameter estimation methods relying on state observers [14].
- **Optimized DC–DC converter based on new interleaved switched inductor capacitor for verifying high voltage gain in renewable energy applications:** This theme introduces an innovative DC-DC converter design. Through the utilization of a modified switched inductor-capacitor technique, the converter adeptly mitigates component stresses, guaranteeing smooth input current and heightened efficiency[15].

1.8 Conclusion

In conclusion, this chapter has immersed us in the fascinating world of DC-DC converters, highlighting essential topologies. By analyzing characteristic equations and regulation modes, as well as examining associated switch control techniques, we have underscored the crucial importance of these converters across various domains. Lastly, by observing the evolution of

research, we have identified a trend towards more holistic approaches aimed at reconciling performance and reliability.

Chapter 2

Emc consideration

2.1 Introduction

Electromagnetic Compatibility (EMC) is crucial in modern power electronics, ensuring devices operate effectively without causing or experiencing interference. In today's world, where electronic systems are everywhere—from home appliances to industrial machinery EMC's importance is paramount. This chapter delves into EMC, highlighting its role in maintaining the functionality and reliability of electronic devices in various electromagnetic environments. By exploring the principles and practices of EMC.

2.2 Electromagnetic Compatibility (EMC)

Electromagnetic Compatibility (EMC) is a field of electronic engineering that ensures electronic devices operate effectively in their electromagnetic environment without interfering with other devices or being affected by them. In essence, EMC involves limiting the electromagnetic emissions of equipment and making them resistant to external electromagnetic disturbances [16].

2.2.1 The EMC issue in power electronics

Electromagnetic Compatibility (EMC) is of crucial importance in power electronics, especially for DC-DC converters, due to their switching mode operation. This operating mode involves rapid changes in current and voltage, resulting in electromagnetic disturbances (EMI). These EMI can interfere with other electronic equipment and cause electromagnetic compatibility issues[17].

2.2.2 Regulation on Electromagnetic Compatibility

Emission and Immunity are the basic concepts in Electromagnetic Compatibility (EMC) in electronics:

- **Emission:** Refers to the generation and release of electromagnetic energy by electronic devices. Devices must comply with regulatory standards for electromagnetic emissions to ensure that they do not interfere with other devices in the environment in which they operate.

- **Immunity:** Immunity describes the electronic device's capacity to resist the effects of EMI from external sources. To function optimally, a device must be able to tolerate a certain level of interference without suffering performance degradation or malfunction.
- **Coupling:** It is the phenomenon of propagation of disturbances that occurs between the source and the victim[18].

EMC standards are developed by national and international standardization bodies, such as the International Special Committee on Radio Interference (CISPR), the International Electrotechnical Commission (IEC), and the International Organization for Standardization (ISO). These standards define the emission and immunity criteria that electronic equipment must comply with to ensure proper operation and prevent harmful interference with other devices.

Table 1: The required EMC standards for converters

Standards	Field of Application
CISPR 11	Standards and measurement techniques for electromagnetic disturbances from industrial, scientific, and medical radio-frequency devices[18].
CISPR 25	Limits and measurement methods of electromagnetic emissions from electronic components installed in vehicles[19] .
IEC 61000-1	Definitions of harmonic, subharmonic disturbances, and flicker[20].
IEC 61000-4-x	Series of international standards defining immunity tests to electromagnetic phenomena for electronic equipment[21].
ISO 7637	International standard for electromagnetic immunity of automotive components[22].

2.2.3 Identifying sources of disturbances in power conversion systems

Identifying sources of disturbances in power conversion systems is essential to ensure optimal operation and reduce the risk of unwanted electromagnetic interference. These disturbances can originate from several components and phenomena present in the power conversion system.

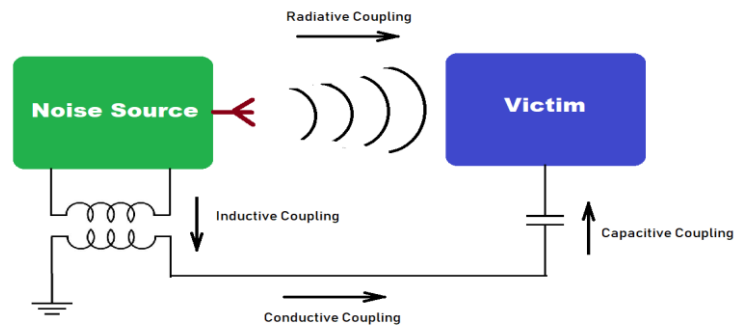


Figure 18: Diagram of EMC Issues

In power electronics converter design, EMC concerns identify the switching cell as the primary source of disturbances.. These disturbances are propagated towards the load and the power network designated as the victims, and the propagation of disturbances is related to their respective environments. Two situations may occur:

- **conducted disturbances** :If the source and the victim are close with or without galvanic connection, the coupling can be capacitive, inductive, or resistive in nature. The disruptive phenomena are rapid variations in current and voltage (di/dt and dv/dt). These disturbances propagate along power or transmission cables as well as in energy sources or loads.
- **radiated disturbances**: If the source and the victim are distant and without galvanic connection, parasitic energy between the source and the victim is transmitted through a magnetic field (H) and an electric field (E), or in the form of an electromagnetic wave [18].

It is essential to consider the common and differential modes of electromagnetic interference (EMI). Common mode noise, resulting from capacitive or inductive coupling, is difficult to filter. In contrast, differential mode noise, due to resistive or inductive coupling, is easier to mitigate using filtering techniques.

2.3 EMI Mitigation Techniques

Electromagnetic Interference (EMI) mitigation techniques are crucial for ensuring reliable operation and compliance with regulatory standards. This section explores various methods to reduce EMI emissions and minimize the risks of harmful interference.

2.3.1 Component selection :

Selecting components for a DC-DC converter is vital for achieving optimal performance and efficiency. Here's why each component matters:

- **Power Semiconductors:** Mosfets and diodes impact efficiency and switching. Consider their on-resistance, voltage, current, and switching speed to minimize losses and maximize performance.
- **Inductors:** These affect output ripple and response. Choosing the right inductor with appropriate values for inductance, current rating, and saturation helps maintain stable output voltage and current.
- **Capacitors:** They filter and smooth voltage and current waveforms. Key considerations include capacitance, voltage rating, ESR (Internal Resistance), and temperature stability to ensure reliable operation and minimize ripple.
- **Controllers and Drivers:** These circuits regulate the converter's operation. Selecting suitable control topology, ensuring feedback loop stability, and incorporating protection features are crucial for reliable and efficient performance [23].



Figure 19: Components for PCB

2.3.2 PCB Design

The PCB layout should start by arranging components to minimize signal interference. High-speed digital parts should be kept separate from sensitive analog ones.

EMC compatibility depends on three factors:

- avoiding disruption to other systems.
- being unaffected by emissions from other systems .
- preventing self-interference [24].

2.3.3 Routing

PCB routing is the process of connecting various elements on a printed circuit board (PCB) or within integrated circuits (ICs). It's a critical step following component placement, where the precise location of each element is determined. The efficiency of PCB routing directly impacts the performance, reliability, and manufacturability of electronic devices [25].

To ensure efficient routing and reduce the risks of emissions or susceptibility to interference, several basic rules should be followed:

- **Using short and direct traces:** Shorter traces reduce loops and areas prone to radiating or picking up electromagnetic interference. Signals should follow the most direct path possible between components.

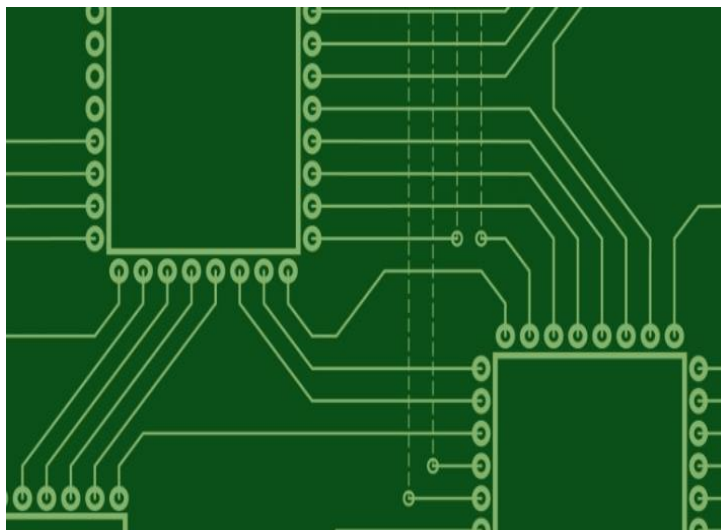


Figure 20: short and direct traces in PCB

- **Minimizing loops:** Loops in circuits create magnetic fields that can radiate interference. Similarly, each via adds inductance and resistance, which can increase noise and susceptibility to interference. It's essential to minimize their use.

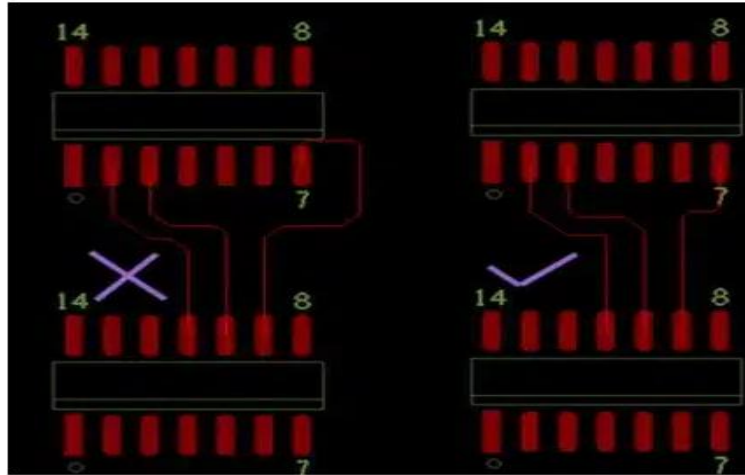


Figure 21: Minimizing loops in PCB

- **Avoiding right angles and tight bends:** Right angles and tight bends can lead to impedance mismatches, signal reflections, and propagation losses, which can disrupt high-frequency signals and generate electromagnetic interference.



Figure 22: Avoiding right angles and tight bends

- **Maintaining constant impedance:** Impedance variations along traces can lead to signal reflections, distortions, and electromagnetic interference. It's important to maintain constant impedance along transmission lines by using appropriate trace widths and well-designed ground or power planes [25].

2.3.4 Grounding

Grounding is like creating a highway system for electricity on a PCB. It's crucial because it gives signals and power a common reference point. Without good grounding, circuits can get noisy, interfering with each other, and causing signal problems that make them unreliable or fail altogether. Grounding techniques aim to :

- **Provide a low-impedance path for return currents:** When currents flow through a circuit, they need to return to their source. A low-impedance return path ensures that return currents can flow freely without encountering excessive resistance. This helps reduce loop voltage and ensures optimal electrical performance.
- **Minimize ground loops:** Ground loops form when there are multiple paths to ground for currents. These loops can act as antennas, picking up electromagnetic interference (EMI) and introducing noise into circuits. Minimizing ground loops helps reduce noise and improve circuit reliability.
- **Isolate different signal domains:** Different signals on a PCB can interfere with each other if they share the same ground return path. To prevent this, it's important to isolate different signal domains as much as possible. This can be achieved by using separate ground planes, dedicated grounding areas, or by limiting the crossing of signal paths [26].

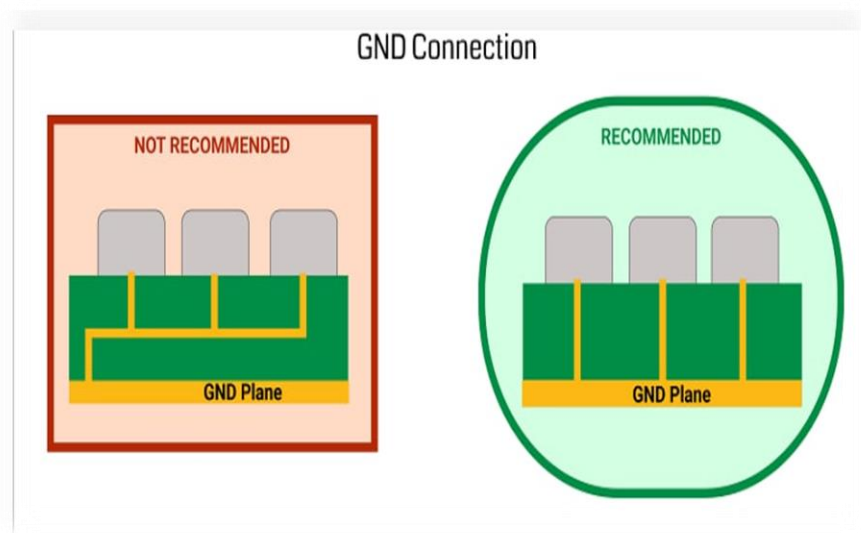


Figure 23: Grounding techniques

2.3.5 Shielding

Shielding involves enclosing or covering a circuit or its components with a conductive material, such as metal or foil. This process blocks or reduces electromagnetic fields or radiation that can interfere with the circuit or cause crosstalk, distortion, or noise. The following guidelines should be followed when using shielding:

- **Grounding the Shield:** The shield's grounding provides a low-impedance path for return currents, ensuring that any unwanted electrical currents or electromagnetic interference absorbed by the shield can flow away from the sensitive circuit and dissipate harmlessly. Without proper grounding, the shield could become charged and potentially cause interference.

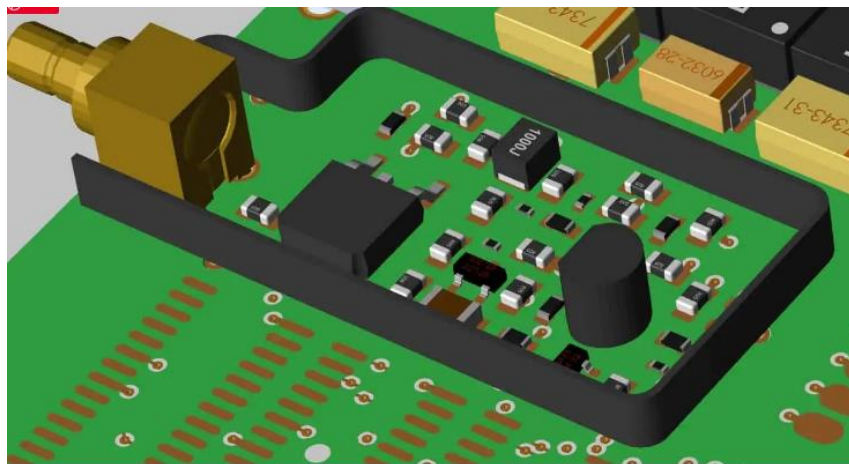


Figure 24: Grounding the Shield

- **Complete Coverage of the Sensitive Circuit:** The shield's complete coverage of the sensitive circuit prevents electromagnetic interference from entering the sensitive area. Gaps or areas left unprotected could allow electromagnetic fields to penetrate and interfere with the circuit's functioning. It protects sensitive components from external interference.

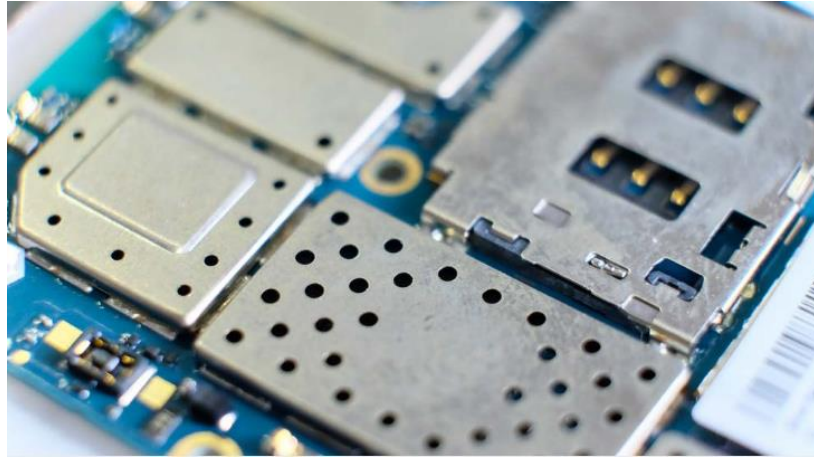


Figure 25: Cover PCB shields

- **Minimizing Leakage of Electromagnetic Fields:** The shield's design minimizes the leakage of electromagnetic fields by constructing it in a way that prevents electromagnetic energy from escaping or coupling with nearby circuits or devices. Gaps, seams, or ineffective shielding materials could compromise protection. Minimizing leakage ensures that the shield effectively contains electromagnetic energy within the shielded area, reducing the risk of interference [27].

2.3.6 Filtering

Filtering is a technique employed to mitigate electromagnetic interference (EMI) in electronic devices. It involves attenuating unwanted frequencies within electronic circuits to decrease the level of EMI generated. Achieved through the use of capacitors, resistors, or inductors, filters can be strategically positioned at different points in a circuit to effectively reduce EMI [27].

Two key aspects of filtering must be considered in power converter design:

- **Filtering of control and switching signals:**

LC filters, consisting of inductors and capacitors, are used in power converter circuits to mitigate electromagnetic emissions. These filters work by creating a resonant circuit that attenuates specific harmonics generated during switching. By selectively allowing certain frequencies to pass through while blocking others [28].

- **Filtering of power lines:**

Input filters in a power converter use inductors and capacitors to attenuate harmonics and transients present in the power lines. The inductors reduce the amplitude of harmonics, while the capacitors smooth out transients by storing and redistributing energy [29].



Figure 26: LC Filter in PCB

2.4 EMC Testing

EMC testing for PCB design in power electronics is a crucial process to ensure that electronic devices operate correctly without emitting or being susceptible to unwanted electromagnetic interference. This testing is essential for complying with regulatory standards and ensuring the reliable performance of electronic systems [27].

2.4.1 Immunity Testing

also known as susceptibility testing ,examines the response of a device when it comes into contact with electromagnetic energy:

- **Radiated Immunity Testing:** This testing involves putting a device in a special room and exposing it to electromagnetic fields from a transmitter. The fields are changed to see how the device reacts to different types of interference.
- **Conducted Immunity Testing:** This testing involves injecting EMI into a device to check how well a device handles electromagnetic interference that might come through its cables or wiring.
- **Transient Immunity Testing:** This testing involves subjecting a device to sudden voltage spikes that may occur due to lightning or other sources. This test evaluates the

device's ability to withstand these sudden voltage peaks and ensure its proper functionin [27].

2.4.2 Emissions testing

Emissions testing involves measuring the level of electromagnetic interference (EMI) produced by a device's internal electrical systems:

- **Conducted emissions testing:** this testing measures the electromagnetic energy transmitted from a device through its power supply. Typically, an analyzer is used to measure the frequency and amplitude of these signals.
- **Radiated emissions testing:** this testing measures the electromagnetic energy emitted by a device into its surrounding environment. This testing typically involves using an antenna and a spectrum analyzer to measure the frequency and amplitude of the electromagnetic signals [27].

2.5 Conclusion

In conclusion, this chapter has highlighted the critical importance of Electromagnetic Compatibility (EMC) in power electronics. By ensuring the optimal functioning of electronic devices within their electromagnetic environments, EMC is essential for the reliability and efficiency of technological systems. The chapter examined international regulatory standards, identified sources of electromagnetic disturbances, and discussed mitigation techniques to reduce interference. A thorough understanding of these challenges and solutions enables the development of more robust and compliant electronic devices, thereby contributing to technological advancement.

Chapter 3

Simulation Methods and Performance Optimization of DC-DC Converters

3.1 Introduction

In this chapter, we apply an optimization method based on the experimental design approach to our project of developing a DC-DC power converter. We aim to understand the impact of parameters such as switching frequency, duty cycle, and resistive load on converter efficiency. Before proceeding, we begin by simulating the proposed system to ensure its proper operation.

3.2 Proposed System

Our focus is on examining the DC-DC power converter employed in electric vehicles. This converter plays a crucial role in efficiently managing power distribution, ensuring that both propulsion and auxiliary systems receive optimal electrical power across different operational modes. This capability enhances overall vehicle efficiency and performance significantly [30].

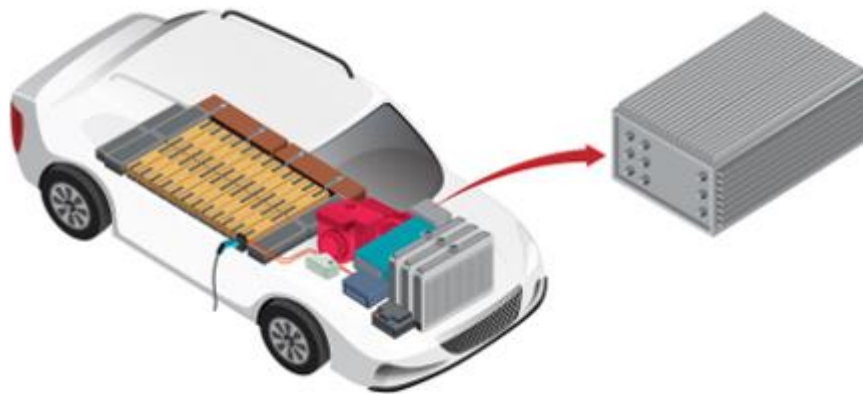


Figure 27: The position of the DC-DC power converter in electric vehicle

The schematic of the proposed bidirectional DC-DC converter is depicted in Figure 28. This converter operates in continuous conduction mode for both forward motoring and regenerative braking of the DC motor[31].

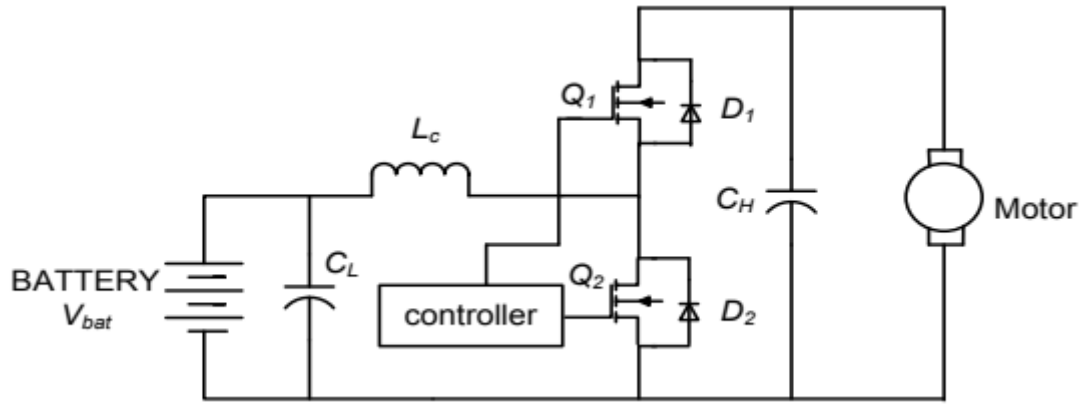


Figure 28 : Bidirectional dc-dc converter with battery and dc motor.

The bidirectional DC-DC converter shown in Figure 1 operates in continuous conduction mode during both forward motoring and regenerative braking of the DC motor.

During forward motion, the converter transforms the DC current from the battery to the motor unit, enabling the vehicle to move. When regenerative braking is engaged, the converter converts the generated power from the braking into a form suitable for storage in the battery, for later reuse in propelling the vehicle [31].

3.3 Simulation of the proposed system

We conducted this simulation using Proteus software, which allowed us to design, test, and validate our circuits efficiently

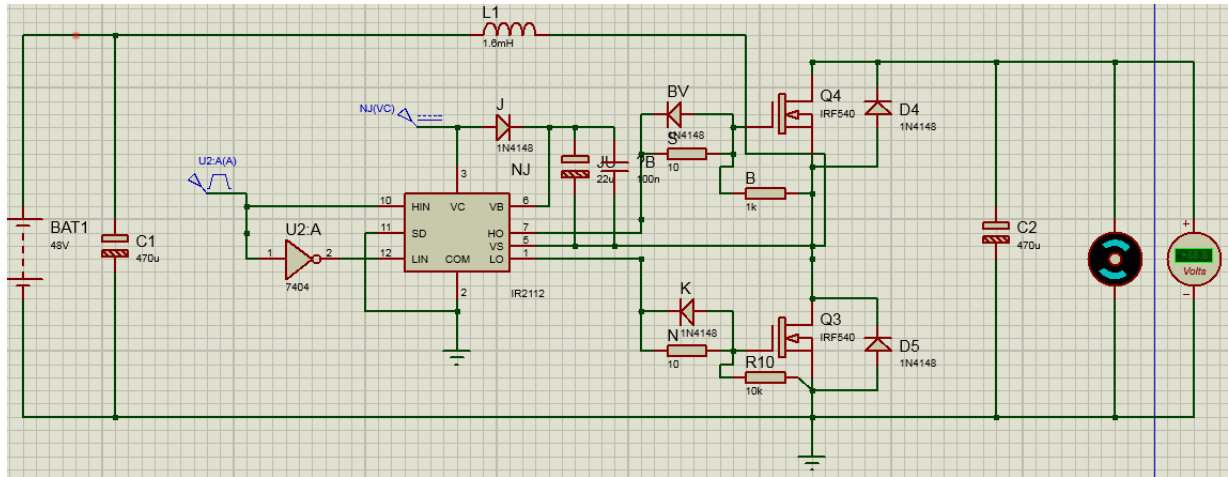


Figure 29 : simulation of Bidirectional dc-dc converter buck- boost

Table 2 : DC DC converter specification

Battery voltage	48 v
Input , output capacitor	470 uf
Inductor	1.6 mh
Motor dc nominal voltage	240V
Pulse width	30% -95%

3.3.1 IR2112 mosfet/igbt driver

The IR2112 is a high voltage IC used to control MOSFETs and IGBTs. It has two outputs for driving both high and low side transistors, can handle up to 600V, and operates within a 10V to 20V range. It includes features that ensure reliable and efficient performance, even in noisy environments.

In the proposed system for motoring and braking, the IR2112 manages power flow in both directions. It increases voltage for forward motoring and reduces voltage for regenerative braking. Its capabilities ensure smooth transitions and efficient energy use in both processes[32].

