Republic of Algeria
Ministry of Higher Education and Scientific Research

University of Boumerdes
Institute of electrical and electronics engineering

Institute of electrical and electronics engineering

**Master's Thesis**
Research Master in engineering

# MASTER'S REPORT

*Submitted to*

Institute of electrical and electronics engineering

*In partial fulfillment of the requirements for the degree of*

MASTER DEGREE IN POWER ENGINEERING

*By*

**Khaldi Yahia**

# IMPLEMENTATION OF A 5 LEVEL MODULAR MULTILEVEL CONVERTER

Dr Metidji Brahim Supervisor

June 2024

# Dedication

I dedicate this work to my family, whose unwavering support, love, and encouragement have been my guiding light throughout this journey.

To my father, whose wisdom, guidance, and belief in me have given me the strength to pursue my dreams and overcome challenges.

To my mother, whose love, patience, and understanding have been a source of comfort and motivation. Your sacrifices and dedication to my well-being have inspired me to push beyond boundaries.

To my sister, whose friendship, laughter, and understanding have made every challenge more manageable and every success more meaningful. Your presence in my life is a constant source of joy and inspiration.

To my brother, whose friendship, loyalty, and support have been a source of strength and inspiration. Your belief in me has given me the courage to pursue my dreams.

To my friends, whose laughter, support, and encouragement have made every moment memorable. Your presence in my life has been a source of joy and inspiration.

This accomplishment is a testament to their belief in me and their unwavering support. I also dedicate this work to all those who have supported and inspired me along the way. Thank you all for being a part of my life's journey.

# Acknowledgments

I am deeply grateful to my supervisor, Dr. Metidji Brahim, for his exceptional guidance, unwavering support, and invaluable mentorship throughout my master's project. His expertise, insightful feedback, and encouragement have been instrumental in shaping the direction and outcomes of this work. I also extend my gratitude to all the members of the MICROTECHNOLOGIES LAB team for their collaboration, assistance, and stimulating discussions that have enriched this project.

I am indebted to the faculty and staff of INELEC for providing a stimulating academic environment conducive to learning and research. Their dedication to fostering academic excellence and providing access to resources has been integral to the successful completion of this project.

Furthermore, I would like to thank my family for their unending love, encouragement, and support. Their belief in me has been a constant source of motivation and inspiration throughout this journey.

# Abstract

This Master 2 project explores the design and implementation of a modular multilevel converter (MMC), focusing on both theoretical and practical aspects. The theoretical component delves into the fundamentals of multilevel converters, detailing various modulation techniques employed to enhance performance and efficiency. Specifically, it examines the advantages and challenges of using these techniques in multilevel converters.

The practical segment involves the simulation of a 5-level inverter using MATLAB Simulink, aimed at evaluating its performance under different conditions. Key meth- ods include the application of advanced pulse width modulation (PWM) techniques to minimize harmonic distortion and improve voltage output quality. The simulation results demonstrate a significant reduction in total harmonic distortion (THD) and efficient power conversion.

Following the simulation, the project transitions to the real-world implementation of the 5-level inverter with actual components. This phase involves constructing the inverter, integrating control strategies, and testing the system's performance. The findings reveal that the implemented inverter closely aligns with the simulated results, confirming the viability of the design for practical applications.

The project concludes that the modular multilevel converter, coupled with effective modulation techniques, presents a robust solution for enhancing power quality and efficiency in renewable energy systems. Future work will explore further optimization and potential scalability of the system for higher-level inverters.

# List of Abbreviations and Terms

| | |
|---|---|
| IEEE | Institute of Electrical and Electronics Engineering |
| NPC | neutral point clamped converter |
| CHB | Cascaded h-bridge converter |
| DC | Direct current |
| K | Coefficient |
| Vd | Voltage across the load |
| Vdc | DC voltage source |
| ia, ib, ic | Current circuits in 3 phase inverters |
| MOSFET | Metal oxide semiconductor field effect transistor |
| IGBT | Insulated gate bipolar transistor |
| GTO | Gate Turn OFF Thyristor |
| LCD | Liquid Crystal Display |
| MMC | Modular multilevl converter |
| HVDC | High voltage direct current |
| VSC | Voltage source converter |
| MPC | Multiple point clamped inverter |
| Bc | Capacitor banks |
| D | Freewheeling diodes |
| N | Power transistor |
| PV | Photovoltaic |
| PWM | Pulse width modulation |
| SVM | Space vector modulation |

| | |
|---|---|
| SVC | Space vector control |
| $V_k$ | k-th level of dc voltage |
| THD | Total harmonic distortion |
| $V_m$ | Sinusoidal modulating wave |
| $V_{cr}$ | Triangular carrier wave |
| $s_1$ | Switche |
| $V_{g1}$ | First gate voltage |
| $V_{g3}$ | Third gate voltage |
| $V_{an}$,$V_{bn}$ | The inverter terminal voltages |
| $V_{ab}$ | The inverter output voltage |
| $m_f$ | Frequency modulation index |
| $f_{cr}$ | Carrier frequency |
| $f_{sw,dev}$ | Switching frequency |
| $T_j$ | Duty cycle |
| DSP | digital signal processor |
| SPWM | Sinusoidal pulse width modulation |
| PSPWM | Phase-shifted multi-carrier modulation |
| H1 | Power cell |
| PCB | Printed Circuit Bo |

# Table of Contents

# List of Figures

# List of Tables

# General Introduction

In the realm of power electronics, the evolution of multilevel converters has revolutionized the landscape, offering unprecedented control, efficiency, and reliability for high-power applications. Among these, the 5-level modular multilevel converter (MMC) stands out as a pinnacle of engineering ingenuity, blending advanced theoretical concepts with practical implementation to deliver a cutting-edge solution. This project embodies the spirit of innovation and exploration, aiming to design, construct, and evaluate a functional 5-level MMC prototype that pushes the boundaries of conventional power conversion systems. The converter's architecture and control strategy are pivotal, with a keen focus on achieving not just functionality, but optimal performance under varying load conditions and switching frequencies. Through a meticulous selection of components, including state-of-the-art IGBTs, custom-designed PCB boards, and a sophisticated microcontroller, the converter is meticulously crafted to deliver stable, precise, and high-quality output voltages. The integration of innovative cooling mechanisms further enhances the converter's reliability and efficiency, ensuring sustained operation even in demanding environments. This project transcends mere technological advancement; it embodies a vision for a sustainable future, where efficient power conversion plays a pivotal role in shaping a greener, more energy-efficient world. Through this endeavor, we seek not only to push the boundaries of power electronics but also to inspire a new generation of engineers to innovate, explore, and drive change for a better tomorrow.

The structure of this report is organized into three comprehensive chapters to provide a detailed understanding of the project and its multifaceted aspects. The first chapter, "Overview on Multilevel Converters," delves into the fundamental principles, types, and advantages of multilevel converters, setting the stage for the subsequent discussion on MMCs. This chapter provides a solid foundation by exploring the historical development, various topologies, and key benefits of multilevel converters, highlighting their significance in modern power electronics.

The second chapter, "Modular Multilevel Converter," focuses on the specific architecture, operational principles, and unique features of MMCs, with an emphasis on the 5-level configuration used in this project. Detailed explanations of the converter's structure, including the arrangement of submodules, the role of capacitors, and the function of switching devices, are provided. This chapter also covers the control strategies employed to manage the converter's performance, ensuring that the reader gains a comprehensive understanding of both the theoretical and practical aspects of MMCs.

The third chapter, "Simulation and Implementation," presents the practical aspects of the project, including the design process, simulation results, and the implementation of the 5-level MMC prototype. This chapter is divided into several sections to cover different stages of the project: from the initial design and component selection to the detailed simulation studies conducted using MATLAB Simulink. The chapter further describes the step-by-step construction of the prototype, the challenges encountered, and the solutions implemented. Additionally, it includes an analysis of the experimental results, comparing the simulated performance with the actual performance of the prototype under various operating conditions and switching frequencies.

The final section of the report summarizes the findings and discusses potential future work. This includes suggestions for further improving the converter’s efficiency and reliability, exploring advanced control strategies, and considering applications in grid integration and renewable energy systems.