3.4 Simulation results

In boost mode, the DC-DC converter increases the voltage from the 48V battery to 75V, as required by the motor during forward motoring. This mode is crucial for delivering the necessary power and torque for vehicle acceleration and maintaining speed.

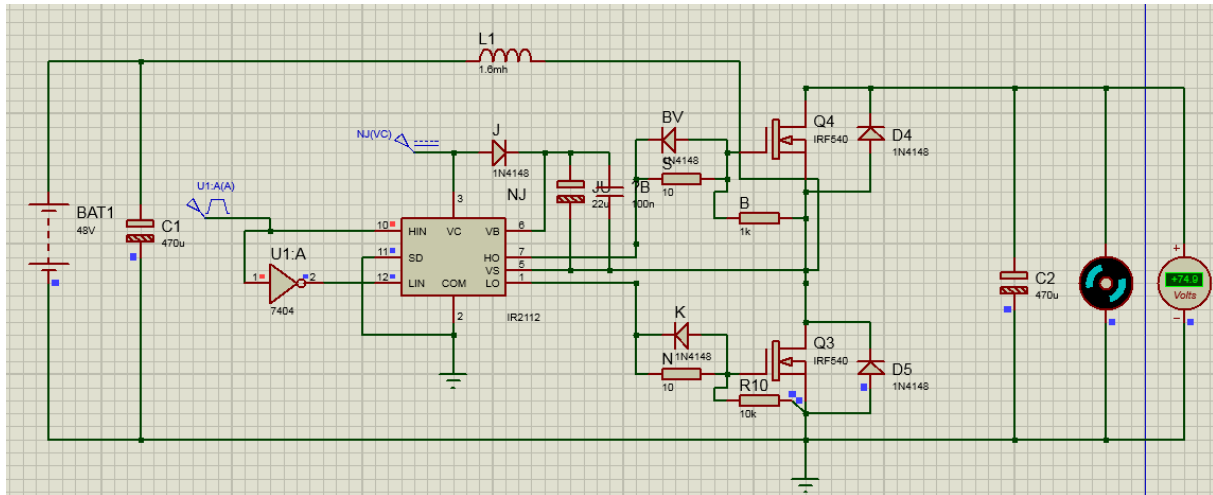


Figure 30 : Simulation for boost mode

In buck mode, the DC-DC converter reduces the voltage from the motor to 47V to charge the battery during regenerative braking. This mode is essential for energy recovery.

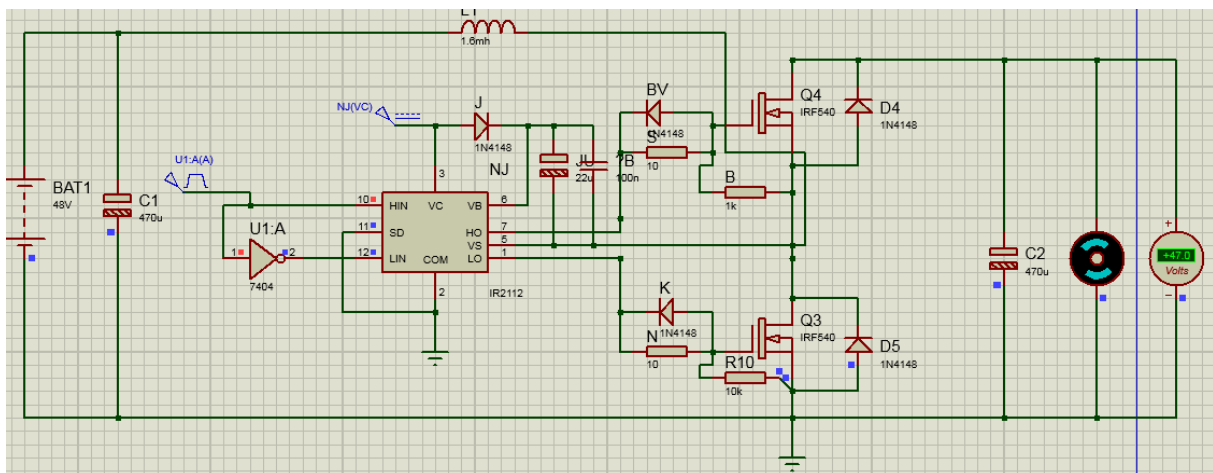


Figure 31 : Simulation for buck mode

The inductor voltage waveform typically shows a cyclical pattern, During the switch's on-time, the inductor stores energy as current flows through it, causing the voltage to rise. When the switch turns off, the inductor releases this stored energy, typically directing it back to the battery during regenerative braking. This cyclic process ensures effective energy transfer between the battery and the motor,

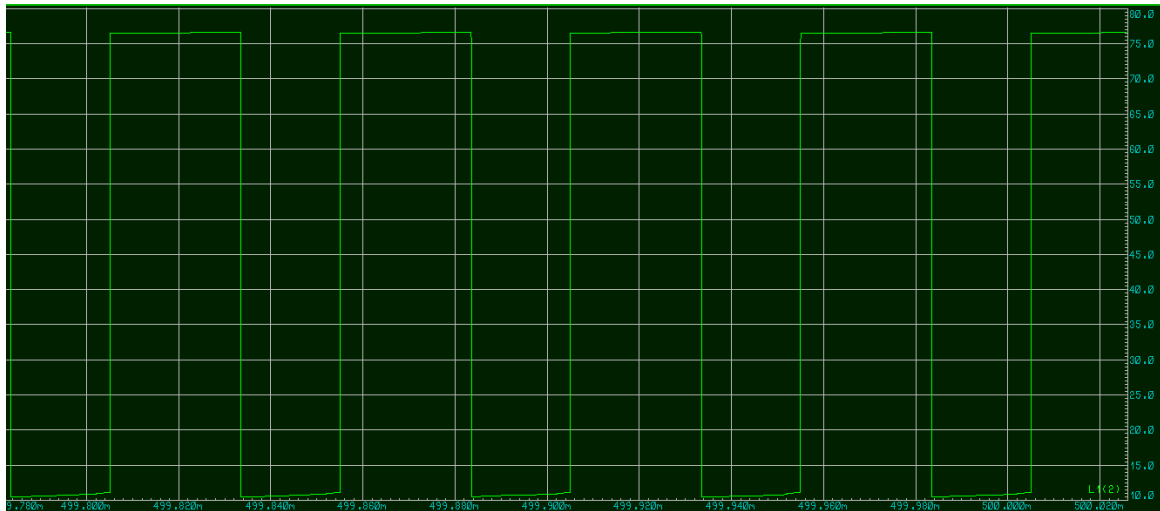


Figure 32 : Inductor voltage during waveform

During forward motoring, the inductor current rises during the switch's on-time, storing energy that is later transferred to the motor when the switch turns off. In regenerative braking, the inductor current reverses as the motor generates electricity, and the converter efficiently charges the battery with this energy

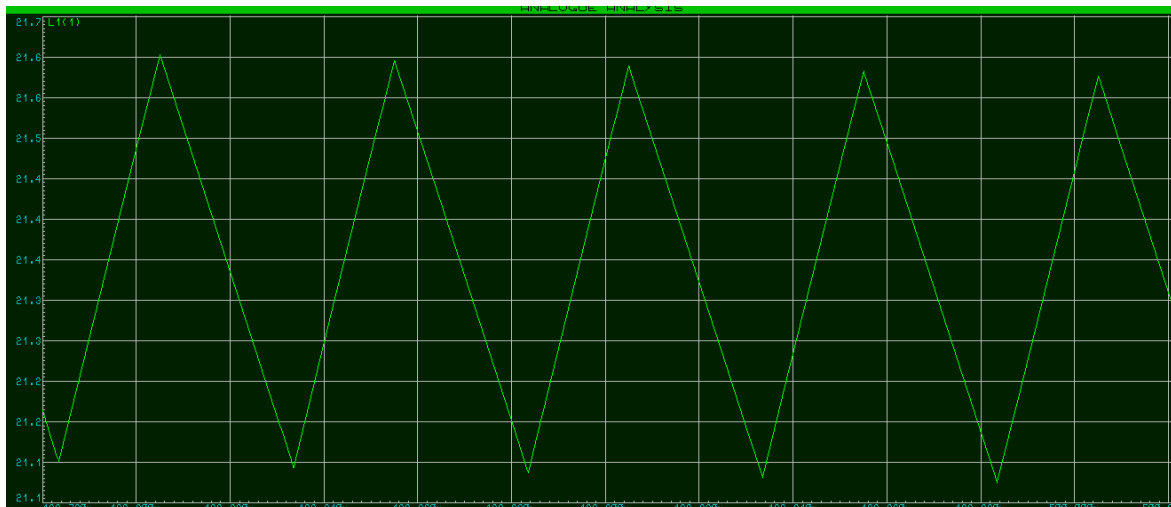


Figure 33 : Inductor voltage waveform

3.5 Testing the circuit

The following figure shows the testing of our circuit on a breadboard. We performed tests to evaluate its efficiency by adjusting parameters such as duty cycle and frequency in the code executed on the Arduino Uno microcontroller, and by varying the resistive load using a variable resistor each time.

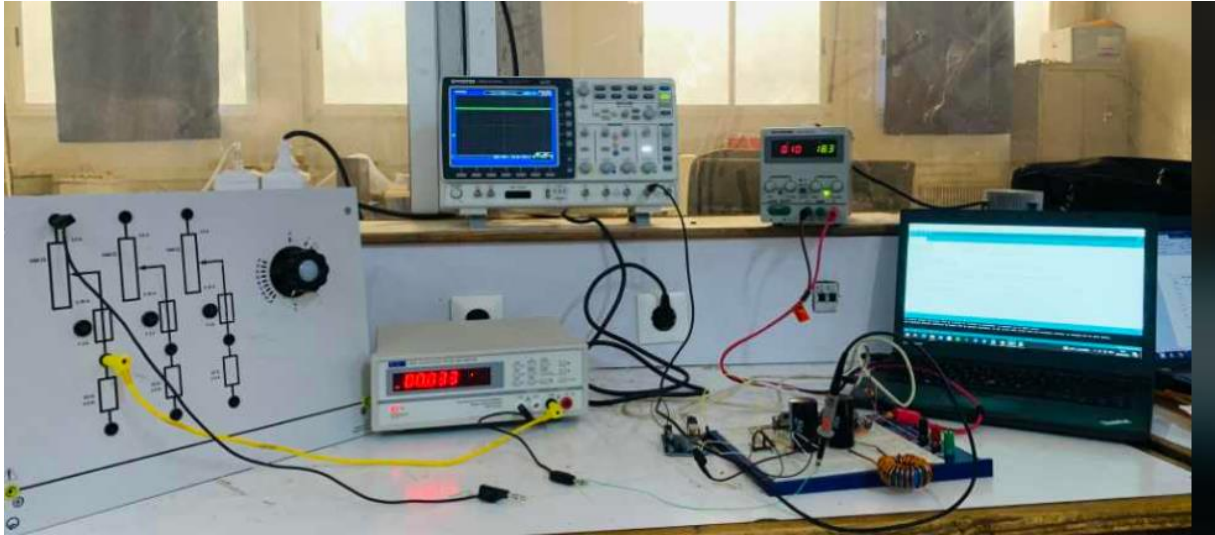


Figure 34 : Testing circuit efficiency

The following section presents the different waveforms for the signals from the inverter and the driver, as well as the resulting output voltage signal.

- For $\alpha = 30\%$

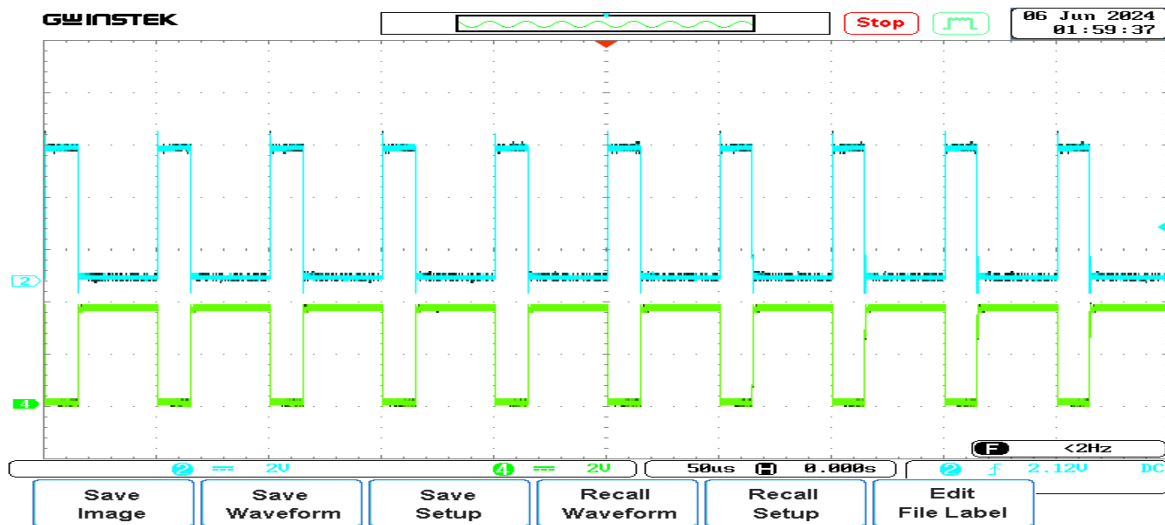


Figure 35 : The control signal and its inverter

Figure 36 : The output signal of the driver and its inverter

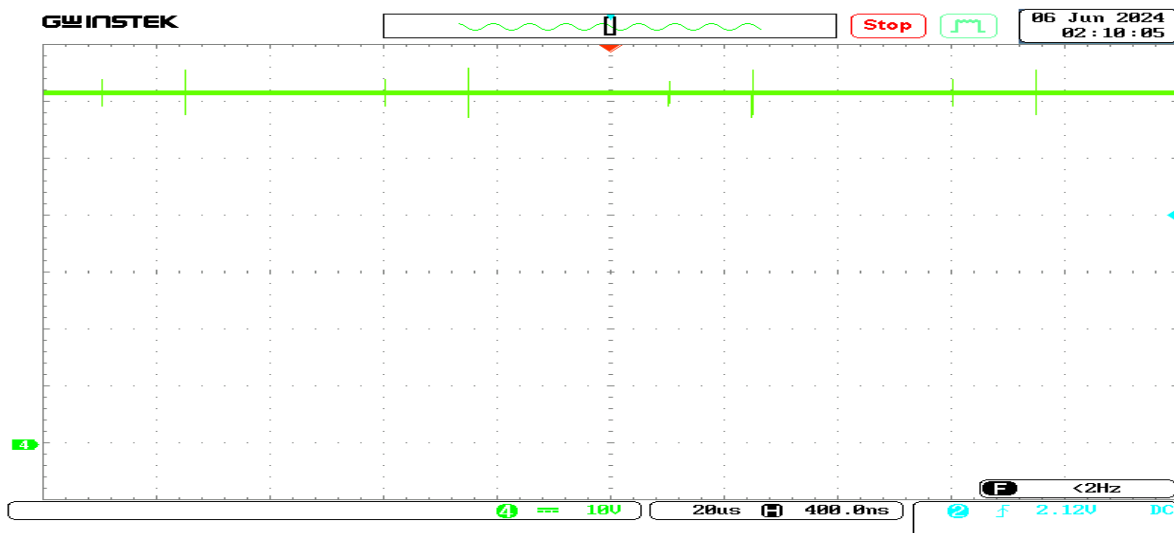
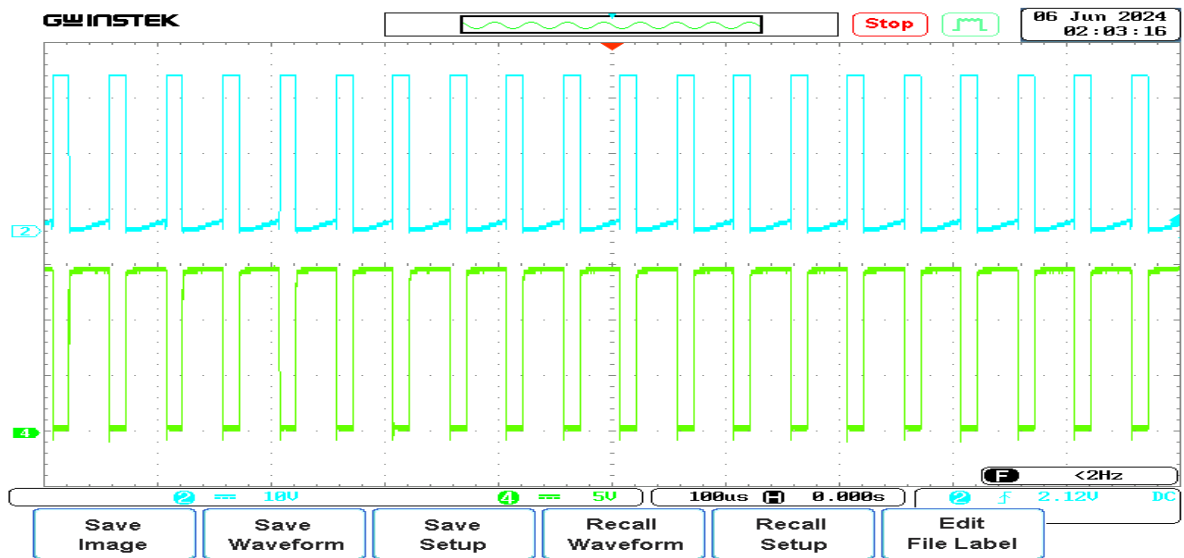


Figure 37 : The output Voltage of the circuit

- For $\alpha = 90^\circ$

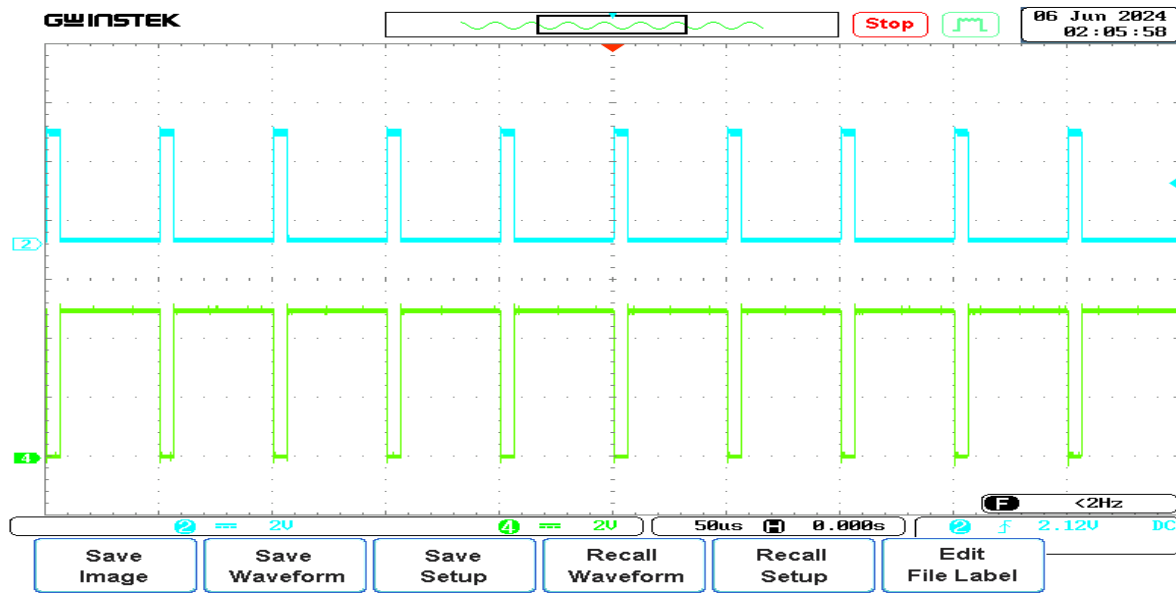


Figure 39: The control signal and its inverter

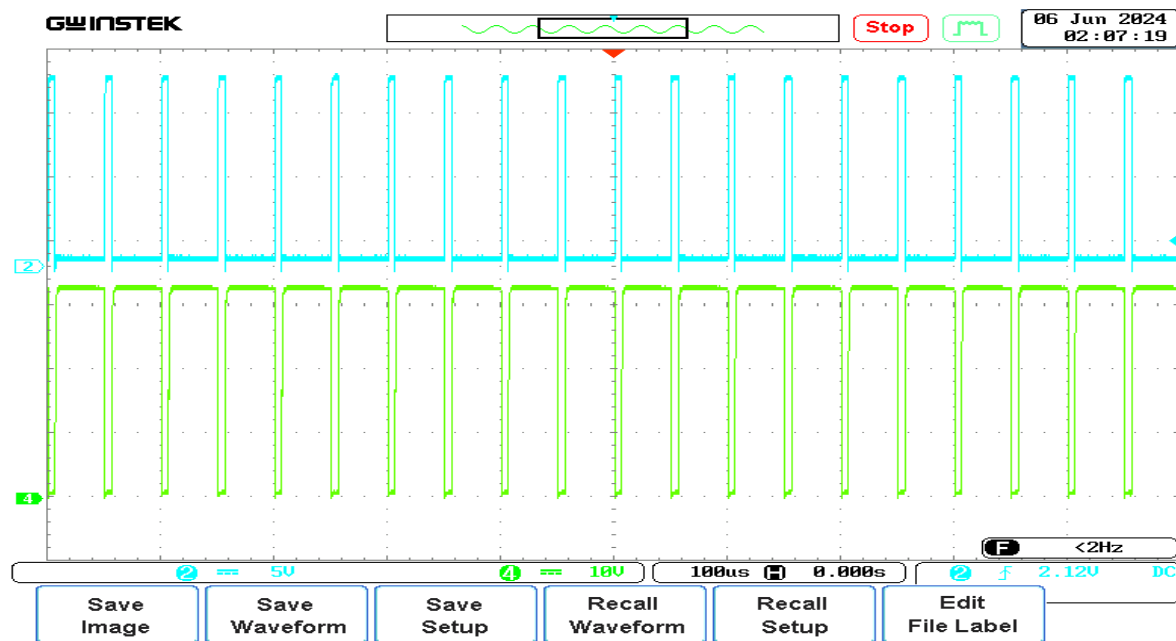


Figure 38: The output signal of the driver and its inverter

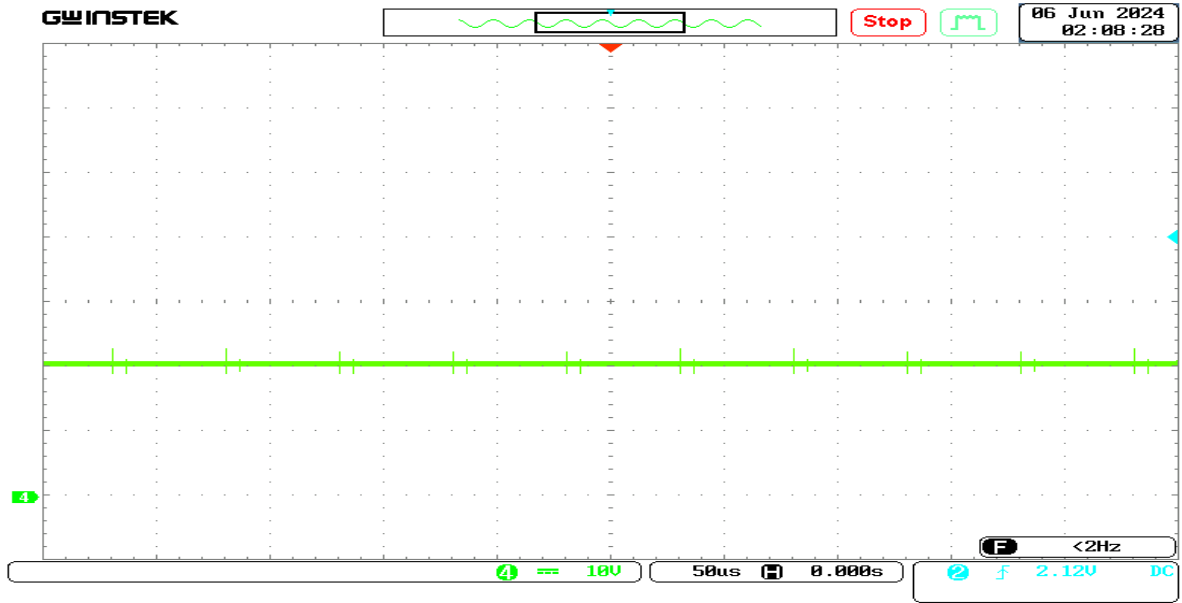


Figure 40: The output Voltage of the circuit

3.6 Optimisation using the method of experimental designs

In this study, we employ an experimental design approach to enhance the efficiency of our DC-DC converter. This approach focuses on optimizing key parameters such as switching frequency, duty cycle, and resistive load.

3.6.1 Design of Experiments (DOE)

The One Variable At a Time (OVAT) method is a traditional experimentation technique where only one variable is modified at a time while keeping the others constant. Although simple and intuitive, this approach has significant limitations: it does not allow for the detection of interactions between variables and requires a large number of experiments, which can be inefficient in terms of time and resources [33].

In contrast, the Design of Experiments (DOE) method is a systematic and statistical approach that allows multiple variables to be varied simultaneously. DOE optimizes experimental parameters, identifies interactions, and provides a more comprehensive and faster exploration of experimental conditions, leading to more precise and reliable results [33].

3.6.2 Principle of DOE method

The chosen experimental method should facilitate result interpretation while minimizing the number of trials without compromising quality. DOE theory ensures conditions for achieving the highest precision with the fewest trials, optimizing efficiency and minimizing costs.

The technique of DOE addresses these requirements by simultaneously varying the levels of one or more factors (variables) in each trial. This significantly reduces the number of experiments required while increasing the factors studied, detecting interactions, and identifying optima relative to a response. The challenge lies in minimizing the number of experiments without sacrificing result precision. While numerous DOE designs exist, each tailored to specific problems, they broadly fall into two categories: those for estimating and comparing parameter effects and those for optimizing parameters to reach an optimum.

To guide an effective experimental approach, the experimenter must devise a tailored experimental plan to address a specific problem. This involves following a precise methodology:

- Defining objectives and criteria.
- Identifying factors to study and the experimental domain.
- Constructing the experimental plan.
- Conducting experiments.
- Analyzing results.
- Deciding to halt or continue the study.
- Validating results.
- Drawing conclusions.