By structuring the report in this manner, we ensure a coherent flow of information, guiding the reader from basic concepts to advanced applications and practical realizations. Each chapter builds upon the previous one, providing a logical progression that enhances the reader’s understanding of the 5-level MMC and its potential impact on the field of power electronics. This comprehensive approach not only highlights the technical achievements of the project but also underscores its broader significance in the pursuit of sustainable and efficient power conversion solutions.

# 1. Overview on Multilevel Converter

## 1.1 Introduction

In this chapter, we present a theoretical study on multilevel converters, focusing on the most important existing topologies: Neutral Point Clamped (NPC) converter, Flying Capacitor (FC) converter, and Cascaded H-Bridge (CHB) converter with separate DC voltage sources. We highlight their significance and interest. Finally, we conclude this chapter with a comparison of the three topologies.

## 1.2 Converter

Power semiconductors (diodes, thyristors, transistors, etc.) are used as switches in converter circuits to change the signal's spectrum (amplitudes, frequencies, and phases) and match the source to the load. Power electronics is the term used to describe the study and design of these devices. The following is how the various types of converters are differentiated: [1]

- **Rectifiers:** These are converters from AC to DC. There is no alternating (non-zero average value) output voltage. If the rectifier is controlled, this average value can be changed. They are mostly used to recharge batteries or power loads that run on DC voltages (in actuality, a rectifier is always included in the chargers for your computers and smartphones).[1]

- **Inverters:** An inverter is a DC to AC converter that is primarily used to feed energy from photovoltaic panels into the grid or to power loads that require an AC voltage when a DC source is available, like batteries.[1]

- **Choppers:** These are DC-DC converters that enable the adjustment of a DC voltage to suit the load, change a DC motor's speed, or change a lamp's brightness. High frequency switching is used in this process. It is the equivalent of the dimmer used in AC systems for DC voltage sources. When the applied input voltage exceeds the output voltage, the chopper is referred to as a step-down converter, also known as a buck converter. In any other case, it's referred to as a boost converter, or step-up converter. Certain helicopters can function in both modes (Buck-Boost).[1]

- **Dimmers:** This AC-AC converter produces an AC voltage with an output frequency equal to the input voltage and a continuously variable effective value. The primary purpose of this converter is to change the supply voltage of AC motors, such as synchronous or asynchronous motors, in order to alter their speed.[1]

- **Cycloconverters:** This is an AC-AC converter that outputs an AC voltage with a frequency and effective value different from those of the input voltage. Cycloconverters change the frequency or effective value of the supplied voltage to adjust the speed of AC motors.[1]

## 1.3 DC-AC Converter (inverter)

A power inverter, inverter, or invertor is a power electronic device that changes direct current (DC) to alternating current (AC) as shown in Figure 1.The resulting AC frequency obtained depends on the particular device employed. Originally designed as huge electromechanical devices that converted AC to DC, rectifiers provide the opposite function that inverters accomplish. [2]

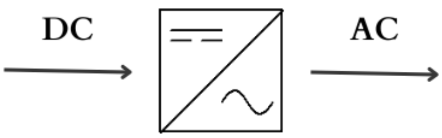


Figure 1.1. *Inverter.*

### 1.3.1 Single phase inverter

To explain how an inverter works, we proceed by creating a single-phase inverter. To do this, we simply need a DC voltage source E and a reversing switch K, as shown in Figure 2.[3]

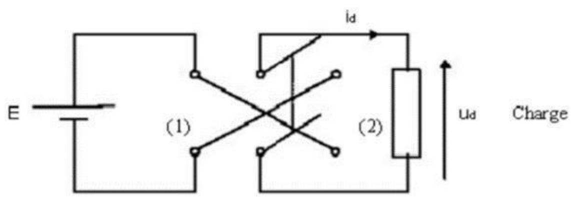


Figure 1. 2. *Single phase inverter.*

The output voltage Ud can only take two values: E and -E. When K is in position (1), the voltage across the load is Ud = E. When K is in position (2), Ud = -E. The waveform of the voltage across the load is represented in Figure 3. [3]

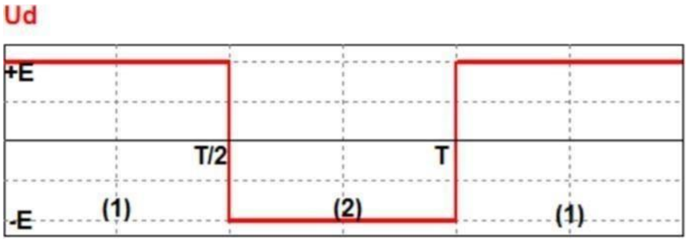


Figure 1. 3. *Waveform of voltage Ud.*

### 1.3.2 Three phase inverter

To obtain a three-phase inverter, it is sufficient to group three single-phase inverters in parallel and control the switches in such a way as to have three output phases shifted by 120°. In fact, this grouping results in a three-phase inverter with six switches, two for each arm as shown in Figure 4. To ensure that the DC voltage source Udc is never short-circuited and the current circuits ia, ib, and ic are never opened, the switches in the same arm must never switch simultaneously, which requires them to have complementary control signals.

These switches must be bidirectional in current, in order to impose the output voltages regardless of the load current. These switches consist of a diode mounted in antiparallel with a semiconductor controlled for opening and closing.

Depending on the power involved, these switches can be realized with MOS or bipolar, IGBT or GTO associated with a diode to ensure reversibility in current. [3]

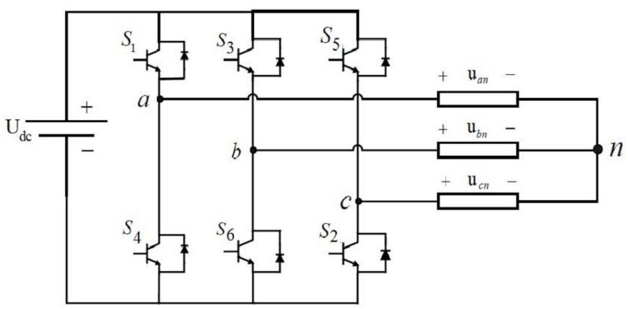


Figure 1.4. *Three phase inverter circuit*

### 1.3.3 Voltage inverter

A voltage inverter is powered by a DC voltage source (with negligible internal impedance). The output voltage "V" is not affected by variations in the load current "i"; the DC source sets the input voltage of the inverter and thus its output. The current "i" depends on the load connected on the AC side, which can be any load as long as it is not another voltage source (like a capacitor or an alternating electromotive force) directly connected between the output terminals. [3]

### 1.3.4 Current inverter

A current inverter (often called a current switch) is powered by a current source, meaning a source with such a large internal inductance that the current "i" flowing through it cannot be affected by variations in the voltage "u" across its terminals.[3]

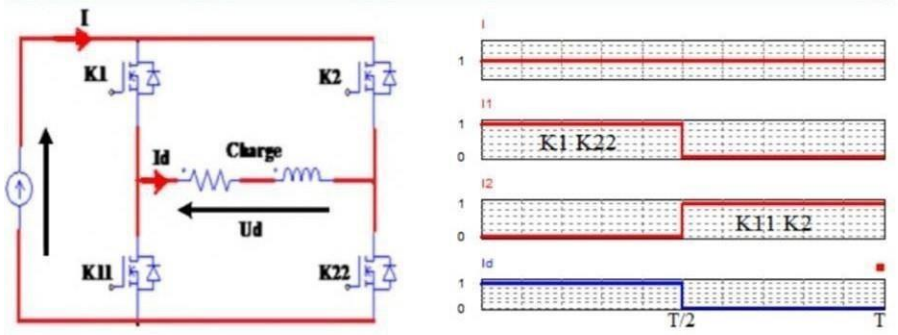


Figure 1.5. *Current inverter*

## 1.4 Multilevel Converter

In recent years, a growing number of industrial applications have started to need higher power equipment. Megawatt power levels and medium voltage are needed for some utility applications and motor drives operating at a medium voltage. It is problematic to directly connect a single power semiconductor switch to a medium voltage grid. As a result, an alternative for high power and medium voltage scenarios is the introduction of a multilevel power converter system. In addition to achieving large power ratings, the multilevel converter makes it possible to use renewable energy sources. For a high power application, photovoltaic, wind, and fuel cell renewable energy sources are simply interfaced to a multilevel converter system.[4]

### 1.4.1 History of Multilevel Converter

Prof. Rainer Marquardt invented the modular multilevel converter (MMC) in 2001, marking the beginning of its history. This new concept has now been acknowledged as a significant development in the field of power electronics. Power conversion technologies have undergone a revolution thanks to MMCs, especially in high-voltage direct current (HVdc) transmission networks.