The Design of Experiments (DOE) method seeks to establish a relationship between two types of variables:

- The response: representing the studied physical quantity.
- The factors: representing the physical quantities subject to modification by the experimenter and expected to impact variations in the response [34].

The value assigned to a factor in an experiment is termed a "level," typically bounded between a lower and upper limit. These levels are defined by the experimenter, encompassing the range of values explored during the study [35].

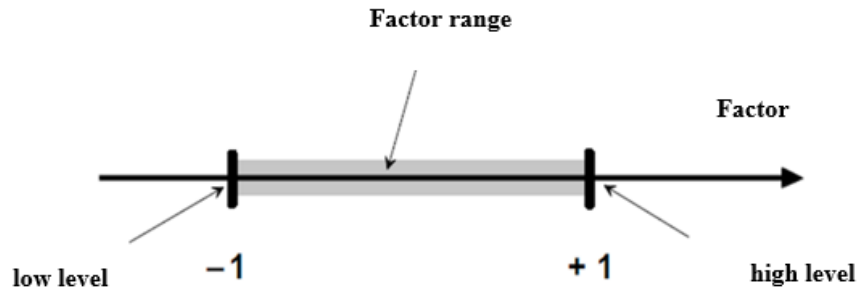


Figure 41: Factor range [35]

To represent the experimental space, a two-dimensional plane is used. One factor is represented by a graduated and oriented axis, and a second factor by a graduated and oriented axis perpendicular to the first. This forms a Cartesian coordinate system, creating a two-dimensional Euclidean space called the experimental space. Each point in this plane represents an experiment [35].

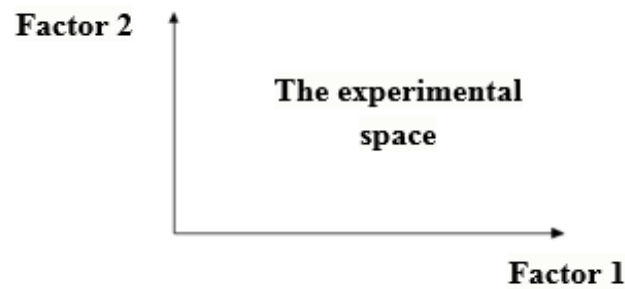


Figure 42: The experimental space [35]

In two dimensions, the levels of factors 1 and 2 are the coordinates of a point in the experimental space. Each experiment is represented by a point, called an experimental point, in this system of axes. A plan of experiments is an ensemble of these points in the experimental space [35].

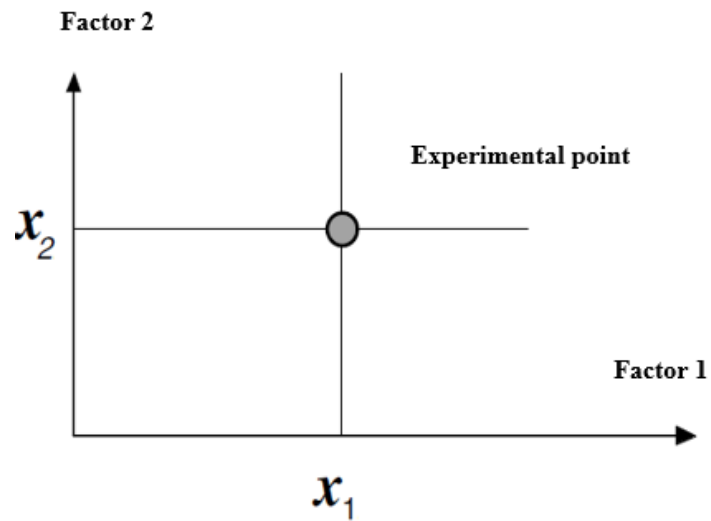


Figure 43: Experimental point [35]

The experimental space is divided into a particular zone called the domain of study, defined by the high and low levels of all factors. In practice, the experimenter selects this part of the experimental space to conduct their study[35].

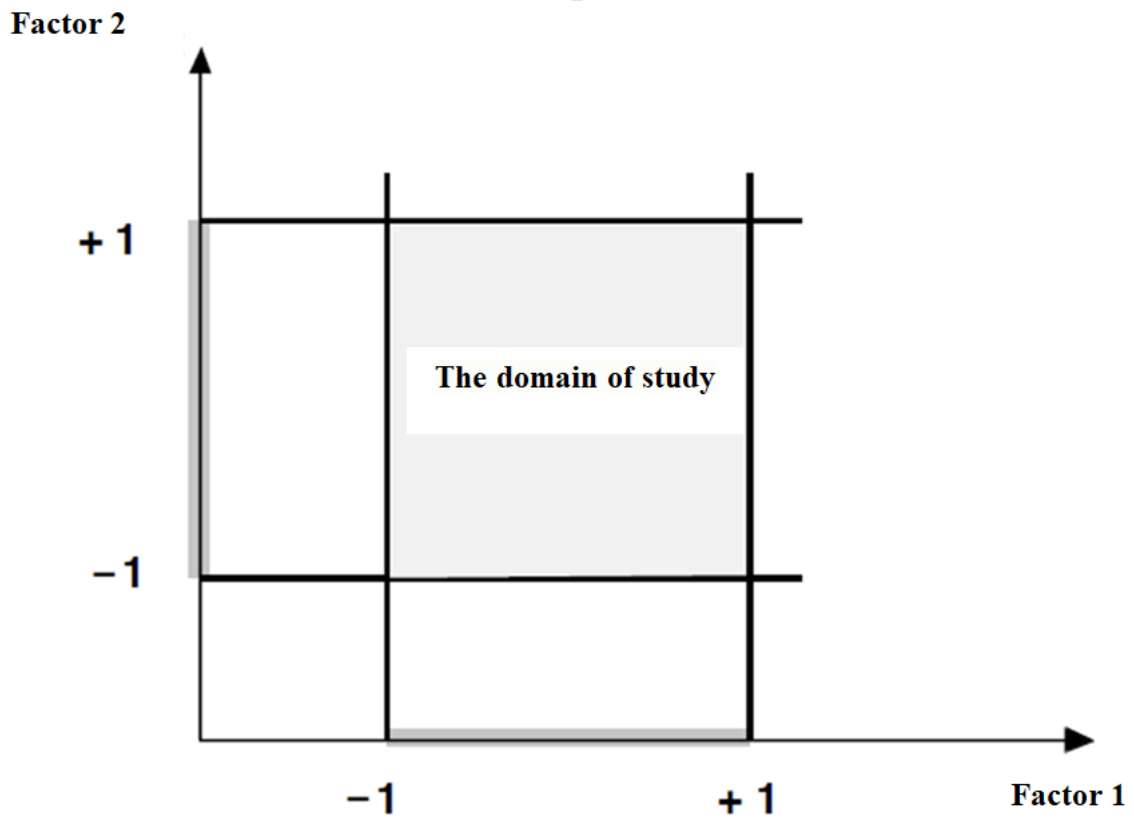


Figure 44: The domain of study[35]

3.6.3 Full Factorial Design

A factorial design is an experimental method that evaluates the effects of multiple factors by testing all possible combinations of their levels. This approach allows for the analysis of individual effects of each factor and their interactions. According to the law of complete factorial design, for k factors each having n levels, the total number of required experiments is n^k , ensuring a comprehensive exploration of all possibilities [35].

For example, in a full factorial design with 3 factors, denoted as 2^3 , the best strategy is to choose measurement points at the extremes of the experimental domain. This increases result precision and requires only 8 trials.

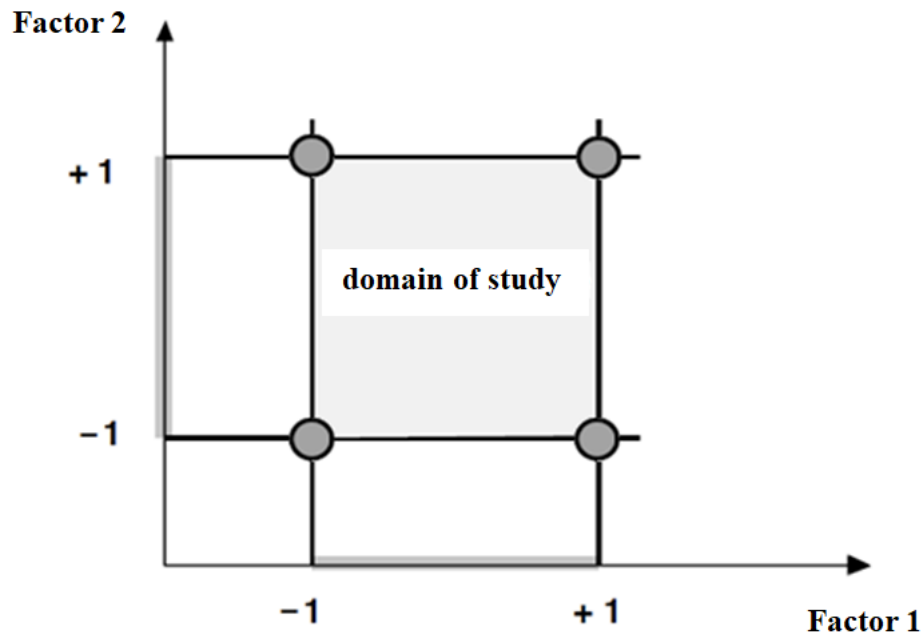


Figure 45: Experimental Points Placement[35]

- Advantages of Full Factorial Designs
 - Easy to construct and control.
 - Simple calculations and interpretation.
 - Immediate mathematical modeling.
 - Results can be reused for further exploration or advanced models.
- Disadvantages of Full Factorial Designs
 - The number of experiments increases rapidly with more factors, making the designs costly and impractical [36].

3.6.4 Response Surfaces

Each point within the study domain corresponds to a response, collectively forming a response surface. A mathematical model is used to interpolate unknown responses from selected experimental points, ensuring optimal precision.

- Primary objectives include:
 - Optimizing one or more response variables.
 - Finding a compromise between multiple variables.
 - Mapping the variation of a response in a plane.
 - Determining optimal proportions for mixing components[35].

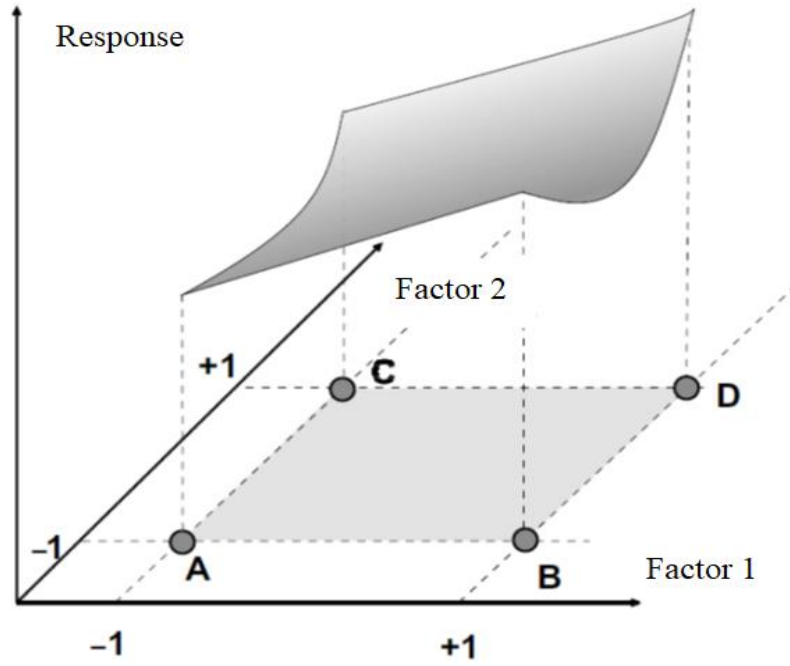


Figure 46 : The response surface[35]

3.6.5 Modeling of the Response

3.6.5.1 Mathematical Modeling

When the relationship between the response and factors is unknown, a general mathematical model is used. For a factorial experimental design with (n) factors, the relationship between the response (y) and the factors (x₁, x₂, ..., x_i, ..., x_n) [37] is described by:

$$y = a_0 + \sum_{i=1}^n a_i X_i + \sum_{\substack{i,j=1 \\ i \neq j}}^n a_{ij} X_i X_j + \sum_{\substack{i,j,k=1 \\ i \neq j \neq k}}^n a_{ijk} X_i X_j X_k + \dots$$

(18)

In this equation:

$a_0, a_1, \dots, a_n$: represent the coefficients of the polynomial.

X_i : represents a level of factor i.

X_j : represents a level of factor j.

y : is the response or the variable of interest.

Terms like $a_{ij}.X_i. X_j$ correspond to second-order interactions et while terms like $a_{ijk}.X_i.X_j.X_k$ correspond to third-order interactions.

For a factorial design with 3 factors X_1 , X_2 , and X_3 , we obtain Equation (19):

$$y = a_0 + a_1.X_1 + a_2.X_2 + a_3.X_3 + a_{12}.X_1.X_2 + a_{13}.X_1.X_3 + a_{23}.X_2.X_3 + a_{123}.X_1.X_2.X_3$$

(19)

This model is referred to as the postulated model. Established models are predictive models valid within the study domain, a domain that must always be specified.

3.6.5.2 Experimental Modeling

Two additional aspects need consideration in the mathematical model described earlier. Firstly, the "lack of fit" addresses the potential disparity between the chosen model and the actual phenomenon. Secondly, acknowledging the random nature of responses is crucial. Measurements taken at the same experimental point may vary due to data dispersion, termed as random errors. These errors, represented by e [37], The general relationship must be modified as follows:

$$y = f(X_1, X_2, X_3, \dots, X_n) + e$$

(20)

3.6.5.3 System of Equations

Each experimental point provides a response value, which is modeled by a polynomial with coefficients to be determined. At the end of the experimental plan, we have a system of n equations (for n trials) with p unknowns (for p coefficients in the model) [37]. This system can be represented simply in matrix notation:

$$y = X.a + e$$

(21)

Where:

- y is the response vector,
- X is the matrix of coefficients of the model, depending on the chosen experimental points,
- a is the vector of effects,
- e is the vector of errors .

The solution to this system is typically carried out using a regression method based on least squares optimization. The estimates of the coefficients, denoted $\hat{a}$ are obtained by:

$$\hat{a} = (X^t X)^{-1} X^t y$$

(22)

- X^t is the transpose of X ,
- $X^t X$ is the information matrix,
- $(X^t X)^{-1}$ is the dispersion matrix.

3.7 DC DC power converter optimisation

We aim to understand the impact of key parameters on the efficiency of the converter, which measures the effectiveness of electrical energy transfer. To achieve this, we design a series of experiments where we vary the frequency, the resistive load, and the duty cycle in different configurations.

The switching frequency determines how quickly the converter switches between its ON and OFF states, while the duty cycle indicates the proportion of time during which the active component is in a conducting state relative to its switching period. Additionally, the resistive load ratio represents the fraction of time during which the load is connected to the converter.

For each configuration, we measure the efficiency of the converter to assess its effectiveness. By analyzing the results of these experiments, we will be able to determine the optimal values of the frequency, the resistive load, and the duty cycle that maximize the converter's efficiency. This approach will enable us to identify the most effective operating conditions for our DC-DC converter.

Table 3 : Different parameters of dc dc converter and the selected levels

N°	Parameters	Symbol	unit	Level	
				Low (-1)	High (+1)
1	Duty ratio	A	%	30	50
2	Frequency	F	Hz	10000	20000
3	Resistive load	R	Ohms	200	600

3.7.1 Encoding of the experimental matrix

The coding of the experimental matrix standardizes the variations of the adjustment parameters, facilitating the use of experimental designs. It relies on a unique coding relationship that

transforms the real values of the factors into dimensionless values ranging between -1 and 1, The encoding of the experimental matrix standardizes the variations of the adjustment parameters, thereby facilitating the utilization of experimental designs. It relies on a unique coding relationship that transforms the real values of the factors into dimensionless values ranging between -1 and 1. The natural variables represent the parameters under study, while the coded variables, associated with each natural variable, simplify data processing by being dimensionless [9] . The equation expressed as follows:

$$X_i = \frac{u_i - \left(\frac{u_{i\max} + u_{i\min}}{2} \right)}{\left(\frac{u_{i\max} - u_{i\min}}{2} \right)}$$

(23)

$U_{\max}$ and $U_{\min}$ being the bounds defined by the user and u_i the actual level given to factor i . The coded factor X , transformed from factor u , is dimensionless, and its values are within the bounded interval $[-1; 1]$.

3.7.2 Experience Matrix

The Table 4 presents the experimental matrix for our DC-DC converter project, where three key factors are studied. Each factor is tested at two levels to evaluate their influence on the property being studied. Using this approach, we can estimate the effects of the factors and their interactions on the converter's efficiency, allowing us to develop a mathematical model to understand the relationship between the input variables and the system's performance [9].

For a full factorial design with three factors, the associated mathematical model y is expressed as follows:

$$y = a_0 + a_1.X_1 + a_2.X_2 + a_3.X_3 + a_{12}.I_{12} + a_{13}.I_{13} + a_{23}.I_{23}$$

(24)

a_0 : Overall average .

a_1, a_2, a_3 : Effect of duty ratio, frequency, resistive load respectively.

a_{12} : Effect of the interaction between duty ratio and frequency .

a₁₃ : Effect of the interaction between duty ratio and resistive load.

a₂₃ : Effect of the interaction between frequency and resistive load.

I₁₂, I₁₃ et I₂₃ : Interaction between the different variables.

Table 4 : Experience matrix

N° trial	Duty ratio (%) (α) $\equiv$ (X_1)	Frequency (Hz) (f) $\equiv$ (X_2)	Resistive load (ohms) (R) $\equiv$ (X_3)	Efficiency (%) (μ)= (Y)
01	30	10000	200	60
02	30	10000	600	81
03	30	20000	200	68
04	30	20000	600	78
05	50	10000	200	92
06	50	10000	600	94
07	50	20000	200	84
08	50	20000	600	71

A 2k experimental design includes 2k experimental points, located at the 2k vertices of a k-dimensional hypercube.

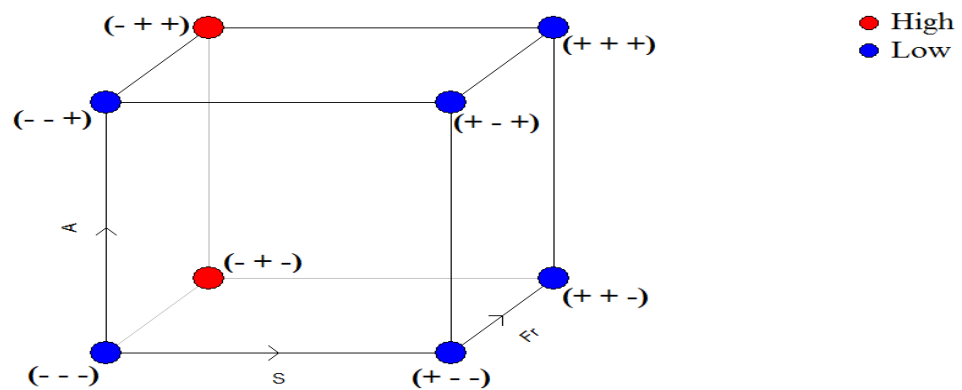


Figure 47: Geometric representation of a plane 2^3 [35]

If we do not take into account experimental errors, this system can be expressed in matrix form:

$$Y = X.a$$

(25)

with :

Y : a vector consisting of the responses of each trial, represented by a column matrix $(2^k, 1)$,
a : a vector consisting of the mean, the effects of the factors, and all the interactions, represented by a column matrix $(2^k, 1)$, these components are the unknowns we seek to determine,
X : a square matrix $(2^k, 2^k)$ composed of -1 and +1 according to the values of the levels x_i .
If we revisit the system of the 2^3 plan, relation (25) takes the following form:

$$\begin{bmatrix} y_1 \\ y_2 \\ y_3 \\ y_4 \\ y_5 \\ y_6 \\ y_7 \\ y_8 \end{bmatrix} = \begin{bmatrix} 1 & -1 & -1 & -1 & 1 & 1 & 1 & -1 \\ 1 & 1 & -1 & -1 & -1 & -1 & 1 & 1 \\ 1 & -1 & 1 & -1 & -1 & 1 & -1 & 1 \\ 1 & 1 & 1 & -1 & 1 & -1 & -1 & -1 \\ 1 & -1 & -1 & 1 & 1 & -1 & -1 & 1 \\ 1 & 1 & -1 & 1 & -1 & 1 & -1 & -1 \\ 1 & -1 & 1 & 1 & -1 & -1 & 1 & -1 \\ 1 & 1 & 1 & 1 & 1 & 1 & 1 & 1 \end{bmatrix} \begin{bmatrix} a_0 \\ a_1 \\ a_2 \\ a_3 \\ a_{12} \\ a_{13} \\ a_{23} \\ a_{123} \end{bmatrix}$$

The matrix **X** has a column of +1 and seven columns each containing an equal number of positive and negative signs. When we multiply the elements pairwise from these columns and sum the products, we obtain zero, which characterizes the matrix as orthogonal. This property is crucial because, in this case, the inverse of **X** is simply the transpose of **X** divided by the number of rows n

for this type of matrix, we have the relation.

$$X^t X = n.I$$

(26)

The calculation of the unknown **a** is performed using this equation

$$\left. \begin{aligned} X^t y &= X^t X . a \\ X^t y &= n . I . a \\ a &= \frac{1}{n} X^t y \end{aligned} \right\}$$

(27)

Each element of **a** is therefore of the form:

$$a_i = \frac{1}{n} [\pm y_1 \pm y_2 \pm y_3 \pm \dots \pm y_n]$$

(28)

We use a table named calculation matrix to summarize all the trials:

Table 5 : Calculation matrix

N° trial	Average	X ₁	X ₂	X ₃	I ₁₂	I ₁₃	I ₂₃	I ₁₂₃	Efficiency (%) (μ)=(Y)
01	1	-1	-1	-1	1	1	1	-1	60
02	1	1	-1	-1	-1	-1	1	1	81
03	1	-1	1	-1	-1	1	-1	1	68
04	1	1	1	-1	1	-1	-1	-1	78
05	1	-1	-1	1	1	-1	-1	1	92
06	1	1	-1	1	-1	1	-1	-1	94
07	1	-1	1	1	-1	-1	1	-1	84
08	1	1	1	1	1	1	1	1	71
effects and interactions	a ₀	a ₁	a ₂	a ₃	a ₁₂	a ₁₃	a ₂₃	a ₁₂₃	
	78,5	2,5	-3,25	6,75	-3,25	-5,26	-4,5	-0,5	
Leve l –		30	10000	200					
Level +		50	20000	600					

Using the least squares method to calculate the effects results in the following adjusted mathematical model:

$$y = 78,5 + 2,5 X_1 - 3,25 X_2 + 6,75 X_3 - 3,25 I_{12} - 5,26 I_{13} - 4,5 I_{23} - 0,5 I_{123}$$

$$\mu = 78,5 + 2,5 \alpha - 3,25 f + 6,75 R - 3,25 \alpha f - 5,26 \alpha R - 4,5 f R - 0,5 \alpha f R$$

3.7.3 Analysis of Effects

3.7.3.1 Main effect of each factor

The Figure 48 illustrates how each factor individually affects efficiency. Since our experimental design is a full factorial design at two levels, all factors vary together systematically and evenly. This allows us to estimate the main effect of each factor independently of the others.

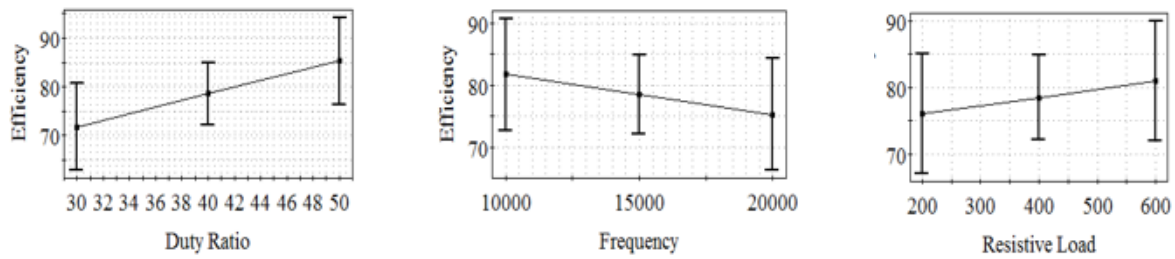


Figure 48 : Illustration of the main effect of the three factors

The main effect of a factor is the change in response when the factor goes from its low level to its high level. In our case, this is the change in efficiency when increasing the values of the factors from 30% to 50% for Duty ratio, from 10,000 Hz to 20,000 Hz for frequency, and from 200 ohms to 600 ohms for resistive load.

Increasing the Duty ratio significantly improves efficiency, making it the most influential factor in this experiment.

Increasing the frequency reduces efficiency. Although this effect is less significant than that of the Duty ratio, it is still important.

The resistive load has the smallest effect, with its increase leading to a slight improvement in efficiency. This effect, while smaller, is still noteworthy.

3.7.3.2 Interaction Effect for Two Factors

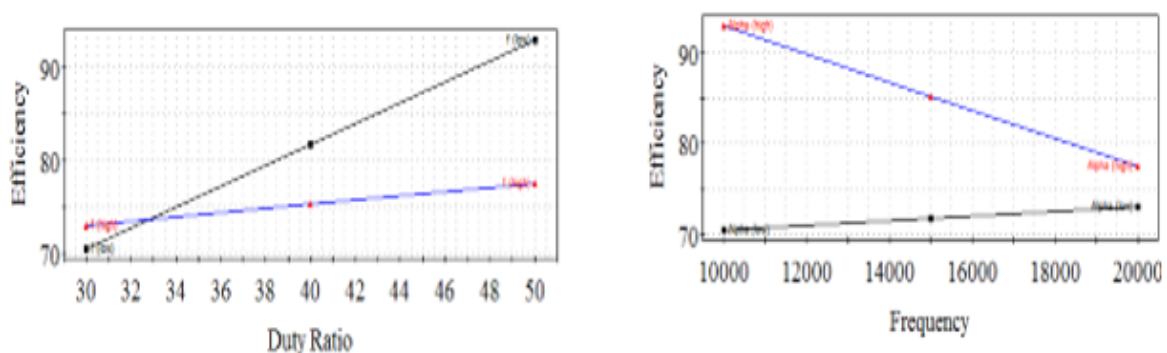


Figure 49 : Interaction between duty ratio and frequency

The left plot in Figure 49 shows that when the Duty ratio is increased, Efficiency slightly increases from 70.6% to 93.5% when Frequency is at its minimum and from 73.2% to 77.9%

when Frequency is at its maximum. However, the variation in Duty ratio has a significant effect on Efficiency only when Frequency is at its minimum.

Similarly, the right plot in Figure 49 shows that when the frequency is increased, Efficiency slightly decrease from 93, 5 % to 77, 6 % when duty ratio is at its maximum.

We conclude that the influence of Duty ratio is more significant than the influence of Frequency.

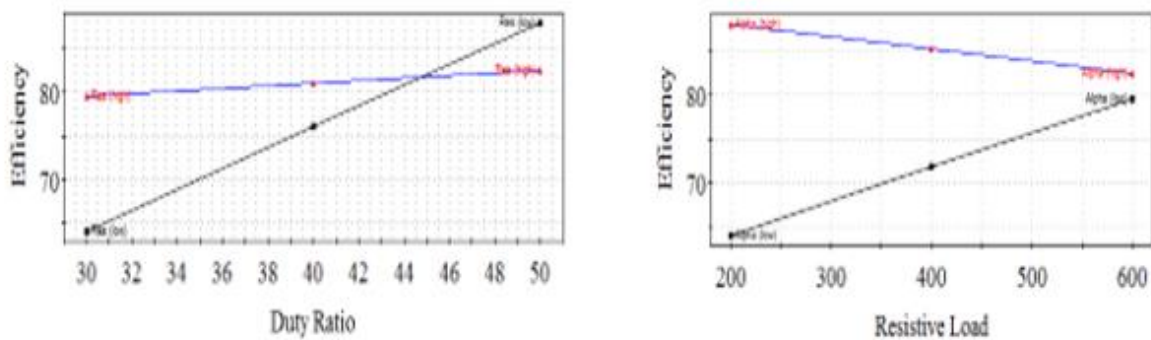


Figure 50 : Interaction between duty ratio and resistor

The left plot in Figure 50 illustrates that with an increase in Duty ratio, Efficiency experiences a slight increase from 64% to 88.6% when resistive load is at its minimum and from 79.5% to 82.6% when resistive load is at its maximum. However, the variation in Duty ratio significantly affects Efficiency only when resistive load is at its minimum.

Similarly, the right plot in Figure 50 demonstrates that with an increase in resistive load, Efficiency slightly increases from 64% to 79.8% when Duty ratio is at its minimum.

Therefore, we can conclude that when Duty ratio is significant, the efficiency is higher, except when the resistive load has higher values.

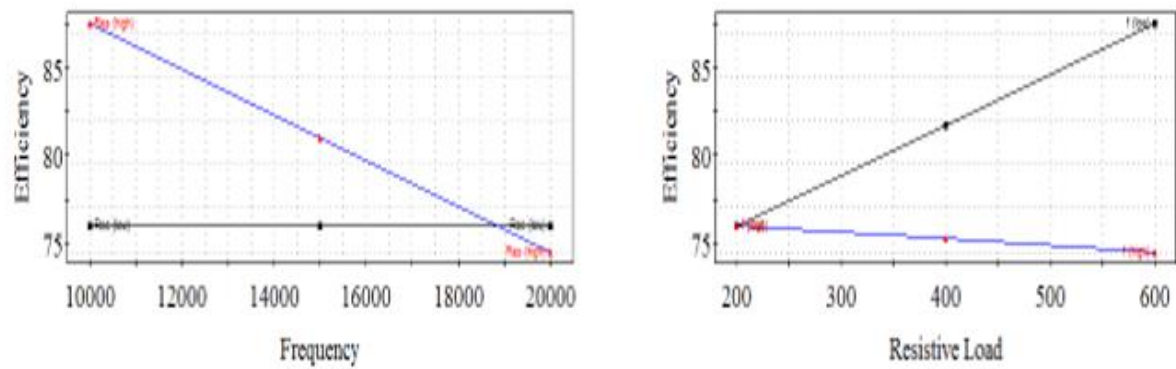


Figure 51 : interaction between frequency and resistor

The left plot in Figure 50 illustrates that as frequency increases, there's a slight rise in Efficiency, particularly noticeable when resistive load is at its maximum. However, the impact of frequency on Efficiency is significant only when resistive load is at its highest.

Similarly, the right plot in Figure 50 shows that with an increase in resistive load, Efficiency also experiences a slight increase, especially when frequency is at its minimum.

In summary, when resistive load is significant, Efficiency tends to be higher, except when frequency reaches high values.

3.7.4 Analysis using the response surface methodology

3.7.4.1 The interaction between duty ratio and frequency

It is evident that the duty ratio, frequency, and resistive load significantly influence efficiency. To obtain an optimal value for efficiency, it is recommended to set one of these parameters to a fixed value while allowing the other two to vary.

The increase in duty ratio values in the case of low resistive load leads to a decrease in efficiency from 92% to 79%, regardless of the frequency value. However, for high resistive load levels, efficiency may exhibit a different trend depending on the duty ratio and frequency. It is observed that for certain combinations of duty ratio and frequency values, efficiency can be maximized, while for others, it may be reduced. The resistive load appears to play a more significant role in this variation, affecting the optimal values of duty ratio and frequency to achieve maximum efficiency.



Figure 52 : Response surface in the case of a low and high resistive load

3.7.4.2 The interaction between duty ratio and resistive load

We observe that frequency has a significant influence on the efficiency of the device. At a higher frequency, the overall efficiency is lower compared to a lower frequency. The interaction between Duty Ratio and Resistive Load is also more pronounced at a lower frequency.

This suggests that to maximize efficiency, it is preferable to operate at a lower frequency and adjust the Duty Ratio and Resistive Load accordingly.



Figure 53 : Response surface in the case of a low and high frequency

3.7.4.3 The interaction between frequency and resistive load

The interaction between frequency and resistive load can have different effects on efficiency depending on the duty ratio. However, in both cases, an simultaneous increase in frequency and resistive load can generally result in a decrease in efficiency.

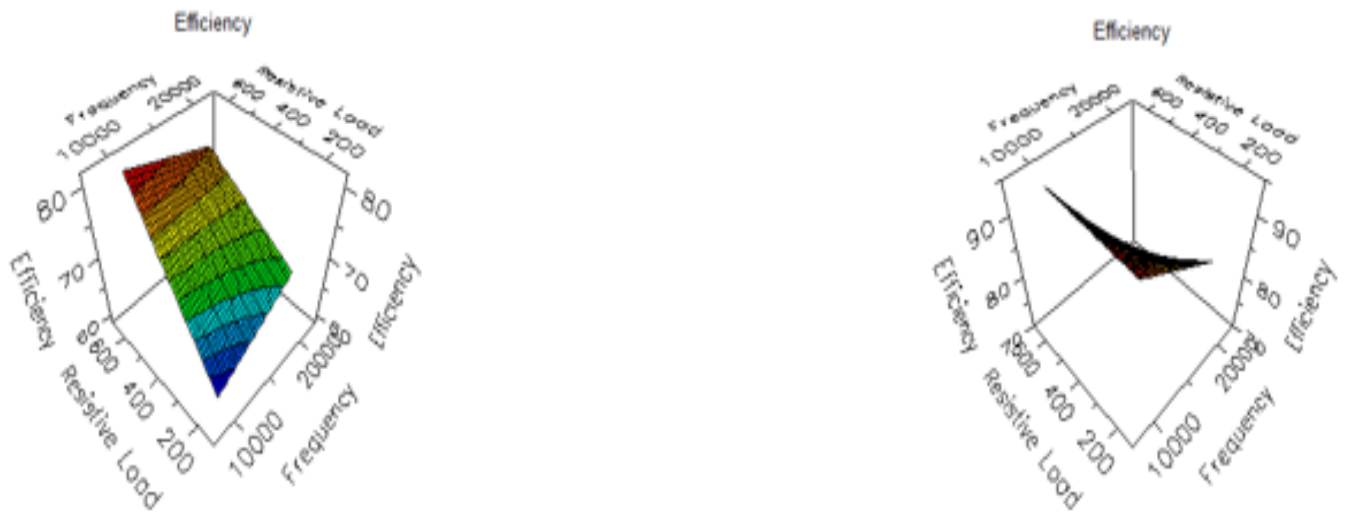


Figure 54 : Response surface in the case of a low and high duty ratio

3.7.5 The influence of all factors

According to the mathematical model relationship found, we calculate the estimated responses

Table 6 : Calculation of estimated responses

y_i	Applied model of each experiment	Y_{es}
y_1	$78,5 + 2,5 (-1) - 3,25 (-1) + 6,75 (-1) - 3,25 (1) - 5,26 (1) - 4,5 (1)$	59,49
y_2	$78,5 + 2,5 (1) - 3,25 (-1) + 6,75 (-1) - 3,25 (-1) - 5,26 (-1) - 4,5 (1)$	81,51
y_3	$78,5 + 2,5 (-1) - 3,25 (1) + 6,75 (-1) - 3,25 (-1) - 5,26 (1) - 4,5 (-1)$	68,49
y_4	$78,5 + 2,5 (1) - 3,25 (1) + 6,75 (-1) - 3,25 (1) - 5,26 (-1) - 4,5 (-1)$	77,51
y_5	$78,5 + 2,5 (-1) - 3,25 (-1) + 6,75 (1) - 3,25 (1) - 5,26 (-1) - 4,5 (-1)$	92,51
y_6	$78,5 + 2,5 (1) - 3,25 (-1) + 6,75 (1) - 3,25 (-1) - 5,26 (1) - 4,5 (-1)$	93,49
y_7	$78,5 + 2,5 (-1) - 3,25 (1) + 6,75 (1) - 3,25 (-1) - 5,26 (-1) - 4,5 (1)$	83,51
y_8	$78,5 + 2,5 (1) - 3,25 (1) + 6,75 (1) - 3,25 (1) - 5,26 (1) - 4,5 (1)$	71,49

The residual for each experiment can be calculated as the absolute difference between the experimental response and the predicted response, utilizing the equation:

$$e_i = |Y_{\text{exp}} - Y_{\text{estimé}}|$$

(29)

Table 7 : Calculation of residuals

y_{exp}	Y_{es}	e_i
60	59,49	0,51
81	81,51	-0,51
68	68,49	-0,49
78	77,51	0,49
92	92,51	-0,51
94	93,49	0,51
84	83,51	0,49
71	71,49	-0,49

We can move on to the next step, which involves conducting a regression analysis and interpreting the model. When fitting a regression model, two important parameters are used: R^2 and Q^2 . R^2 measures the quality of the model's fit to the raw data, with a maximum value of 1 indicating a perfect fit, and a minimum value of 0 indicating no fit. In contrast, Q^2 is an indicator of the model's predictive quality, Q^2 is the right bar in Figure 55, and it equals 0.86.. It also ranges from 0 to 1, where higher values indicate better predictive capability for new data. For a model to be considered good, Q^2 generally needs to be above 0.5, and ideally above 0.9.

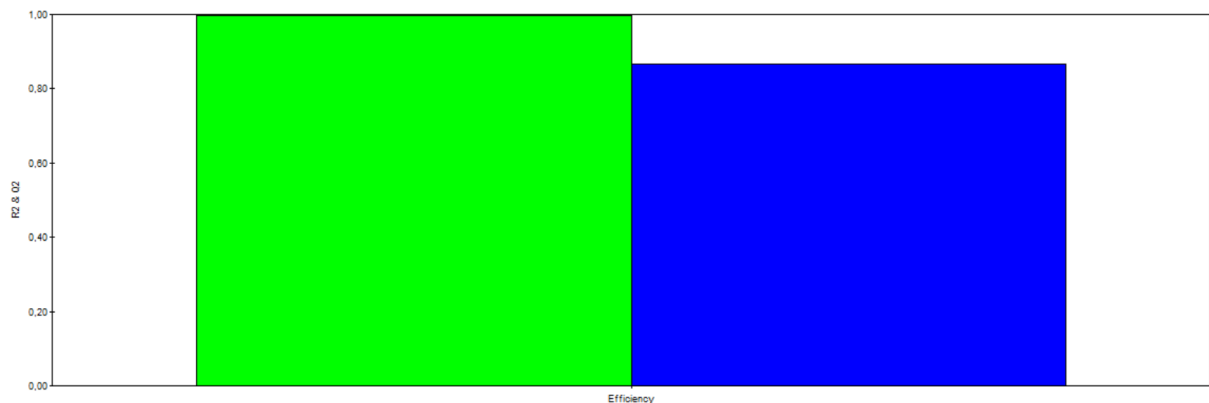


Figure 55 : Fitting parameters

In the next figure, the fit is excellent as all the points are near the line. However, there are minor discrepancies between the calculated and observed (measured) response values.

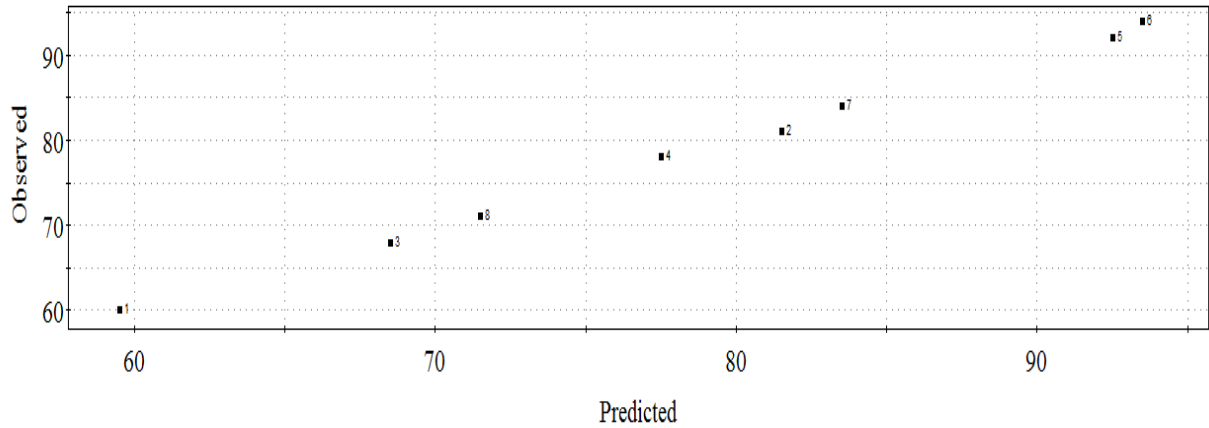


Figure 56 : The relationship between the calculated and observed response values for the efficiency

3.7.5.1 Significance of Effects

We want to determine which variable or interaction between variables has a significant impact on the response, with a 5% risk. To do this, we use the Student's t-test to compare each effect to zero.

We will test the hypothesis: The effect is null, $H_0 = a_i = 0$

Against the hypothesis: The effect is not null, $H_1 = a_i \neq 0$

For this, we use the Student's t-test given by the relation:

$$t_i = \frac{|a_i|}{\sigma_i}$$

(30)

If the test statistic (t_i) is greater than the critical value (t_{crit}), we reject H_0 and consider the effect as significant.

3.7.5.2 Experimental variance

the degrees of freedom is estimated with $v=n-p$ where :

n : represents the total number of conducted experiments,

p : signifies the count of effects, inclusive of the average .

it is impossible to calculate the common variance of residuals, especially in a complete design where n equals p . Consequently, in practice, it is often preferred to ignore higher-order interactions (third order or above). This approach simplifies the model and facilitates statistical calculations, based on an understanding of the context and the laws governing the studied phenomenon.

The statistical procedures used to determine the significance of effects, establish confidence intervals, and confirm the linearity of the model require the use of residuals (e_i), representing the disparity between experimental values and those predicted by the model. In parallel, they require the use of an estimator for the common variance of residuals, which is calculated according to the relation:

$$\sigma^2 = \frac{1}{n-p} \sum e_i^2$$

(31)

Under these conditions, it can be shown that all effects have the same variance given by the relation:

$$\sigma_i^2 = \frac{\sigma^2}{n}$$

(32)

Let's take into account our 2^3 experimental setup, where we ignore the third-order interaction. We collect the residuals and the respective variances for each effect in this table:

Table 8: Calculation of residuals and variances

Y_i estimated	e_i^2	σ_i
59,49	0,26	0,25
81,51	0,26	0,25
68,49	0,24	0,25
77,51	0,24	0,25
92,51	0,26	0,25
93,49	0,26	0,25

83,51	0,24	0,25
71,49	0,24	0,25

According to the Student's t-table, for a 5% significance level with $\nu = n - p = 8 - 7 = 1$ degree of freedom: $t(\alpha, \nu) = t(0.05; 1) = 12.706$. An effect will be considered significant at the 5% level if its "ti" exceeds 12.706. The resulting table is:

Table 9: signification of effects

t_i	Result	Note
$t_0 = 314 > 12,71$	significant	The effect of the average value is significant
$t_1 = 10 < 12,71$	non significant	The effect of duty ratio is not significant.
$t_2 = 13 > 12,71$	significant	The effect of frequency is significant.
$t_3 = 27 > 12,71$	significant	The effect of resistive load is significant.
$t_{12} = 13 > 12,71$	significant	The effect of the interaction between duty ratio and frequency is significant.
$t_{13} = 21,04 > 12,71$	significant	The effect of the interaction between duty ratio and resistive load is significant.
$t_{23} = 18 > 12,71$	significant	The effect of the interaction between frequency and resistive load is significant.

it can be concluded that the coefficients a_1 is not significantly different from zero. Thus, based on this analysis, only variables X_2 , X_3 , and the all interactions are deemed significant. Consequently, we should consider a model in the following form:

$$y = 78,5 - 3,25 X_2 + 6,75 X_3 - 3,25 I_{12} - 5,26 I_{13} - 4,5 I_{23}$$

$$\mu = 78,5 - 3,25 f + 6,75 R - 3,25 \alpha f - 5,26 \alpha R - 4,5 f R$$

3.7.5.3 Confidence interval for the effects

We will determine a confidence interval, with a 5% risk level, for the coefficients of the significant effects: a_2 , a_3 , a_{12} , a_{13} , a_{23} . By choosing a risk level α , we use the Student's t-table to

find the value $t(\alpha, \nu)$. The confidence interval for an effect is then given by the following formula:

$$\text{risk } \alpha_i : [(a_i - t(\alpha, \nu) \sigma_i) ; (a_i + t(\alpha, \nu) \sigma_i)]$$

After substituting $t(\alpha, \nu)$ and σ_i with their respective values, we obtain:

$$\alpha_i = [a_i - 12,706*0,25 ; a_i + 12,706*0,25]$$

Table 10: Confidence interval for the effects

	a_i	Upper limit	Lower limit
α_2	- 3,25	- 0,07	- 6,43
α_3	6,75	9,93	3,75
α_{12}	- 3,25	- 0,07	- 6,43
α_{13}	-5,26	-8,43	-2,08
α_{23}	-4,5	-7,67	-1,32

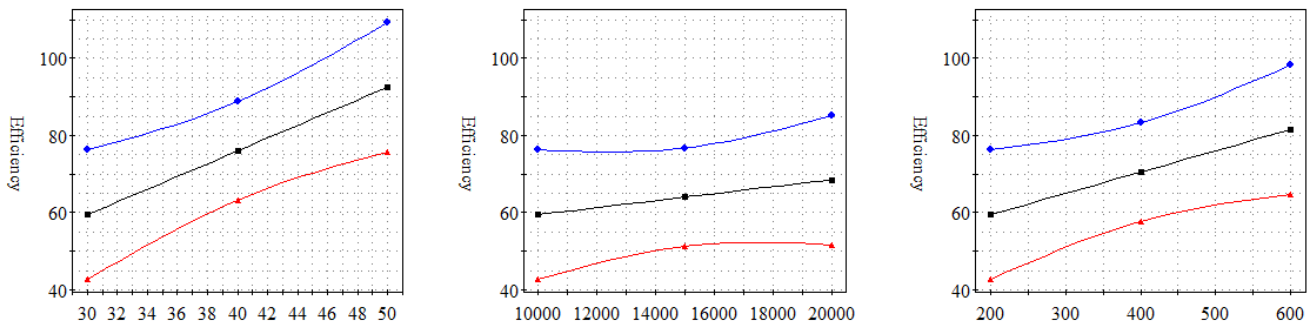


Figure 57 : prediction plot for low values

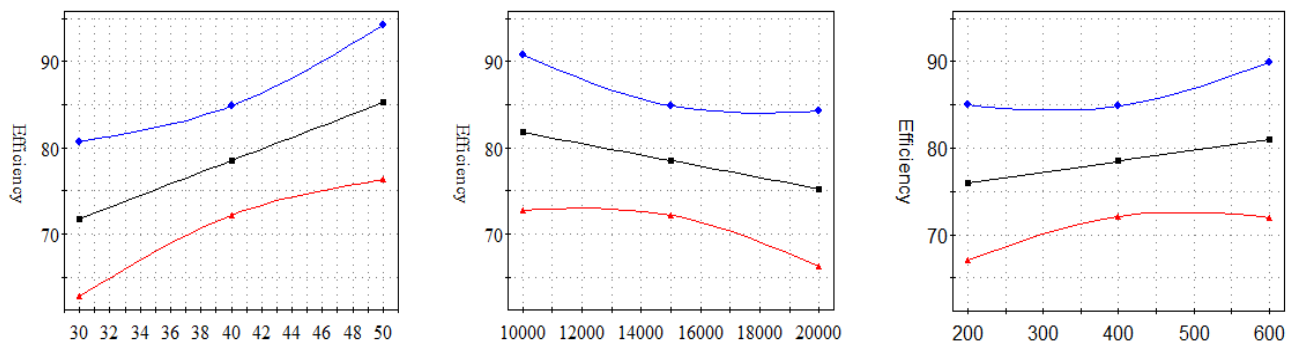


Figure 58: prediction plot for center values

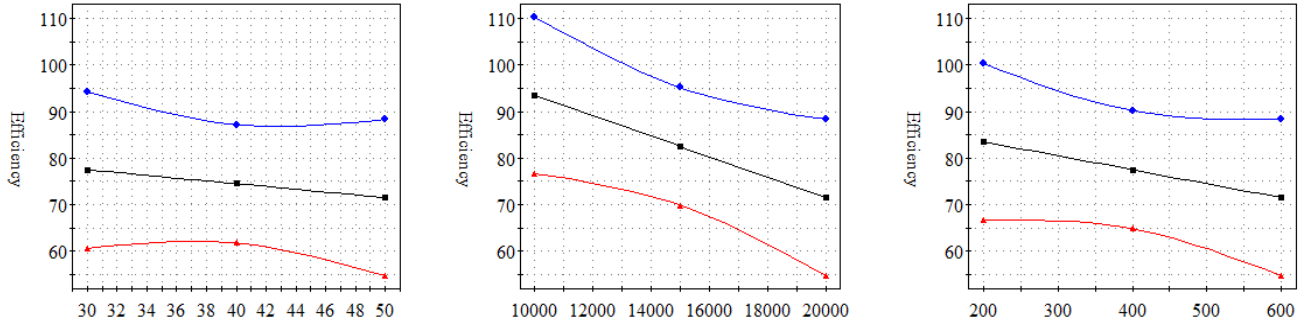


Figure 59 : prediction plot for high values

3.8 Conclusion

This chapter provides a comprehensive study on the simulation and optimization methods of bidirectional DC-DC converters used in electric vehicles for propulsion and regenerative braking. The simulations highlight the converter's efficiency in both boost and buck modes. Through the design of experiments (DOE) method, it was found that the interaction between the duty cycle and switching frequency is more significant than other effects for performance optimization. Mastering and enhancing this interaction is crucial to maximize the converter's efficiency in both modes of operation.

Chapter 4

EMI Emissions Analysis and PCB Implementation of Bidirectional Dc-Dc Converters for Electric Vehicles

4.1 Introduction

Analyzing EMI emissions in Bidirectional converters is crucial for ensuring vehicle reliability, as these converters are significant EMI sources. Compliance with standards like CISPR 25 is essential to prevent interference with critical vehicle systems. In the previous chapter, the efficiency of the bidirectional converter was optimized by adjusting switching frequency, duty cycle, and resistive load. This chapter aims to analyze EMI emissions under these optimized conditions to ensure comprehensive performance assessment.

4.2 CISPR 25 Compliance

CISPR 25 is an International Electrotechnical Commission (IEC) standard that specifies test methods and limits for measuring radio disturbance characteristics. Its purpose is to protect receivers used in vehicles, boats, and devices powered by internal combustion engines or electric propulsion systems [38].

4.2.1 Emission limits set by CISPR 25

The standard sets limits for conducted and radiated electromagnetic emissions across a frequency range of 150 kHz to 2.5 GHz to ensure that the operation of electronic devices does not interfere with the functioning of other devices in the vehicle [39] .

Table 1. CISPR 25 peak and quasi-peak limit levels											
Service / Band	Frequency (MHz)	Levels in dBμV									
		Class 1		Class 2		Class 3		Class 4		Class 5	
		Peak	Quasi-Peak	Peak	Quasi-Peak	Peak	Quasi-Peak	Peak	Quasi-Peak	Peak	Quasi-Peak
Broadcast											
LW	0.15 - 0.30	110	97	110	87	90	77	80	67	70	57
MW	0.53 - 1.8	86	73	78	65	70	57	62	49	54	41
SW	5.9 - 6.2	77	64	71	58	65	52	59	46	53	40
FM	76 - 108	62	49	56	43	50	37	44	31	38	25
TV BAND 1	41 - 88	58		52		46		40		34	
Mobile Services											
CB	26 - 28	68	55	62	49	56	43	50	37	44	31
VHF	30 - 54	68	56	62	49	56	43	50	37	44	31
VHF	64 - 87	62	49	56	43	50	37	44	31	38	25

Figure 60 : Peak and quasi peak limit levels by CISPR 25

Table 2.		CISPR 25 average limit levels				
Service / Band	Frequency (MHz)	Levels in dBµV				
		Class 1	Class 2	Class 3	Class 4	Class 5
		Average	Average	Average	Average	Average
Broadcast						
LW	0.15 - 0.30	90	80	70	60	50
MW	0.53 - 1.8	66	58	50	42	34
SW	5.9 - 6.2	57	51	45	39	33
FM	76 - 108	42	36	30	24	18
TV BAND 1	41 - 88	48	42	36	30	24
Mobile Services						
CB	26 - 28	48	42	36	30	24
VHF	30 - 54	48	42	36	30	24
VHF	64 - 87	42	36	30	24	18

Figure 61 : Average limit levels by CISPR 25

4.2.2 Classes of emissions

- **Class 1:** Industrial, scientific, and medical (ISM) equipment generate or use radio frequency energy in a controlled manner for specific applications like industrial heating or medical treatments.
- **Class 2:** ISM equipment use radio frequency energy for processes like spark erosion, which is used in the precise machining of metals.
- **Class 3:** ISM equipment, utilized in non-domestic environments, can interface with Class A equipment, which is specifically engineered for high reliability and performance in industrial settings.

- **Class 4:** ISM equipment are suitable for domestic use and must avoid causing interference in households.
- **Class 5:** This equipment can be used in any environment, domestic or professional, without causing or being affected by interference[38].

4.2.3 CISPR 25 Testing Methods

Testing employs two primary methods:

- **Voltage Method:** This method involves measuring the electromagnetic interference (EMI) using a voltage probe. The limits for peak voltage vary depending on the frequency range being tested. These limits are specified in CISPR 25 standards and are crucial for assessing the levels of electromagnetic emissions from electronic components used in vehicles.
- **Current Probe Method:** In this method, instead of measuring voltage directly, the EMI emissions are measured using a current probe. The peak limits obtained from this method are often converted to decibels relative to microvolt (dB μ V) for standardized comparison and reporting [39].

4.3 Experimental Setup

4.3.1 Test Equipment and Configuration

4.3.1.1 The spectrum analyzer

A spectrum analyzer visually represents signal amplitudes across various frequencies, enabling analysis to verify compliance with specified limits. It detects and displays spurious signals, complex waveforms, infrequent short-duration events, and noise. Additionally, spectrum analyzers excel at analyzing transient signals, capturing burst transmissions and glitches, and identifying instances where stronger signals may obscure weaker ones [40].

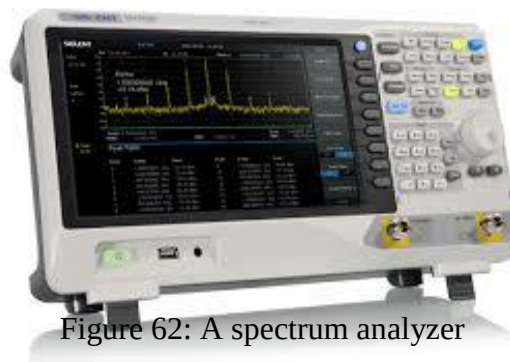


Figure 62: A spectrum analyzer

4.3.1.2 Line Impedance Stabilization Network

A Line Impedance Stabilization Network (LISN) is used in EMC/EMI tests to measure conducted RF emissions, which are electromagnetic emissions along power cables, and to establish a stable source impedance. It is inserted into the power lines of the equipment under test, ensuring precise testing by isolating the equipment from the variable impedance of the power sources. The role of the LISN is crucial in providing consistent and reliable test conditions, ensuring that conducted emissions from the equipment can be accurately measured and analyzed according to EMC/EMI standards. This setup helps in evaluating the electromagnetic compatibility of the equipment and assessing its potential interference with other electronic devices [41].



Figure 63 : A Line Impedance Stabilization Network (LISN)

4.3.1.3 Differential mode and common mode measurements

- Differential mode currents: are currents that flow in opposite directions through a pair of lines, representing the normal operation of a circuit where the signal or power follows a specific path defined by the circuit designer. These currents are equal in magnitude but opposite in direction.
- Common mode currents flow in the same direction through a pair of lines, typically caused by parasitic elements such as capacitances and inductances in the circuit. They are often undesirable and can be much smaller than differential mode currents, but they can still disrupt other circuits due to their ability to radiate and couple with them [42].

4.3.1.4 The bidirectional converter

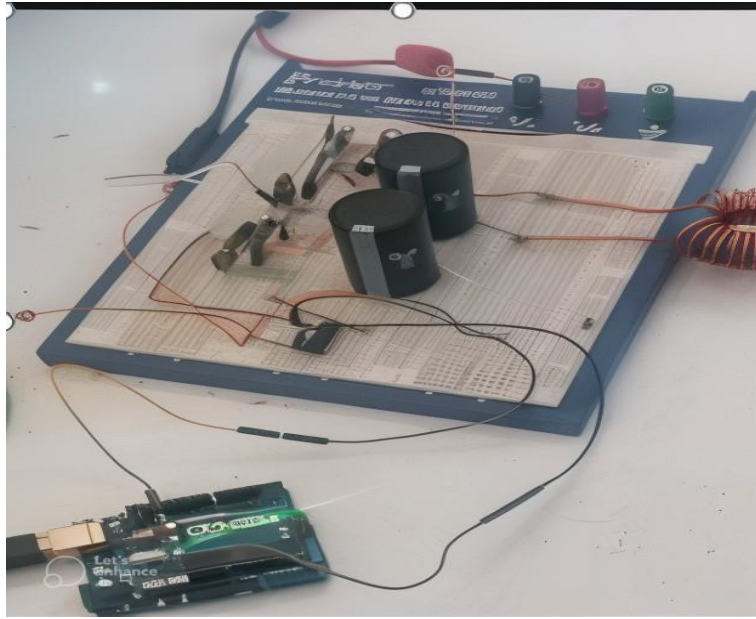


Figure 64 : the bidirectional converter

The bidirectional buck-boost DC-DC converter implemented incorporates a stable voltage generator, electrolytic capacitors for voltage filtering, IGBT transistors for precise current regulation, and an inductor for energy storage and voltage modulation. A fast-recovery diode ensures efficient current switching, preventing undesirable reverse currents. Control is managed by an Arduino Uno microcontroller generating PWM signals to drive the IGBTs, enabling smooth transitions between operation modes. Additionally, an inverter is included to effectively handle signal inversion.

4.4 Parameters and Test Conditions

In the previous chapter, we identified the optimized parameters for the bidirectional DC-DC converter, which include the switching frequency, duty cycle, and resistive load. These parameters were found to significantly influence the converter's efficiency. For the upcoming EMI emissions tests, these optimized settings will serve as the baseline conditions. By maintaining these parameters, we aim to ensure consistency and accuracy in evaluating the electromagnetic interference characteristics of the DC-DC converter under realistic operational scenarios.

4.4.1 Resistive Load Conditions

Table 11: Resistive Load Conditions in common and differential mode

N° trial	Duty ratio (%) (α) $\equiv$ (X_1)	Frequency (Hz) (f) $\equiv$ (X_2)	Resistive load (ohms) (R) $\equiv$ (X_3)
01	30	10000	200
02	30	10000	600
03	30	20000	200
04	30	20000	600
05	50	10000	200
06	50	10000	600
07	50	20000	200
08	50	20000	600

4.4.2 Motor Load Conditions

Table 12: Motor Load Conditions in common and differential mode

Trails	Duty ratio	Frequency
01	30	20
02	30	10
03	50	20
04	50	10

4.4.3 Measurement Procedure

In the context of Electromagnetic Emissions (EMI) testing, we begin by securely placing the Equipment Under Test (EUT) on a stable table, ensuring all cables and connections are properly secured. Using a spectrum analyzer connected to a laptop, we capture data focusing on the 30 MHz frequency band after powering on the EUT and configuring essential parameters like switching frequency, duty cycle, and resistive load tailored to our specific testing needs. We conduct tests in both common and differential modes, supported by a Line Impedance Stabilization Network to maintain consistent test conditions. Software records emission levels, which are stored for subsequent analysis. We then thoroughly analyze results to confirm that the EUT complies with EMI standards. Detailed documentation of procedures and configurations is included in a comprehensive final report to maintain transparency throughout our testing process.



Figure 65 : The Equipment Under Test

4.5 Results

4.5.1 Data Presentation

The raw data obtained from the spectrum analyzer is presented in the tables below:

Table 13 : raw data for long wave band

N° Essai	Duty ratio (%)	Frequency(Hz)	Resistive load(ohms)	Common mode EMI Peak Value (dBuV)	Differential mode EMI Peak Value (dBuV)	LW band EMI Peak Limit (dBuV)
1	30	10000	200	120,261906	120,247258	110
2	30	10000	600	120,25214	120,247258	110
3	30	20000	200	120,257023	120,242375	110
4	30	20000	600	120,25214	120,237492	110
5	50	10000	200	120,247258	120,227726	110
6	50	10000	600	120,257023	120,25214	110
7	50	20000	200	120,247258	120,242375	110
8	50	20000	600	120,257023	120,247258	110
9	30	10000	Motor	120,237492	120,217961	110
10	30	20000	Motor	120,227726	120,237492	110
11	50	10000	Motor	120,217961	120,237492	110
12	50	20000	Motor	120,222844	120,217961	110

Table 14 : raw data for Medium wave band

N° Essai	Duty ratio (%)	Frequency(Hz)	Resistive load(ohms)	Common mode EMI Peak Value (dBuV)	Differential mode EMI Peak Value (dBuV)	MW band EMI Peak Limit (dBuV)
1	30	10000	200	117,67115	117,666267	86
2	30	10000	600	117,67115	117,676033	86
3	30	20000	200	117,666267	117,685798	86
4	30	20000	600	117,680916	117,651619	86
5	50	10000	200	117,676033	117,661384	86
6	50	10000	600	117,67115	117,651619	86
7	50	20000	200	117,666267	117,685798	86
8	50	20000	600	117,685798	117,67115	86
9	30	10000	Motor	117,646736	117,651619	86
10	30	20000	Motor	117,661384	117,656501	86
11	50	10000	Motor	117,661384	117,656501	86
12	50	20000	Motor	117,646736	117,622322	86

Table 15 : raw data for short wave band

N° Essai	Duty ratio (%)	Frequency(Hz)	Resistive load(ohms)	Common mode EMI Peak Value (dBuV)	Differential mode EMI Peak Value (dBuV)	SW band EMI Peak Limit (dBuV)
1	30	10000	200	64,93199	66,79606	77
2	30	10000	600	66,70445	65,53746	77
3	30	20000	200	65,02964	63,41343	77
4	30	20000	600	67,54313	67,02067	77
5	50	10000	200	64,8234	67,66148	77
6	50	10000	600	63,41832	62,51011	77
7	50	20000	200	63,37925	68,00211	77
8	50	20000	600	64,13981	59,55113	77
9	30	10000	Motor	64,39372	64,257	77
10	30	20000	Motor	62,1525	60,64976	77
11	50	10000	Motor	66,43473	60,69743	77
12	50	20000	Motor	64,37046	67,80192	77

Table 16 : raw data for frequency modulation band

N° Essai	Duty ratio (%)	Frequency(Hz)	Resistive load(ohms)	Common mode EMI Peak Value (dBuV)	Differential mode EMI Peak Value (dBuV)	FM band EMI Peak Limit (dBuV)
1	30	10000	200	69,54299	68,34999	62
2	30	10000	600	70,04456	68,70799	62
3	30	20000	200	70,17585	68,31552	62
4	30	20000	600	69,41112	68,57459	62
5	50	10000	200	68,75114	70,21004	62
6	50	10000	600	69,08875	68,5315	62
7	50	20000	200	69,43284	69,12199	62
8	50	20000	600	69,10894	70,27579	62
9	30	10000	Motor	69,21576	69,61856	62
10	30	20000	Motor	68,84775	69,3889	62
11	50	10000	Motor	69,23111	70,74901	62
12	50	20000	Motor	68,94862	69,67323	62

Table 17: raw data for TV band 1

N° Essai	Duty ratio (%)	Frequency(Hz)	Resistive load(ohms)	Common mode EMI Peak Value (dBuV)	Differential mode EMI Peak Value (dBuV)	TV BAND 1 EMI Peak Limit (dBuV)
1	30	10000	200	69,54299	69,08196	58
2	30	10000	600	70,04456	69,35389	58
3	30	20000	200	70,64627	69,09213	58
4	30	20000	600	69,4117	69,35525	58
5	50	10000	200	69,17659	70,21004	58
6	50	10000	600	70,54499	70,90195	58
7	50	20000	200	70,38733	68,78179	58
8	50	20000	600	69,30042	69,72353	58
9	30	10000	Motor	69,21576	69,61856	58
10	30	20000	Motor	70,09066	71,0697	58
11	50	10000	Motor	70,52876	69,4491	58
12	50	20000	Motor	70,61145	69,67323	58

Table 18 : raw data for citizen's band

N° Essai	Duty ratio (%)	Frequency(Hz)	Resistive load(ohms)	Common mode EMI Peak Value (dBuV)	Differential mode EMI Peak Value (dBuV)	CB Band EMI Peak Limit (dBuV)
1	30	10000	200	66,8016	69,6347	68
2	30	10000	600	67,21283	67,04339	68
3	30	20000	200	67,38309	68,39872	68
4	30	20000	600	67,49242	67,38436	68
5	50	10000	200	67,39964	68,06117	68
6	50	10000	600	66,83451	66,18617	68
7	50	20000	200	67,91805	67,70492	68
8	50	20000	600	66,30887	67,4786	68
9	30	10000	Motor	68,42694	65,65882	68
10	30	20000	Motor	68,79295	66,80902	68
11	50	10000	Motor	66,73919	68,77298	68
12	50	20000	Motor	66,46024	67,46248	68

Table 19 : raw data for very high frequency band 1

N° Essai	Duty ratio (%)	Frequency(Hz)	Resistive load(ohms)	Common mode EMI Peak Value (dBuV)	Differential mode EMI Peak Value (dBuV)	VHF 1 band EMI Peak Limit (dBuV)
1	30	10000	200	68,87671	69,76076	68
2	30	10000	600	79,12992	69,71158	68
3	30	20000	200	70,64627	68,33435	68
4	30	20000	600	69,4117	68,53672	68
5	50	10000	200	69,27629	69,20705	68
6	50	10000	600	70,54499	70,00663	68
7	50	20000	200	70,3873	68,40266	68
8	50	20000	600	69,30042	68,35033	68
9	30	10000	Motor	69,01909	69,21748	68
10	30	20000	Motor	67,87936	69,23722	68
11	50	10000	Motor	70,52876	68,86498	68
12	50	20000	Motor	70,61145	68,5261	68

Table 20 : raw data for very high frequency band 2

N° Essai	Duty ratio (%)	Frequency(Hz)	Resistive load(ohms)	Common mode EMI Peak Value (dBuV)	Differential mode EMI Peak Value (dBuV)	VHF 2 band EMI Peak Limit (dBuV)
1	30	10000	200	69,54299	68,87627	62
2	30	10000	600	70,04456	69,30262	62
3	30	20000	200	70,17585	69,09213	62
4	30	20000	600	69,06865	69,1826	62
5	50	10000	200	69,17659	70,21004	62
6	50	10000	600	69,42029	70,90195	62
7	50	20000	200	69,01943	68,78179	62
8	50	20000	600	69,20296	69,72353	62
9	30	10000	Motor	69,21576	69,61856	62
10	30	20000	Motor	70,09066	71,0697	62
11	50	10000	Motor	69,2596	69,4491	62
12	50	20000	Motor	68,89495	69,68294	62

The graphs showing EMI emissions for each test condition are displayed below:

4.5.2 Common mode

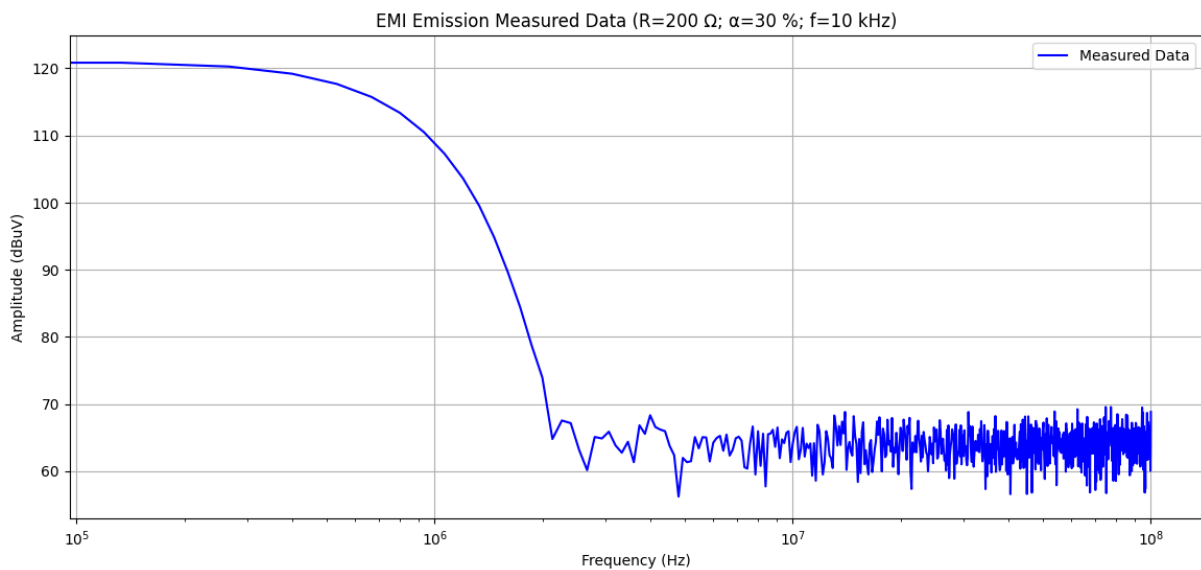


Figure 66: EMI Emission Measured Data (R= 200 ohms; α= 30 %; f= 10 KHz

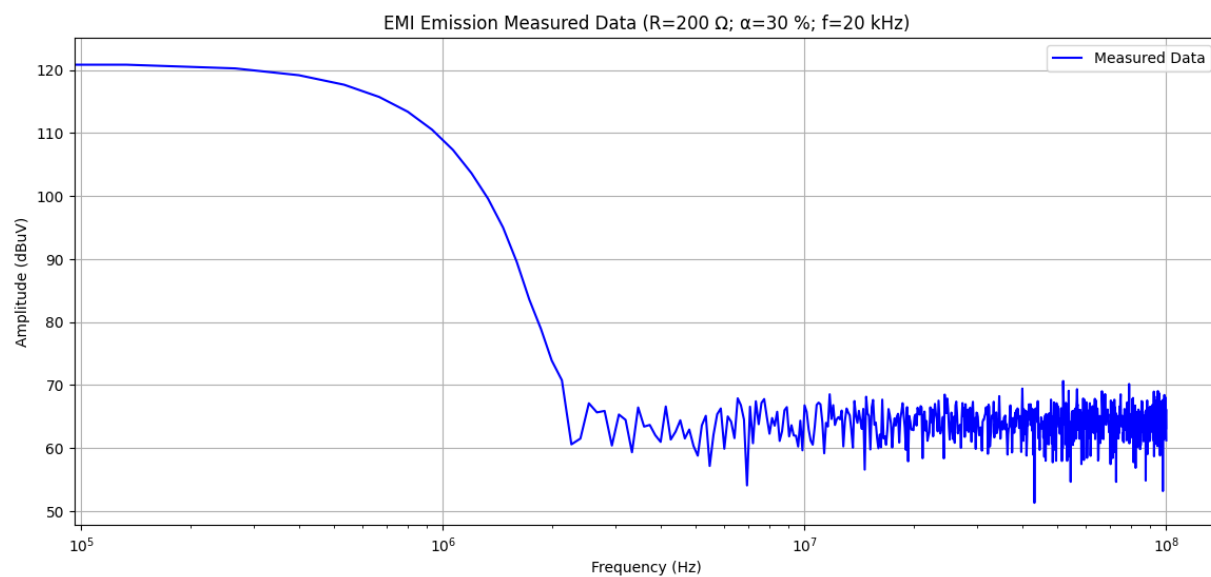


Figure 67: EMI Emission Measured Data ($R= 200\text{ ohms}$; $\alpha= 30\%$; $f= 20\text{ KHz}$)

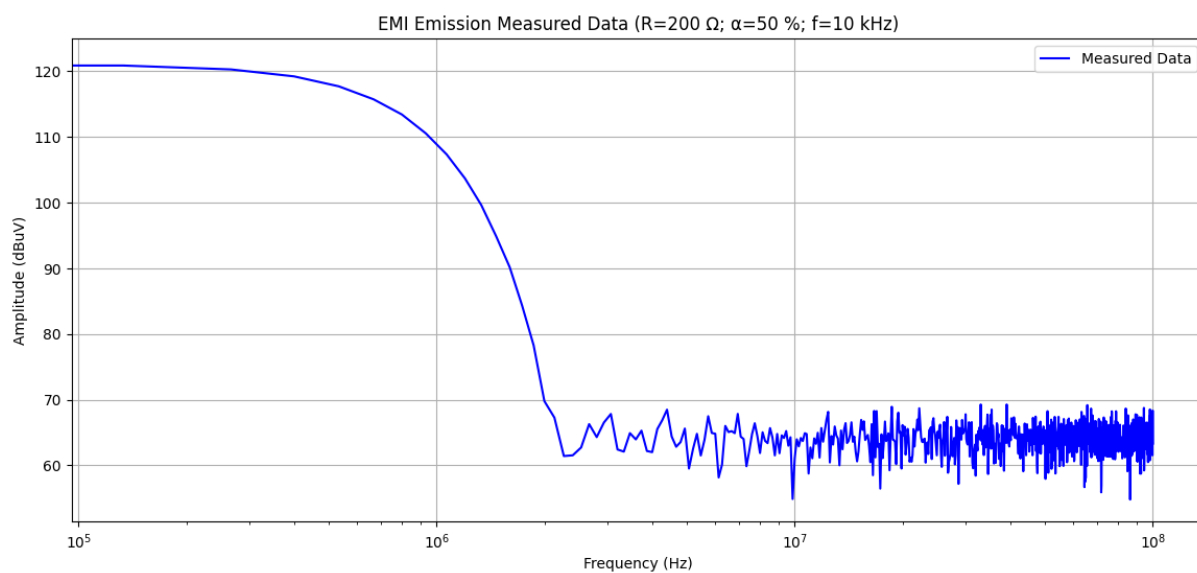


Figure 68: EMI Emission Measured Data ($R= 200\text{ ohms}$; $\alpha= 50\%$; $f= 10\text{ KHz}$)

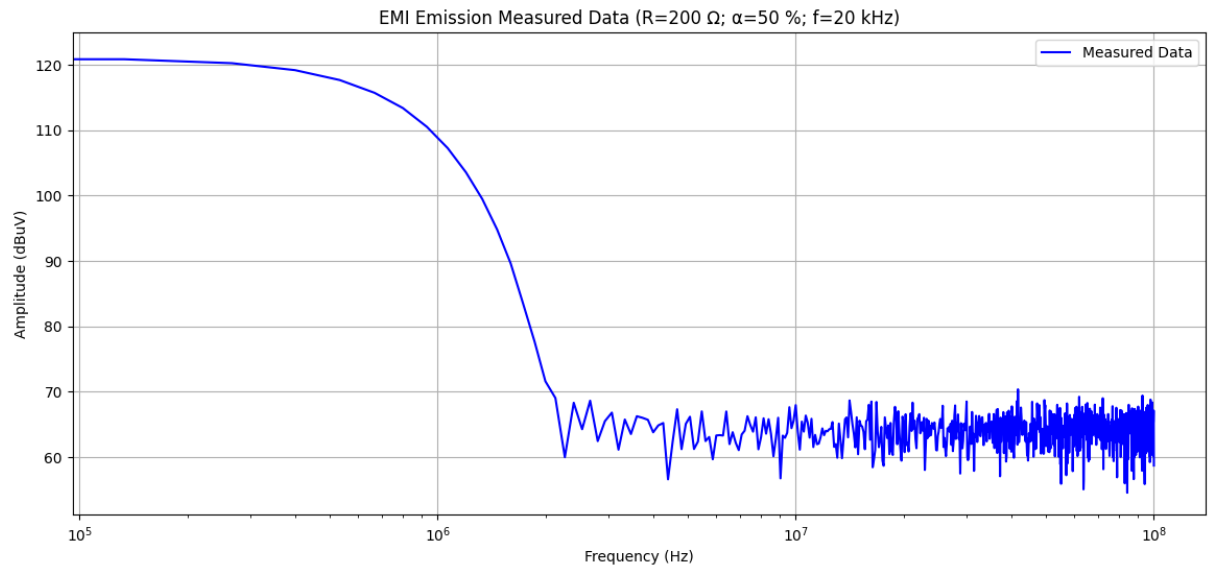


Figure 70: EMI Emission Measured Data ($R= 600\text{ ohms}$; $\alpha= 30\%$; $f= 10\text{ KHz}$)

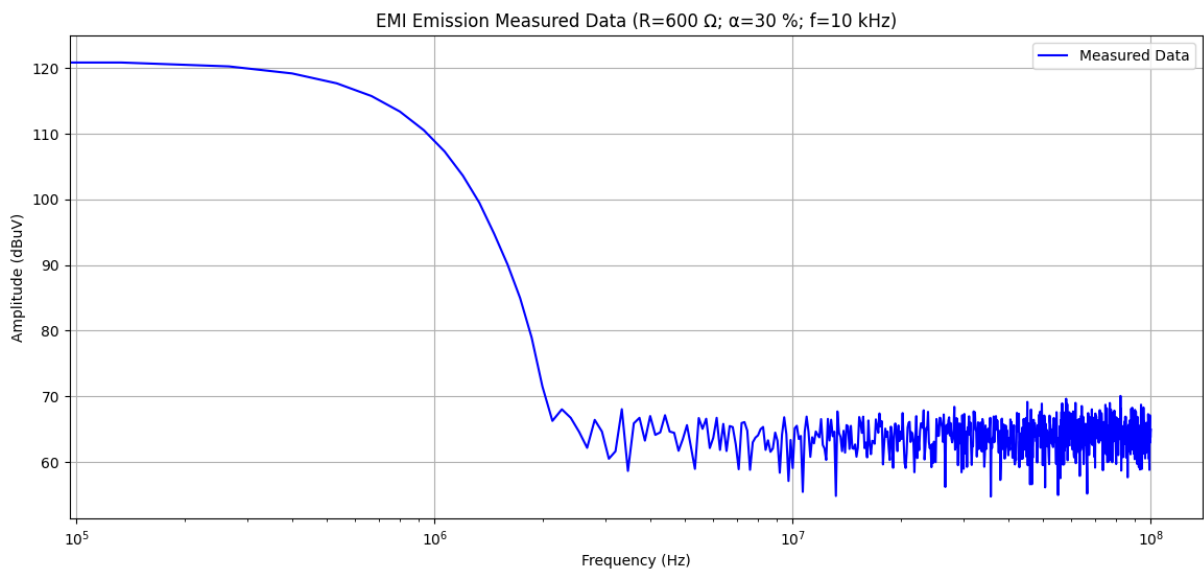


Figure 69 : EMI Emission Measured Data ($R= 200\text{ ohms}$; $\alpha= 50\%$; $f= 20\text{ KHz}$)

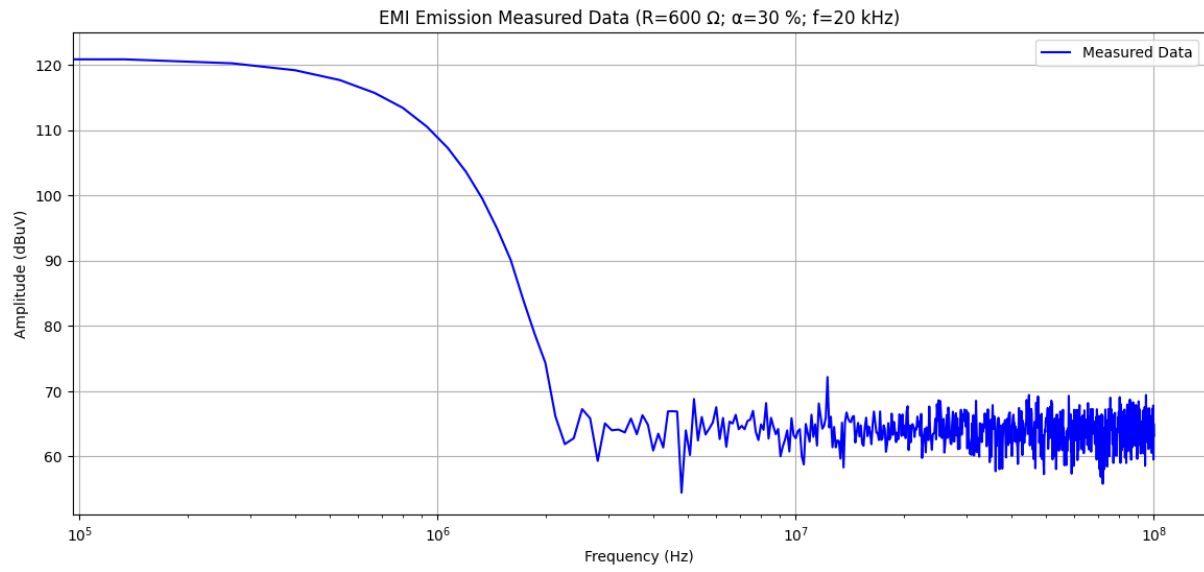


Figure 71: EMI Emission Measured Data ($R= 600\text{ ohms}$; $\alpha= 30\%$; $f= 20\text{ KHz}$)

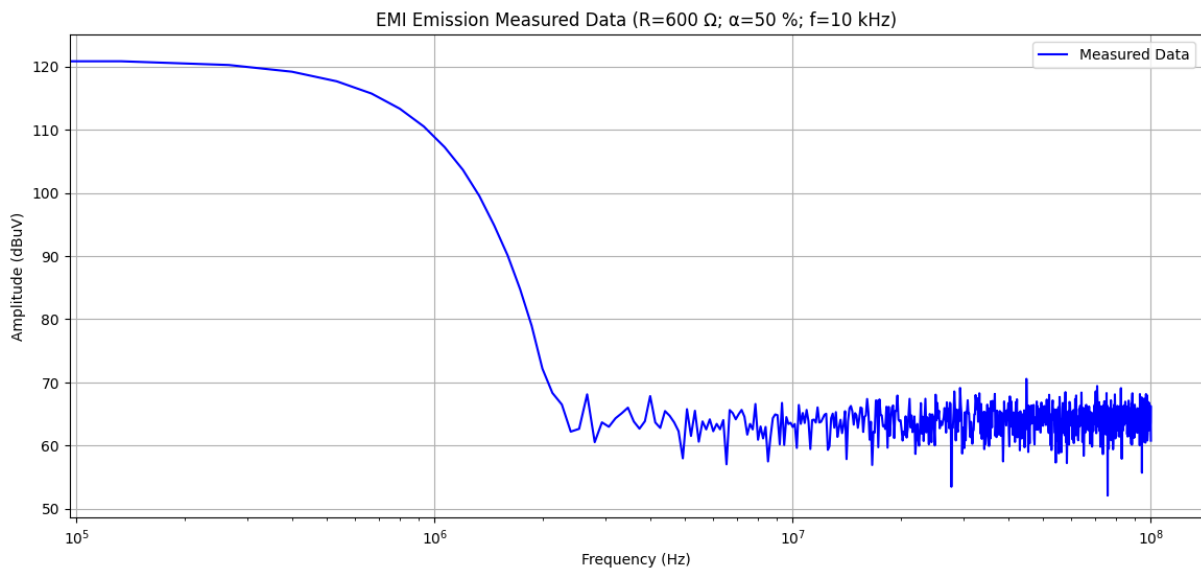


Figure 72: EMI Emission Measured Data ($R= 600\text{ ohms}$; $\alpha= 50\%$; $f= 10\text{ KHz}$)

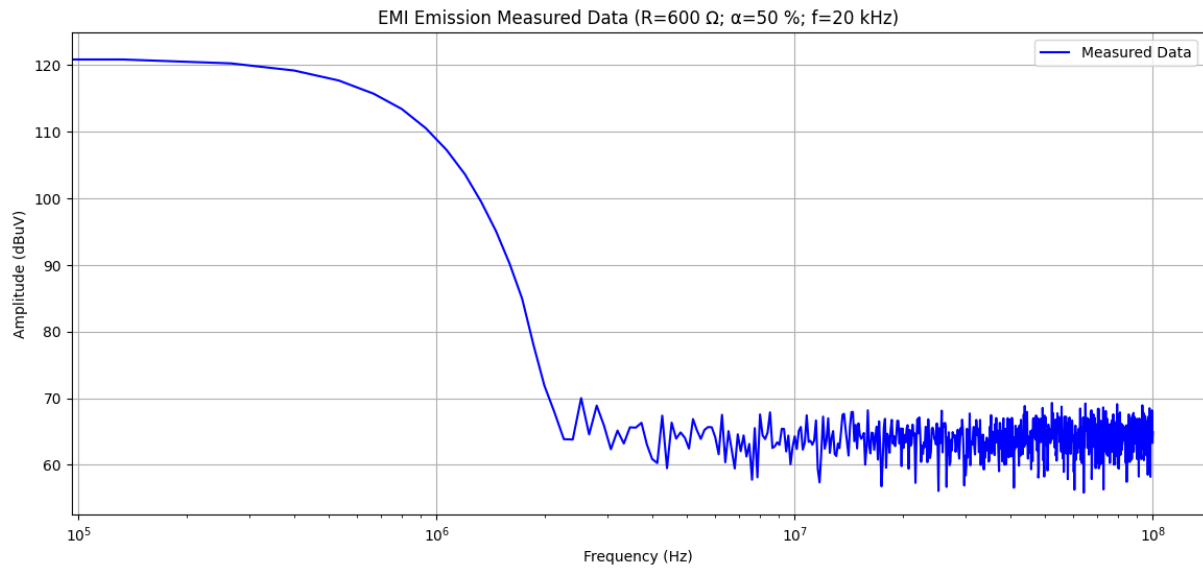


Figure 73: EMI Emission Measured Data ($R= 600\text{ ohms}$; $\alpha= 50\%$; $f= 20\text{ KHz}$)

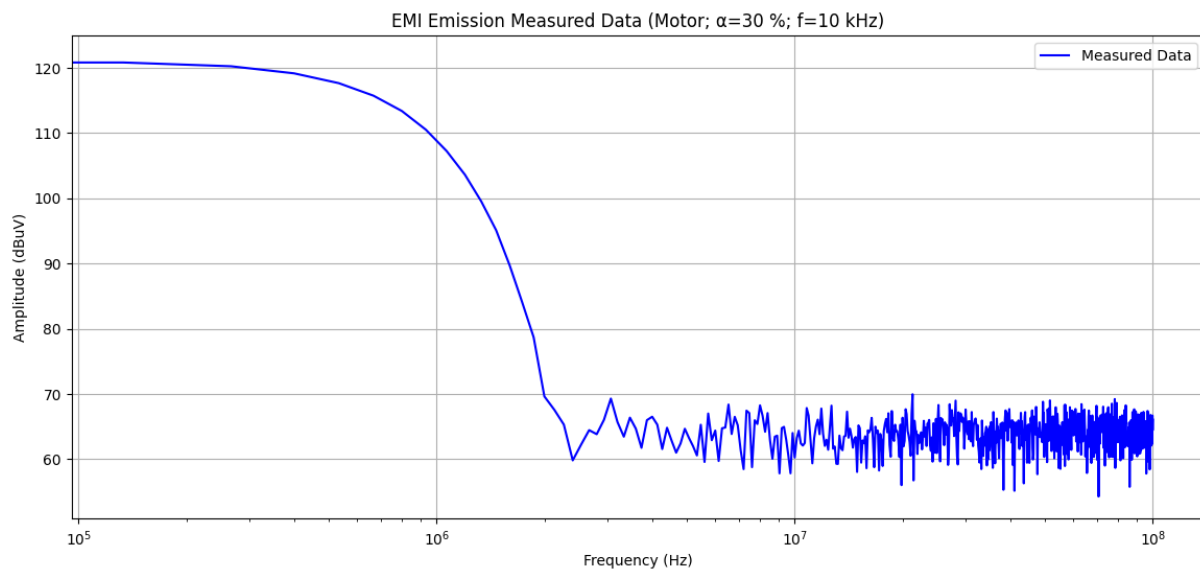


Figure 74: EMI Emission Measured Data (Motor; $\alpha= 30\%$; $f= 10\text{ KHz}$)

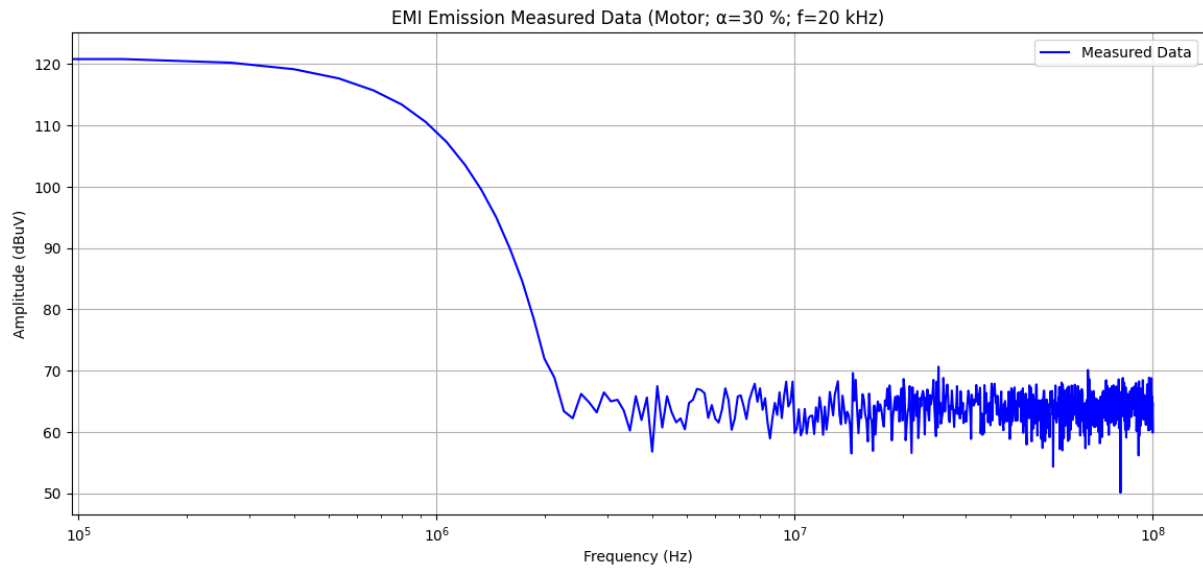


Figure 75: EMI Emission Measured Data (R=Motor; $\alpha= 30\%$; $f= 10\text{ KHz}$)

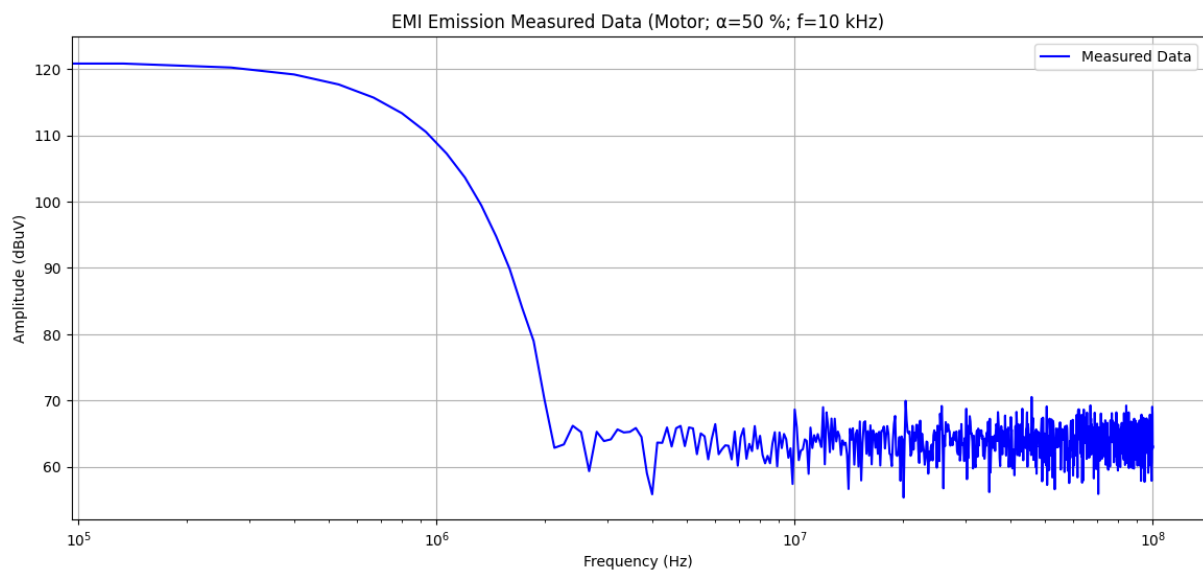


Figure 76: EMI Emission Measured Data (Motor ; $\alpha= 50\%$; $f= 10\text{ KHz}$)

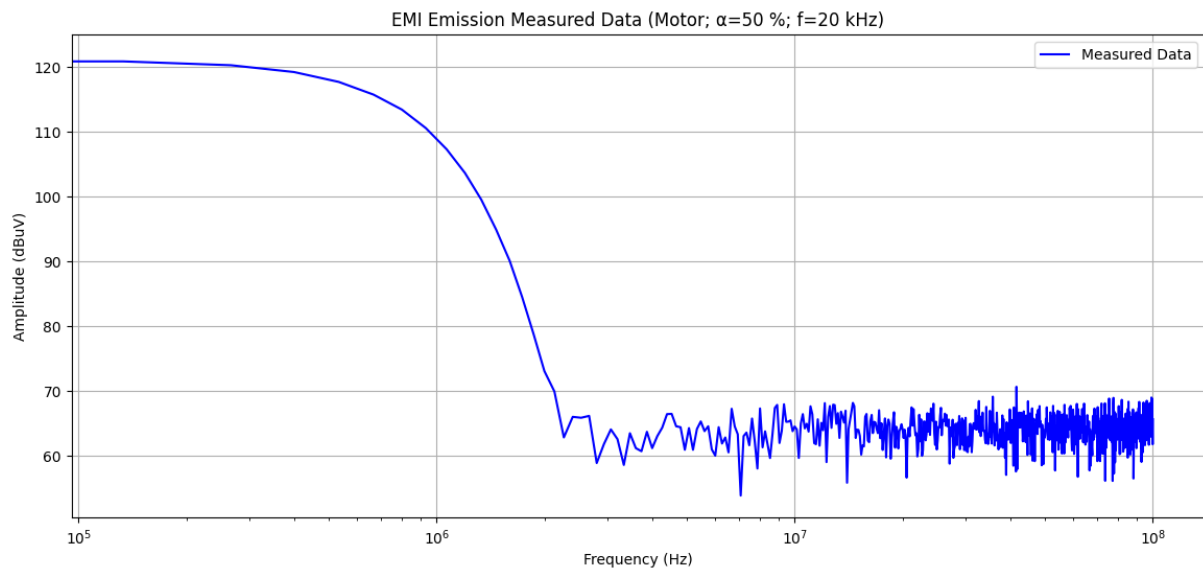


Figure 77: EMI Emission Measured Data (Motor ; $\alpha=50\%$; $f=20$ KHz)

4.5.3 Differential mode

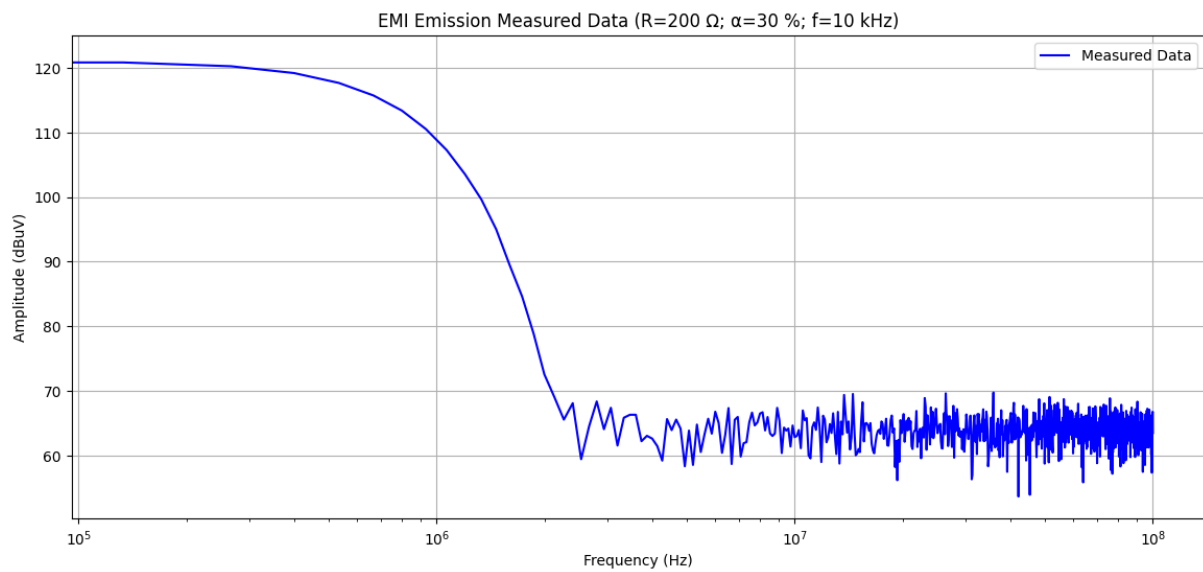


Figure 78: EMI Emission Measured Data (R= 200 ohms; $\alpha=30\%$; $f=10$ KHz)

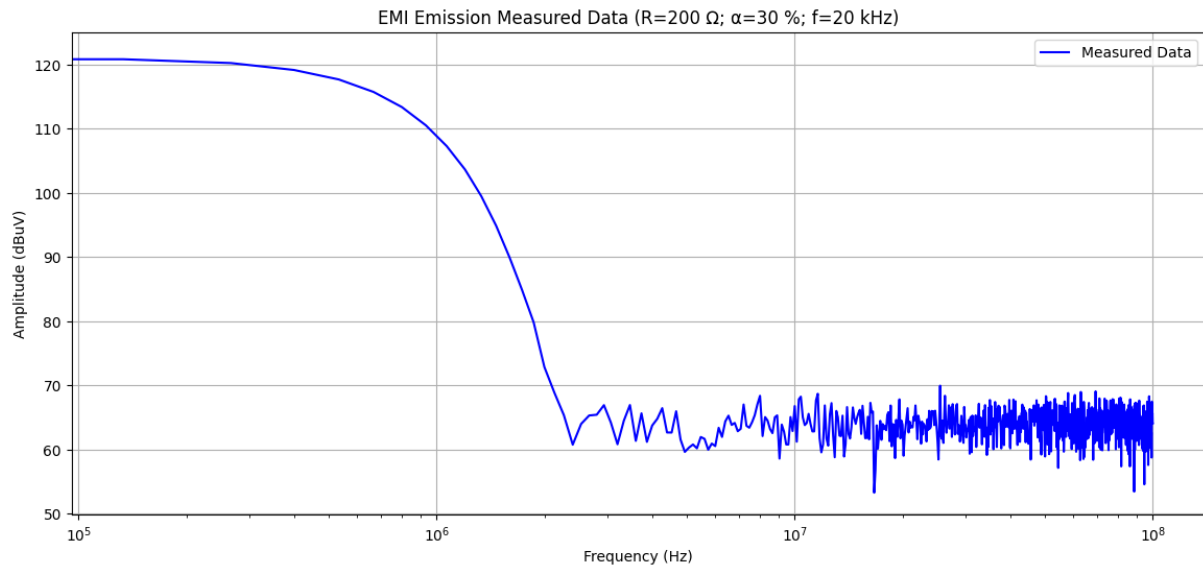


Figure 79: EMI Emission Measured Data ($R= 200$ ohms; $\alpha= 30\%$; $f= 20$ KHz)

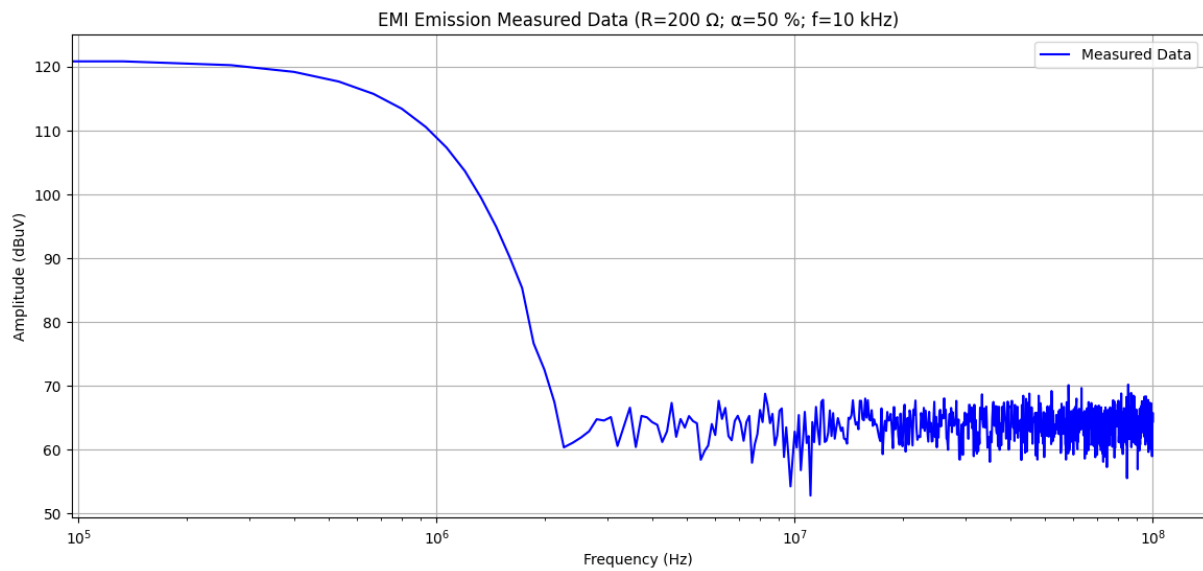


Figure 80: EMI Emission Measured Data ($R= 200$ ohms; $\alpha= 50\%$; $f= 10$ KHz)

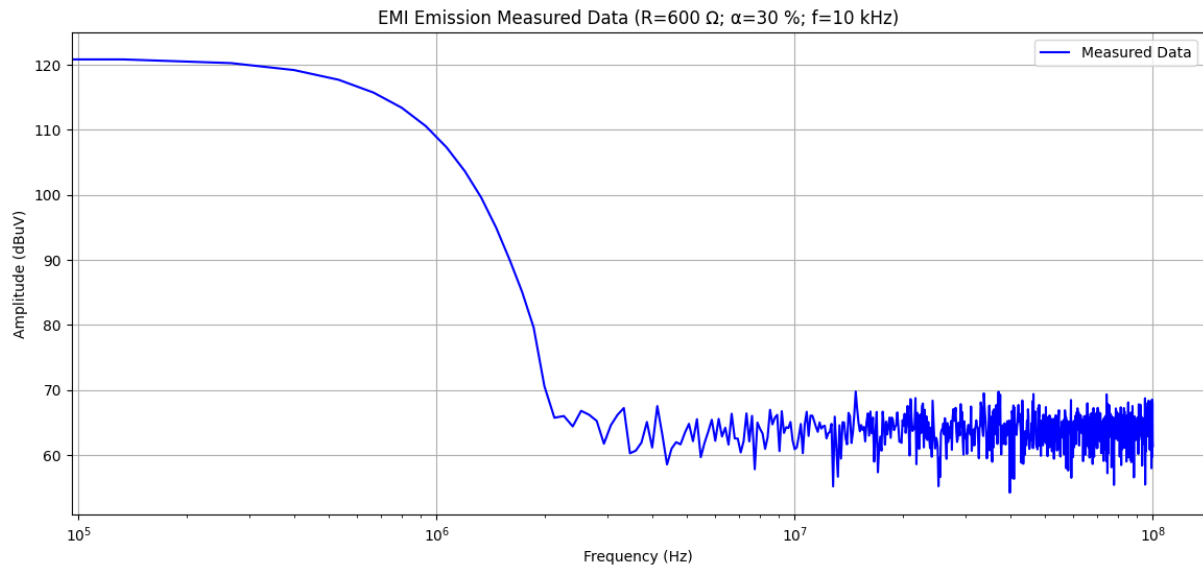


Figure 81: EMI Emission Measured Data ($R= 600\text{ ohms}$; $\alpha= 30\%$; $f= 10\text{ KHz}$)

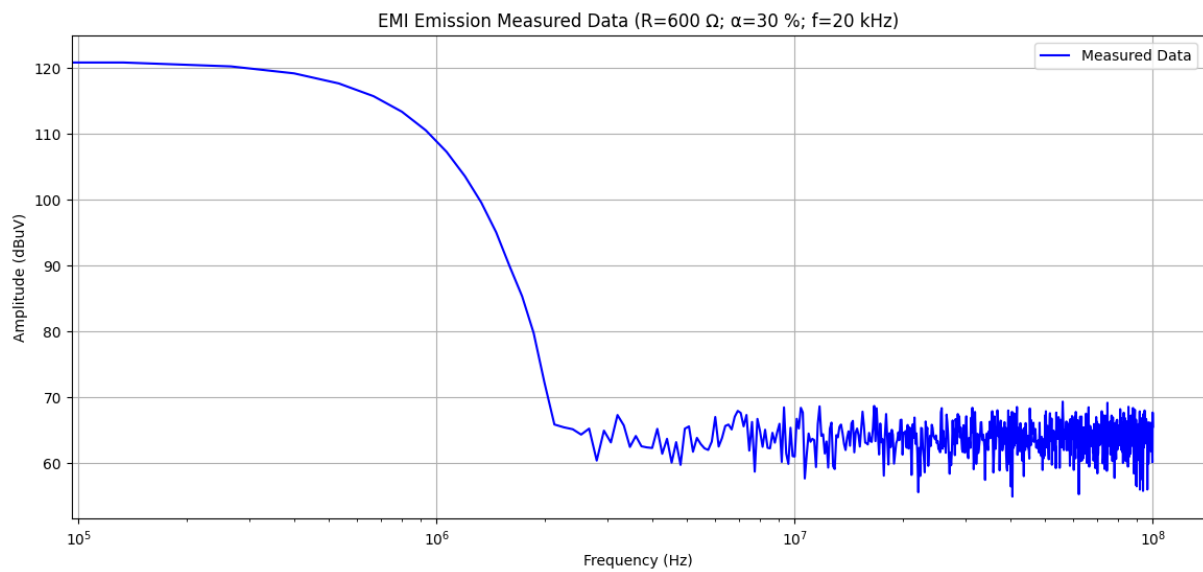


Figure 82: EMI Emission Measured Data ($R= 600\text{ ohms}$; $\alpha= 30\%$; $f= 20\text{ KHz}$)

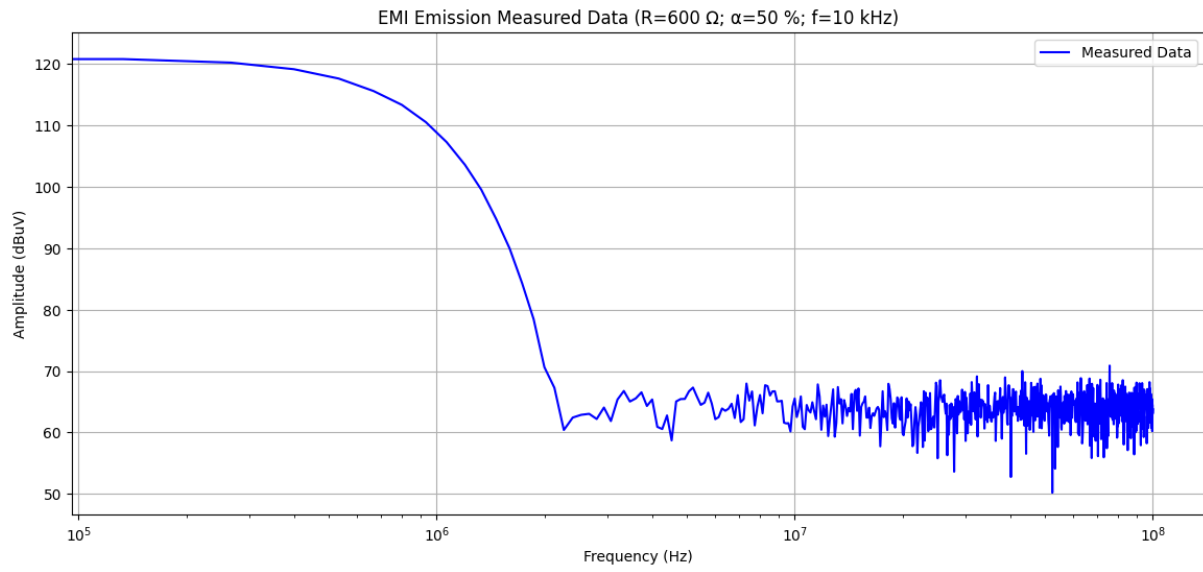


Figure 83: EMI Emission Measured Data (R= 600 ohms; α = 50 %; f= 10 KHz)

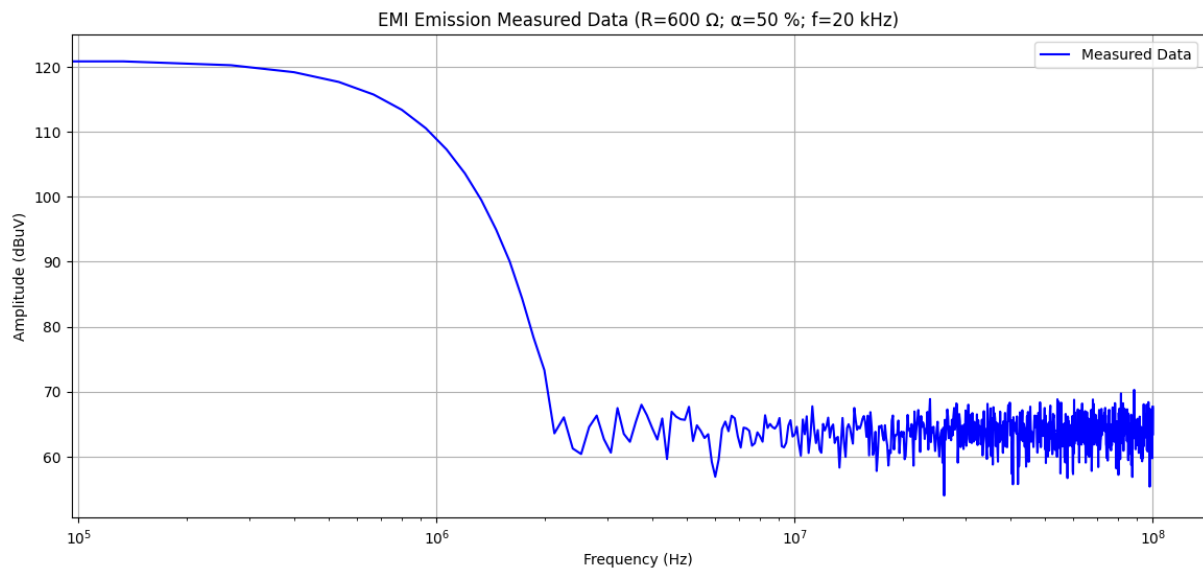


Figure 84: EMI Emission Measured Data (Motor; α = 50 %; f= 20 KHz)

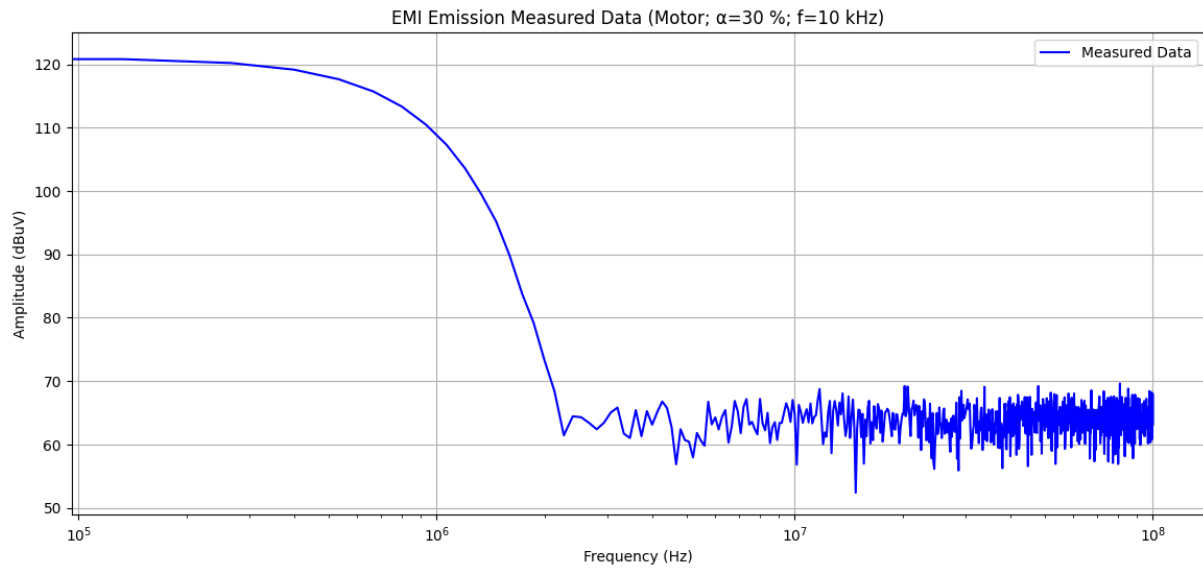


Figure 85: EMI Emission Measured Data (Motor; $\alpha= 30\%$; $f= 10\text{ KHz}$)

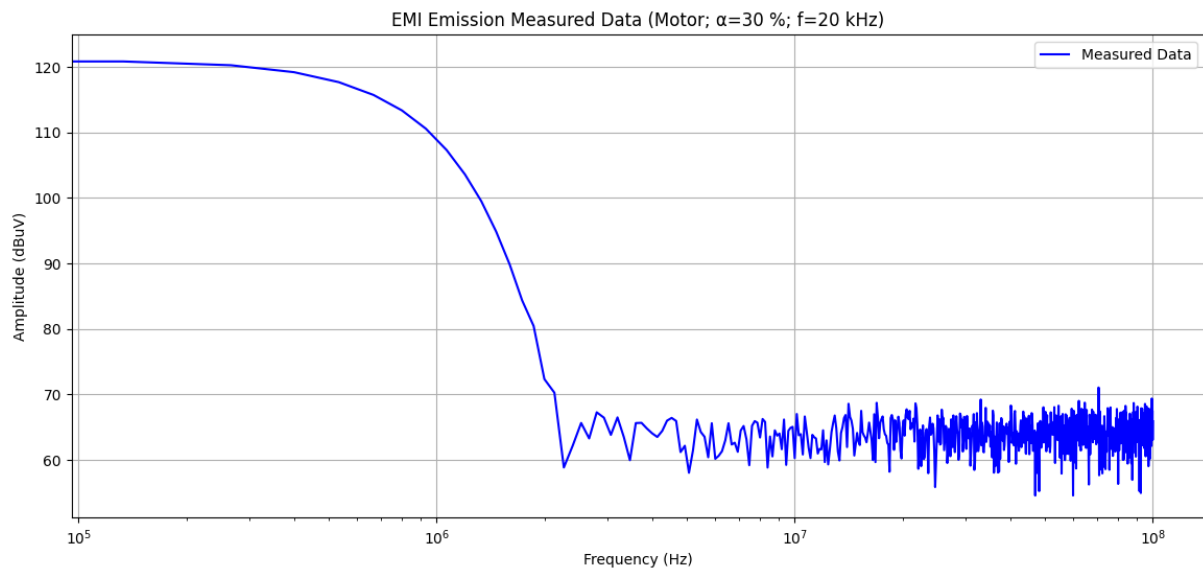


Figure 86: EMI Emission Measured Data (Motor ; $\alpha= 30\%$; $f= 20\text{ KHz}$)

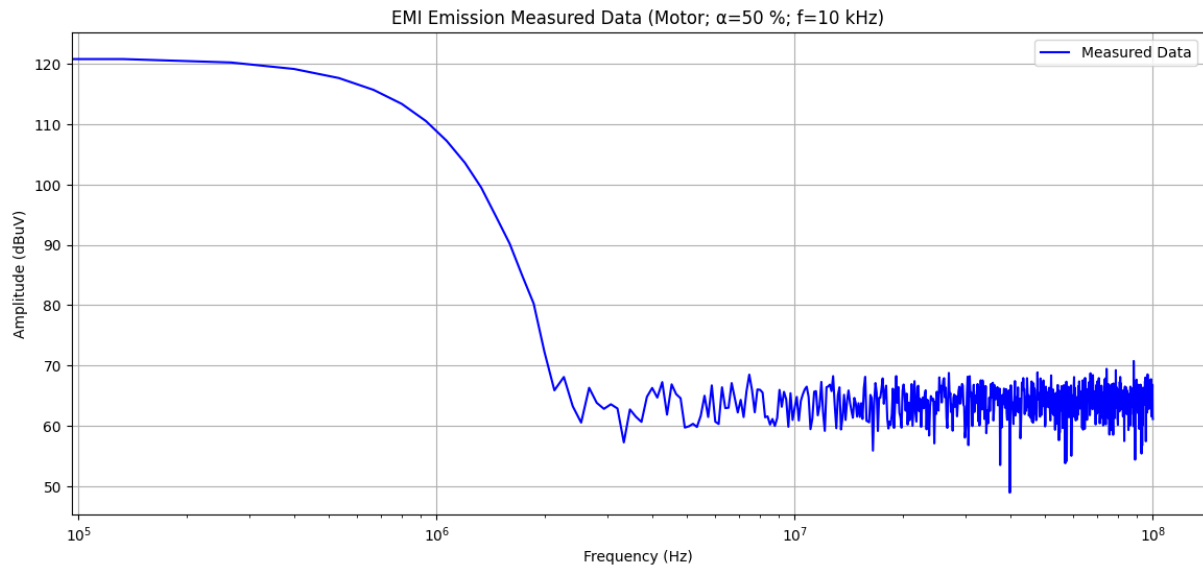


Figure 87: EMI Emission Measured Data (Motor ; $\alpha=50\%$; $f=10\text{ KHz}$)

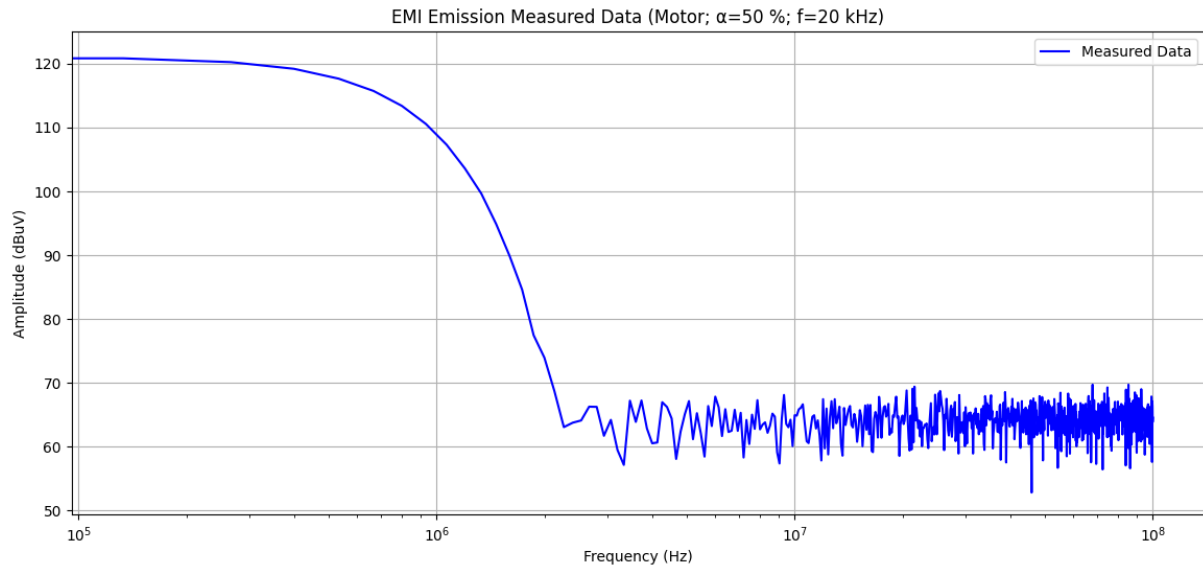


Figure 88: EMI Emission Measured Data (Motor ; $\alpha=50\%$; $f=20\text{ KHz}$)

4.5.4 Analysis of Resistive Load

The graphs of peak Common Mode EMI values illustrate that the 600 Ohms load occasionally displays slightly higher peaks than the 200 Ohms load, Meanwhile, the graphs of peak Differential Mode EMI values generally show comparable levels between the two loads, although some variations may occur under specific test conditions.

The duty cycle has a significant impact on EMI emissions in both common mode and differential mode configurations. At a 30% duty cycle, peak common mode EMI levels are slightly lower, for both 200 ohms and 600 ohms resistive loads. At 50% duty cycle, although

common mode EMI peaks may show slight increases at specific frequencies, the peak levels generally remain comparable between the loads. In differential mode, EMI peaks stay stable at 30% duty cycle, with slightly more noticeable fluctuations observed at 50%. These findings underscore the critical role of duty cycle management in mitigating EMI.

Frequency also plays a crucial role in shaping EMI emissions whether in common mode or differential mode configurations. At a frequency of 10kHz, common mode EMI peaks often reach high levels. Increasing the frequency to 20kHz generally results in a slight decrease in common mode EMI peak levels. In differential mode, although the impact of frequency is less pronounced, it can still influence EMI levels.

4.5.5 Analysis of Motor Load

The graphs of common mode EMI peaks demonstrate a significant decrease as frequency increases, whether for 30% or 50% duty cycles. This reduction is particularly noticeable for lower common mode EMI values. Regarding differential mode, frequency also plays a crucial role, with higher frequencies generally associated with lower EMI peaks.

The duty cycle and frequency significantly impact EMI emissions in motor systems. Higher duty cycles generally lead to slightly higher EMI emissions, particularly at lower frequencies, whereas higher frequencies typically result in lower EMI peaks.

4.6 Discussion

4.6.1 Interpretation of Results

The analysis of EMI emissions data reveals key insights into the influence of duty ratio, frequency, and resistive load on system performance. Increasing the duty ratio significantly improves efficiency by maintaining a longer active state, with minimal impact on EMI emissions. This makes the duty ratio the most influential factor for enhancing efficiency. In contrast, increasing the frequency tends to raise EMI emissions due to more frequent switching events, although this effect is less pronounced than the impact of the duty ratio. Therefore, finding a balance in frequency settings is crucial to avoid excessive EMI while achieving acceptable efficiency. The resistive load has the smallest effect on both EMI emissions and efficiency. While increasing the resistive load slightly improves efficiency, its impact on EMI is negligible compared to the other parameters. Overall, optimizing the duty ratio provides the most significant efficiency gains with minimal EMI concerns, while frequency adjustments

require careful consideration to balance EMI and efficiency, and resistive load adjustments offer minor benefits.

4.6.2 Comparison with EMI Standards

In the summary of measurements across different frequency bands and conditions, it is consistently observed that peak values exceed their respective peak limits in common mode, differential mode, or both modes across all bands. Specifically, for the CB band, peak values exceed the limit only in common mode and not in differential mode. This suggests a general trend of peak values exceeding expected thresholds, indicating potential deviations from load, duty ratio, and frequency parameters in various operational scenarios.

Similarly, average values across all frequency bands consistently exceed their respective average limits in common mode, differential mode, or both modes. This consistency suggests that average measurements frequently fall outside acceptable ranges in terms of load, duty ratio, and frequency across different operational conditions and frequency bands.

We conclude that the both peak and average measurements consistently exceed their specified limits across all examined frequency bands and operational conditions. This underscores the critical importance of monitoring and potentially adjusting load, duty ratio, and frequency parameters to ensure compliance with required performance standards.

4.6.3 PCB Implementation

Once the circuit construction on the breadboard is successfully completed, we proceed to the development of a printed circuit board.

We utilized TCI software to ensure precise arrangement and optimization of circuit components.

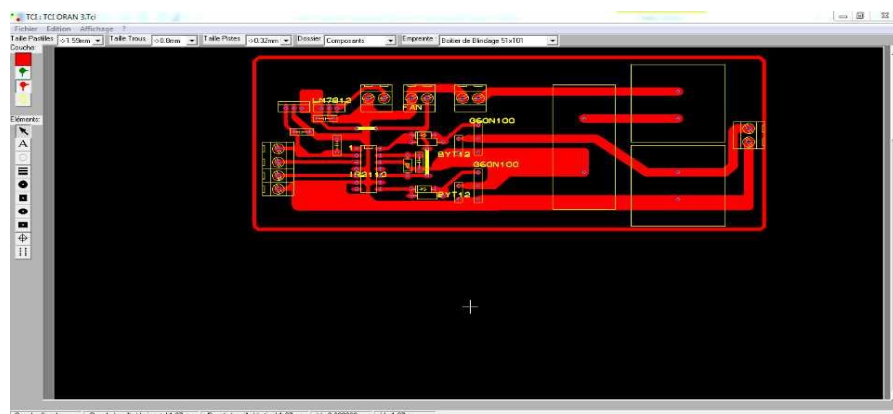


Figure 89: PCB Design Utilizing TCI Software

After this design stage, we used acetate sheets to transfer and visualize the circuit design

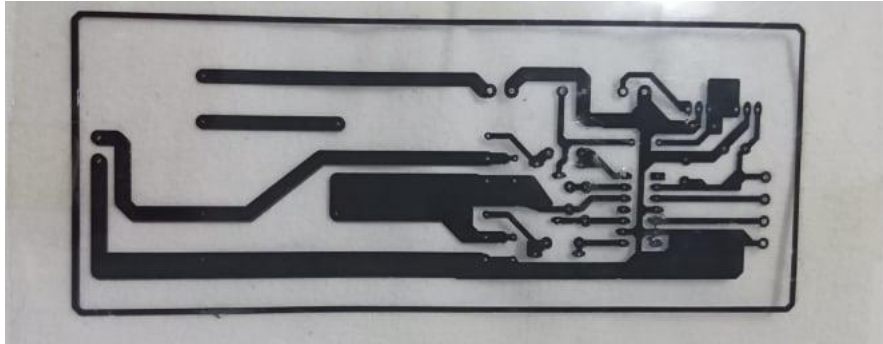


Figure 90: PCB Layout Visualization Using Acetate Sheets

The next step involved measuring these acetate sheets to accurately cut the copper plates for PCB to the same dimensions using the machine shown in the figure 91.



Figure 92: Copper plates for PCB



Figure 91: Plate Cutting Machine

After that, we print the circuit onto the copper board using a printer, which takes approximately two minutes.



Figure 93: Circuit Printer on Copper Plate

Afterward, the plate is washed with a specialized developer acid, Developer N11, to reveal the circuit on the plate.



Figure 94: Washing the Plate to Reveal the Circuit

Next, the copper plate is immersed in a device filled with a specialized solution that removes the copper from the plate in just 10 minutes.



Figure 95: Machine for Copper Removal from the Plate

Finally, we identify the component hole locations on the PCB with exactitude and methodical accuracy.



Figure 96: Component Hole Location Identification on PCB

After soldering the components onto the PCB, the circuit is ready for inspection and testi



Figure 97: final prototype

4.7 Conclusion

In conclusion, this chapter thoroughly investigated the electromagnetic compatibility (EMC) emissions of a bidirectional DC-DC converter for electric vehicles, ensuring compliance with CISPR 25 standards. Test conditions were tailored to optimize the converter's parameters for a comprehensive performance evaluation. Measurements indicated that peak and average values consistently exceeded the limits specified in CISPR 25. However, additional adjustments to operational parameters are required to achieve full compliance with CISPR 25 requirements.

Additionally, the implementation of PCB design steps was carried out to further enhance the converter's performance and compliance.

General conclusion

In this thesis, we explored the multi-objective optimization of DC-DC converters with a focus on electromagnetic compatibility (EMC). We began by examining the essential topologies of DC-DC converters, analyzing their characteristic equations, regulation modes, and switch control techniques, highlighting their crucial importance across various application domains.

Next, we emphasized the critical significance of Electromagnetic Compatibility (EMC) in power electronics. This included studying international standards, identifying sources of electromagnetic interference, and discussing interference reduction techniques to enhance the reliability and efficiency of technological systems. Optimizing bidirectional DC-DC converters for electric vehicles presented significant challenges.

Through a systematic approach to experimental design, we quantified the effects of key parameters and their complex interactions, enabling precise modeling of the converter's performance variations.

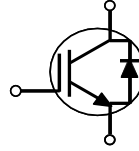
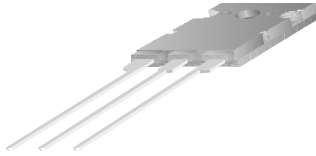
Finally, we underscored the crucial importance of reducing electromagnetic interference (EMI) emissions in bidirectional DC-DC converters, particularly for electric vehicles. Future research in these areas will be essential for improving converter reliability and optimizing the operational efficiency of electric vehicles and their associated systems.

Perspective

In the future, we aim to optimize the sizing of filters for our DC-DC converters to effectively reduce electromagnetic interference. This will be achieved by strategically adjusting their placement along critical transmission lines, based on specific interference frequencies. Additionally, we plan to package our converter in an efficient enclosure to ensure adequate protection and optimal operation.

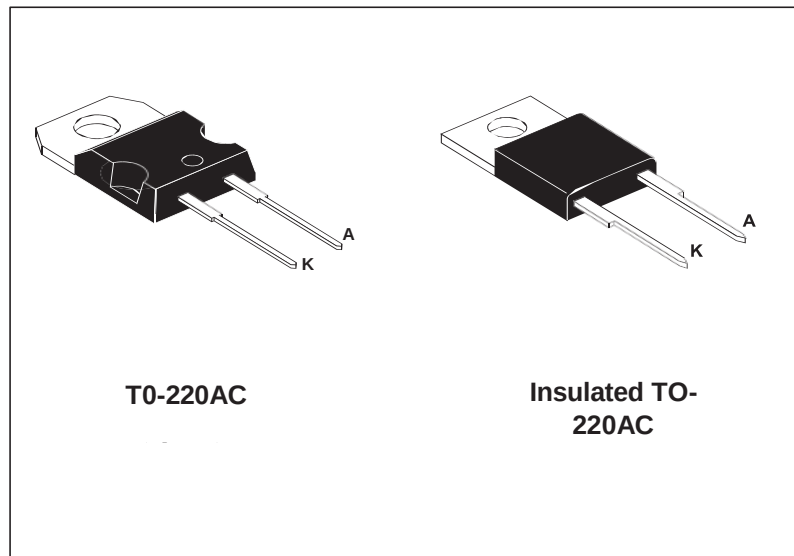
Appendix

Appendix A



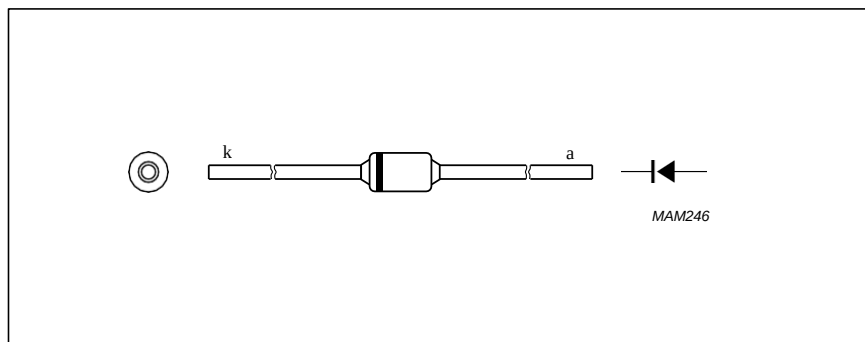
Symbol	Description	FGL60N 100BNT D	Units
V _{CES}	Collector-Emitter Voltage	1000	V
V _{GES}	Gate-Emitter Voltage	± 25	V
I _C	Collector Current @ T _C = 25°C	60	A
	Collector Current @ T _C = 100°C	42	A
I _{CM} (1)	Pulsed Collector Current	120	A
I _F	Diode Continuous Forward Current @ T _C = 100°C	15	A
P _D	Maximum Power Dissipation @ T _C = 25°C	180	W
	Maximum Power Dissipation @ T _C = 100°C	72	W
T _J	Operating Junction Temperature	-55 to +150	°C
T _{stg}	Storage Temperature Range	-55 to +150	°C
T _L	Maximum Lead Temp. for soldering Purposes, 1/8" from case for 5 seconds	300	°C

Appendix B



Symbol	Parameter			Value	Unit
VRRM	Repetitive peak reverse voltage			400	V
IFRM	Repetitive peak forward current	tp=5 μs F=5kHz		200	A
IF(RMS)	RMS forward current			16	A
IF(AV)	Average forward current	TO-220AC	Tc = 120°C δ = 0.5	8	A
		Insulated TO-220AC	Tc = 105°C		
IFSM	Surge non repetitive forward current	tp = 10 ms Sinusoidal		100	A
Tstg	Storage temperature range			- 40 to+ 150	°C
Tj	Maximum operating junction temperature			150	°C

Appendix C



SYMBOL	PARAMETER	CONDITIONS	MIN.	MAX.	UNIT
VRRM	repetitive peak reverse voltage		–	75	V
V_R	continuous reverse voltage		–	75	V
I_F	continuous forward current	See Fig.2; note 1	–	200	mA
IFRM	repetitive peak forward current		–	450	mA
IFSM	non-repetitive peak forward current	square wave; T _j = 25 °C prior to surge; see Fig.4 t = 1 μs t = 1 ms t = 1 s	– – –	4 1 0.5	A
P_{tot}	total power dissipation	T _{amb} = 25 °C; note 1	–	500	mW
T_{stg}	storage temperature		–65	+200	°C
T_j	junction temperature		–	200	°C

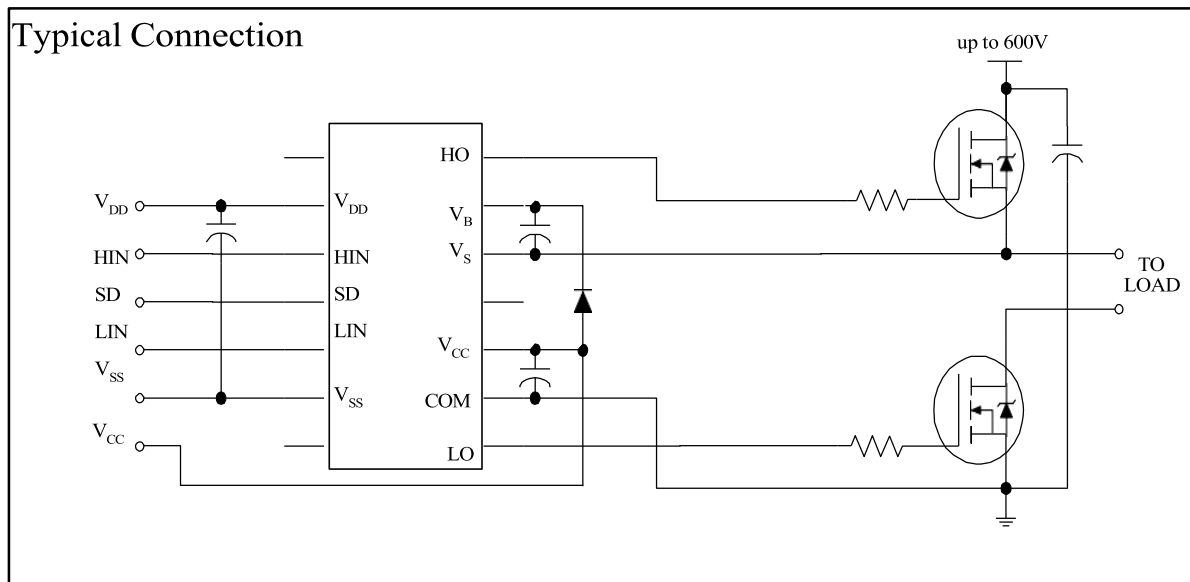
Appendix D

Specifications	
Capacitance:	560 uF
Capacitance Tolerance:	20 %
Voltage DC:	450 VDC, 495 VDC (Surge)
Temperature Range:	-40/+85°C
Rated Temperature:	85°C
Life:	15000 Hrs (Rated Voltage And Ripple Current At 85C), 24000Hrs (Rated Voltage at 85C)
Resistance:	253 mOhms (100Hz 20C), 143.1 mOhms (10kHz 20C)
Ripple Current:	2.799 Amps (100Hz 85C), 6.452 Amps (10kHz 85C)
Leakage Current:	1512 uA (5min 20°C)

Appendix E

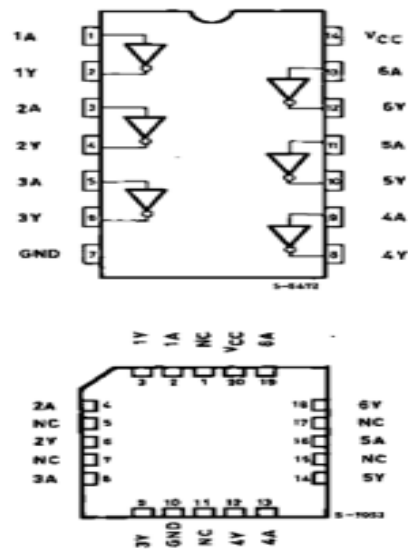
Specifications	
Voltage AC:	1000 VAC/VDC
Voltage DC:	1000 VDC
Inductance:	1.6 mH
Current:	19 A
Temperature Range:	-40/+150°C
DC Resistance:	3.07 mOhms

Appendix F



Symbol	Definition		Min.	Max.	Units
VB	High Side Floating Supply Voltage		-0.3	625	V
VS	High Side Floating Supply Offset Voltage		VB – 25	VB + 0.3	
VHO	High Side Floating Output Voltage		VS - 0.3	VB + 0.3	
VCC	Low Side Fixed Supply Voltage		-0.3	25	
VLO	Low Side Output Voltage		-0.3	VCC + 0.3	
VDD	Logic Supply Voltage		-0.3	VSS + 25	
VSS	Logic Supply Offset Voltage		VCC – 25	VCC + 0.3	
VIN	Logic Input Voltage (HIN, LIN & SD)		VSS - 0.3	VDD + 0.3	
dVs/dt	Allowable Offset Supply Voltage Transient (Figure 2)		—	50	V/ns
PD	Package Power Dissipation @ TA □ +25°C	(14 Lead DIP)	—	1.6	W
	(16 Lead SOIC)		—	1.25	
RTHJA	Thermal Resistance, Junction to Ambient	(14 Lead DIP)	—	75	°C/W
	(16 Lead SOIC)		—	100	
TJ	Junction Temperature		—	150	°C
TS	Storage Temperature		-55	150	
TL	Lead Temperature (Soldering, 10 seconds)		—	300	

Appendix G



Symbol	Parameter	Value	Unit
VCC	Supply Voltage	-0.5 to +7	V
V _I	DC Input Voltage	-0.5 to V _{CC} + 0.5	V
V _O	DC Output Voltage	-0.5 to V _{CC} + 0.5	V
I _{IK}	DC Input Diode Current	± 20	mA
I _{OK}	DC Output Diode Current	± 20	mA
I _O	DC Output Source Sink Current Per Output Pin	± 25	mA
I _{CC} or I _{GND}	DC V _{CC} or Ground Current	± 50	mA
P _D	Power Dissipation	500	mW
T _{stg}	Storage Temperature	-65 to +150	°C T _L
T _{stg}	Storage Temperature	-65 to +150	°C T _L

Appendix H



SYMBOL	PARAMETER	RATING	UNIT
Vi	DC input voltage	35	V
Io	Output current	internally limited	
Ptot	Power dissipation	internally limited	
TOP	Operating junction temperature	-40~125	°C
Tstg	Storage temperature	-55~150	°C

Appendix I

Symbol	Parameter	Test conditions	Min.	Typ	Max.	Unit
V_O	Output voltage	$T_J = 25^\circ\text{C}$	14.4	15	15.6	V
V_O	Output voltage	$I_O = 5\text{ mA to }1\text{ A},$ $P_O \leq 15\text{ W}$ $V_I = 18.5$ to 30 V	14.25	15	15.75	V
$\Delta V(1)O$	Line regulation	$V_I = 17.5\text{ to }30\text{ V}, T_J = 25^\circ\text{C}$			150	mV
		$V_I = 20\text{ to }26\text{ V}, T_J = 25^\circ\text{C}$			75	
$\Delta V(1)O$	Load regulation	$I_O = 5\text{ mA to }1.5\text{ A}, T_J = 25^\circ\text{C}$			150	mV
		$I_O = 250\text{ to }750\text{ mA}, T_J = 25^\circ\text{C}$			75	
I_d	Quiescent current	$T_J = 25^\circ\text{C}$			6	mA
ΔI_d	Quiescent current change	$I_O = 5\text{ mA to }1\text{ A}$			0.5	mA
		$V_I = 18.5\text{ to }30\text{ V}$			0.8	
$\Delta V_O/\Delta T$	Output voltage drift	$I_O = 5\text{ mA}$		1.8		mV/ $^\circ\text{C}$
E_n	Output noise voltage	$B = 10\text{ Hz to }100\text{ KHz}, T_J = 25^\circ\text{C}$			40	$\mu\text{V/V}_O$
SVR	Supply voltage rejection	$V_I = 18.5\text{ to }28.5\text{ V}, f = 120\text{ Hz}$	60			dB
V_d	Dropout voltage	$I_O = 1\text{ A}, T_J = 25^\circ\text{C}$		2	2.5	V
R_O	Output resistance	$f = 1\text{ KHz}$		19		m Λ
I_{sc}	Short circuit current	$V_I = 35\text{ V}, T_J = 25^\circ\text{C}$		0.75	1.2	A
I_{scp}	Short circuit peak current	$T_J = 25^\circ\text{C}$	1.3	2.2	3.3	A

Appendix J

```
#include <TimerOne.h>

const int outputPin = 9;           // Pin de sortie PWM
int frequency = 10000;             // Fréquence initiale en Hertz
int dutyCycle = 10;                // Rapport cyclique initial en pourcentage (de 0 à 100)

void setup() {
    pinMode(outputPin, OUTPUT);

    Timer1.initialize(1000000 / frequency);    // Initialise le timer avec une fréquence
    initiale

    Timer1.pwm(outputPin, dutyCycle * 10);      // Initialise le signal PWM avec un rapport
    cyclique initial
}

void loop() {
    // Vous pouvez ajouter ici votre logique pour changer la fréquence et le
    rapport cyclique

    // Par exemple, augmenter la fréquence toutes les 5 secondes :

    Timer1.setPeriod(1000000 / frequency);

    // Ou changer le rapport cyclique toutes les 5
    secondes :

    Timer1.setPwmDuty(outputPin, dutyCycle * 10);
}
```

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Part 02

Startup

Chapitre 5

Startup

4.8 Introduction

In this section, we will focus on the economic aspect of our project by highlighting the Business Plan (BP) and the Business Model Canvas (BMC). This approach will allow us to precisely define the commercial and operational structure of our company, as well as the necessary strategies to achieve our goals.

4.9 First axis: project presentation

4.9.1 Project idea

Eco-Drive revolutionizes the electric vehicle industry by offering an advanced solution for optimizing DC-DC converters using software with integrated Electromagnetic Compatibility (EMC). Our intuitive model enables automotive engineers to design more efficient and environmentally friendly power systems. By maximizing energy efficiency and ensuring compliance with EMC standards, Eco-Drive accelerates the transition to electric mobility.

4.9.2 The suggested values

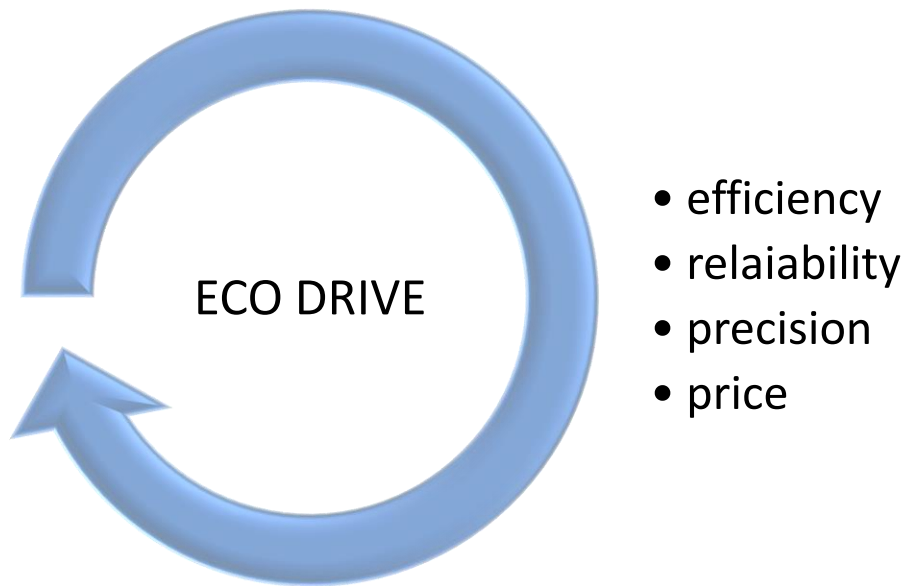


Figure 98: the suggested value

4.9.3 Team members

- **Students**
 - FAR Ouidjdane
 - DJADAOUADJI Imane

Profile: Master Instrumentation and Metrology (IM).

- **Supervisors**
 - GOURBI Abdelkader
 - CHAIB Mohammed

4.9.4 Physical location

- Oran – Algeria.

4.9.5 Project objective

Our objectives are as follows:

- Raise awareness about the importance of electric driving for a more sustainable environment.
- Integrate the latest technological advancements in the field of electric vehicles.

- Facilitate the optimization of DC-DC converters to enhance their efficiency.
- Achieve a substantial market share in the electric vehicle industry.

4.9.6 Project realization plan

4.9.6.1 Project Study (2 months)

- Conducting comprehensive research on optimizing DC-DC converters with integrated electromagnetic compatibility.
- Evaluate competition in the Algerian market and identify key players.
- Searching the best materials and potential suppliers.
- Define our target customer base.
- Gather feedback from potential customers on the project.

4.9.6.2 Launching the Venture (7 months)

- Choosing the ideal business location and necessary equipment.
- Establishing direct contact with suppliers to validate materials and work techniques.
- Installing and maintaining the required equipment.
- **Using simulation software to model the converter's behavior and assess its efficiency and EMI emissions.**

4.9.6.3 Finishing products:

- Finalize product design.
- Conducting tests to verify efficiency, stability, and EMI emissions.
- Participating in events, launching online marketing.

4.10 Second axis: Innovative aspects

4.10.1 The nature of innovations

Despite competition in the market, our solution stands out with its multi-objective approach and integration of electromagnetic compatibility, offering a unique competitive advantage. Quality, reliability, and compliance with EMC standards are key differentiating factors that enhance our market position.

4.10.2 The innovation field

Critical for the automotive industry, providing an advanced technological solution for optimizing DC-DC converters.

4.11 Third axis: Strategic market analysis

4.11.1 The market segment

- **Target customers**

For our project, the main customers are automotive engineers and manufacturers who require advanced software solutions for optimizing DC-DC converters in electric vehicles. Additionally, research institutions and laboratories may also be targeted for collaborative research and development purposes. Furthermore, automotive companies, including those involved in electric vehicle production, as well as companies specializing in power electronics and renewable energy, are key segments within our customer base.

- **Target market**

For our project, the target market initially consists of automotive engineers and manufacturers in the Algerian market, with plans to expand to the international market.

4.11.2 Measuring the intensity of competition

We are the first local producer of bidirectional DC-DC converters with EMC consideration, specifically designed for electric vehicles in Algeria. We offer immediate availability of our products, competitive in price compared to imported models, and respecting EMC standards.

The price of our bidirectional DC-DC converter is reasonable and competitive, approximately 30000,00 DZD.

4.11.3 Marketing strategy

- **Market landscape:** We are the first local producer of bidirectional DC-DC converters with EMC consideration, specifically designed for electric vehicles in Algeria, providing a unique opportunity for our product to establish itself.
- **Target audience:** The initial focus will be on electric vehicle manufacturers, charging station operators, and research institutions with a strong interest in adopting new technologies. Following successful market penetration, the strategy will expand to encompass other industries that require efficient energy conversion.

- **Value proposition:** Our proposed value for bidirectional DC-DC converters is to provide a solution that is more efficient, effective, and accessible than existing solutions. We believe that our solution will provide significant benefits to our customers.
- **Marketing initiatives:**
 - Content marketing: Develop and share content such as reports, case studies, and articles that explain our product's unique advantages. This will inform our audience, demonstrate the product's value, and position our brand as a leader in the field.
 - Building credibility: Share customer reviews, get industry certifications, and feature expert recommendations to build trust and show our product's reliability.
 - Multi-Channel approach: Use multiple communication channels such as social media, emails, webinars, and events to reach a wide audience.
 - Premium pricing strategy: setting higher prices, this reflects its exceptional performance and unique features in enhancing efficiency and ensuring electromagnetic compatibility.
 - Special offers and promotion: We provide special offers for our first-time buyers and bundled deals for our DC-DC converter. Additionally, we will organize events to showcase its advantages.

4.12 Forth axis: Production and organization plan

4.12.1 Production process

Our production process follows these steps:

1. **3D Conception:** We begin by creating a 3D design of the dc-dc converter using computer-aided design software, ensuring precise specifications and functionality.
2. **Material Reception and Validation:** Upon receiving raw materials, we carefully validate their quality, ensuring they meet our standards before proceeding with production.
3. **3D Printing and Assembly:** Our dedicated team utilizes 3D printing technology to bring the design to life. They expertly assemble the product, ensuring each component fits perfectly.
4. **Quality Inspection:** We conduct thorough checks to identify and address any flaws in the product, ensuring it meets our quality standards and specifications.

5. **Final Packaging:** Once the product passes inspection, it is meticulously packaged to ensure protection during transit and storage, safeguarding its integrity until it reaches the customer.
6. **Distribution and Delivery:** Finally, we distribute the product according to customer orders, employing reliable shipping methods to ensure prompt and secure delivery to their destination.

4.12.2 Supply

- Subcontract with local suppliers to support the local economy and reduce lead times.

4.12.3 Job positions to be created

- Electrical Engineers
- EMC Specialists.
- **Design Engineer**
- **Logistics Coordinator**
- **Project Manager**

4.12.4 Main partnerships

Forming strategic partnerships is crucial for our DC-DC converter production. We work with reliable suppliers, manufacturers, testing labs, and logistics partners to ensure high-quality, scalable production and efficient global delivery. Collaborations with academic institutions, marketing agencies, and financial institutions further support innovation, market reach, and compliance, ensuring overall project success.

4.13 Fifth axis: Financial plan

4.13.1 Costs and charges

Table 21: Variable costs

	Gross product	Total quantity	Unit	Gross product value (DA)	Unit quantity (per 1 unit)	Unit	Unit cost price (DA)
Raw materials	Igbt 60N100	1	piece	800,00	2	piece	1600,00
	Diodes BYT12	1	piece	400,00	2	piece	800,00
	Capacitors 560 uF	1	piece	200,00	2	piece	400,00
	Inductor 1.6 mH	1	piece	1000,00	1	piece	1000,00
	Driver ir2112	1	piece	350,00	1	piece	350,00
	Regulator LM7805	1	piece	100,00	1	piece	100,00
	Regulator LM7815	1	piece	100,00	1	piece	100,00
	Diodes 1N4148	1	piece	30,00	2	piece	60,00
	Capacitors 47uF	1	piece	30,00	4	piece	120,00
	Resistors	1	piece	40,00	2	piece	120,00
	Inverter 74N04	1	piece	100,00	1	piece	100,00
	Arduino Uno	1	piece	560,00	1	piece	560,00
	PCB sheets	20808	cm ²	2000,00	110,5	cm ²	10,62
consumable	Enclosure	1	piece	1000,00	1		1000,00
Total variable costs				6316,40	///		6280,62

Table 22: Equipment cost

Equipment	Designation	Unit value	Quantity	Total value DA
	Pc	60000	2	120 000
	Wi-Fi modem	3000	1	3000
	PCB Machine	50000	1	50000
	Laser printer	40000	2	80000
	3D printer	150000	1	150000
	EMI/EMC test Equipment	400 000	1	400 000
	Cooling systems	50 000	1	50 000
	Total		/	853000
	Depreciation allocation over 5 years			170600

Table 23: Cost of various services

Costs and various services	Costs and various services	Number	Annual amount (DA/An)
	Internet subscription	1	30 000
	electricity subscription	1	72 000
	Cleaning	1	30 000
	Rent costs	1	240 000
	Total services	4	372000

Table 24: Cost of layout and installation

layout and installation	Designation	Value (DA)
	Paint	15000
	Decoration	60000
	Desk +chair	40000
	various works	2500
	Total	117500
	Capital investment allocation (Over 10 years)	11750

Table 25: Salary cost

Organization/Labor	Post	Number	Monthly Salary	Gross Salary
	Engineer	2	60000	1440000
	Senior Technician	2	40000	960000
	Accountant	1	40000	480000
	IT Specialist	1	40000	480000
	Delivery and distributing responsible	1	35000	420000
	Total Salary Mass	8	250000	3780000

Table 26: Marketing budget

	Month												Total
	1	2	3	4	5	6	7	8	9	10	11	12	
Monthly Budget x1000 DA	20	20	20	20	20	20	20	20	20	20	20	20	240

Table 27: Product Sales

Goods and Services			Month												Total
			1	2	3	4	5	6	7	8	9	10	11	12	
Product/Service	Units Sold	Q1	0	5	15	20	25	30	35	40	50	55	60	70	405
	Selling Price (x1000 DA)	P1	300,000	30,000	30,000	30,000	30,000	30,000	30,000	30,000	30,000	30,000	30,000	30,000	///
	Sales (x1000 DA)	CA1	0,00	150,00	450,00	600,00	750,00	900,00	1050,00	1200,00	1500,00	1650,00	1800,00	2100,00	10125,00

Table 28 : Final balance sheet

	Formule	Montant (DA)
Initial unit cost (DA)		6280,62
Fixed unit charges (DA)		10251,85
Unitary depreciation allowance (over 5 years)		421,23
Unit investment allocation (over 10 years)		29,01
Final Unit Cost (DA)	$A+B+C+D$	16982,72
Production capacity (units/year)		405
Marketing budget (DA/year)		240000,00
Annual project cost (DA)	$(E * F) + G$	7118001,84
Annual turnover (DA)		12150000,00
Annual profit (DA)	$I - H$	5031998,16
Profit margin (%)	$J * 100 / I$	41,42 %

4.13.2 Business Model Canvas (BMC)

Table 29: Business Model Canvas Table

BUSINESS MODEL CANVAS		Designed by : Djadaouadji Imane Far Ouidjdane		Version: 01
Key Partnerships - Manufacturing partners. - Research institutions.	Key Activities - Integration of EMC Standards - Manufacturing. - Marketing. - Sales. - Accuracy. - Precision.	Value Propositions - Faster. - Simpler - Less costing. - Available. - Optimization of Energy Efficiency	Customer Relationship - Technical support. - Online resources. - Available.	Customer Segments - Automotive manufacturing companies - Research laboratories - Maintenance companies - Regulatory agencies - Metrology services
	Key Resources - Modeling and optimization software - Knowledge of EMC standards - Testing and validation equipment - Qualified technical personnel		Channels - online platforms - Automotive industry trade shows and conferences - Direct sales	
Cost Structure - Research & Development. - Manufacturing. - Marketing and promotion. - Annual project cost (DA) : 7118001,84 - Fixed unit charges (DA) : 10251,85 - Initial unit cost (DA) : 6280,62		Revenue Streams - Consultation and training services. - Maintenance and support contracts. - Strategic partnerships. - Sales		
Incubator of Oran 1 University – Ahmed Ben Bella				

4.14 Sixth axis: experimental prototype



Figure 99: Final Prototype

4.15 Conclusion

In conclusion, these tools enable us to precisely define the commercial and operational structure of our company, as well as the strategies necessary to achieve our goals. The BP helps us analyze the market, plan our financial operations, and define our marketing and sales strategy. The BMC assists us in visualizing and adjusting our business model clearly and concisely. By combining these two approaches, we gain a comprehensive view of our company, facilitating informed decision-making and adaptation to market changes. Thanks to this technical approach, we are confident in our ability to transform our vision into a successful commercial reality, creating a strong and sustainable business.