Because it offers a reliable and adaptable substitute for conventional two- and three-level voltage source converters (VSCs), the MMC is currently the most well-known type of VSC for HVdc. The MMC has also become more popular outside of HVdc thanks to its scalable system design, small size, flexible control, low switching frequency, and harmonic distortion. [5]

### 1.4.2 Structure of Multilevel Converter

The term multilevel began with the three-level converter. Several multilevel converter topologies have been created as a result. However, the basic idea behind a multilevel converter is to create a staircase voltage waveform by combining multiple lower voltage dc sources with a series of power semiconductor switches to convert power. Several dc voltage sources such as batteries, capacitors, and renewable energy sources can be employed. The power switches' commutation combines these several dc sources to produce a high voltage at the output; yet, the power semiconductor switches' rated voltage is solely determined by the rating of the dc voltage sources they are linked to. [4]

## 1.5 Topologies of Multilevel Converters

### 1.5.1 NPC neutral point clamped converter

The Neutral Point Clamped (NPC) inverter was proposed by Baker. This inverter allows for an odd level of voltage. The first NPC inverter was developed for a three-level output voltage by superimposing two elementary switches, each powered by a separate DC voltage source. After Baker's patented first NPC inverter, other researchers have developed different structures based on NPC. The NPC inverter allows for an odd number of levels in the output voltage waveform. However, the Multiple Point Clamped (MPC) inverter was developed in the 1990s for an even number of voltages. These two types of inverters are shown in the figure 10.[6]

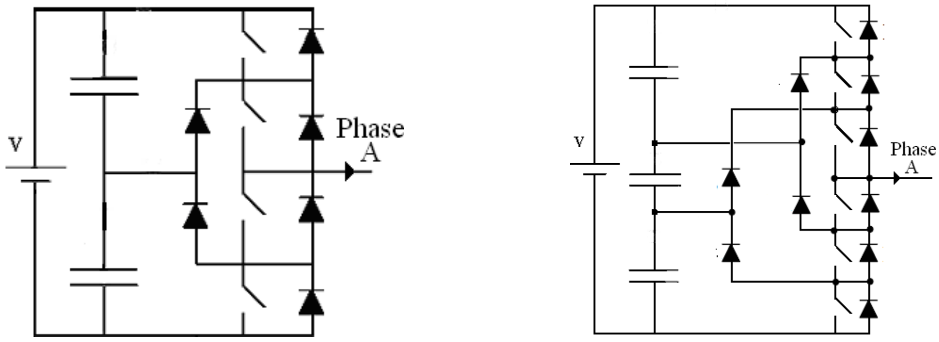


Figure 1.6. *NPC and MPC converters.*

For an NPC or MPC inverter with k levels, the numbers of elements constituting the NPC and MPC topologies, S for the DC source, Bc for the capacitor banks, N for the power transistors, and D for the freewheeling diodes are given, for each phase, by the relationships in the following table: [6]

Table 1.1. Comparison table between NPC and MPC.

| | NPC | MPC |
|---|---|---|
| S | 1 | 1 |
| Bc | 2*(k-1) | (k-1) |
| N | (k-1) | 2*(k-1) |
| D | 2*(k-2) | K |

**Advantages:**

- Power semiconductors block a reverse voltage is equal to half of the DC link voltage.
- The basic topology can be easily generalized to create a converter with a higher number of levels. [6]

**Disadvantages:**

- For topologies with more than three levels, the clamping diodes can increase voltage stresses. A series connection of diodes may therefore be required, which complicates the design and raises reliability and cost issues.
- Maintaining balanced capacitor voltages remains an open question for NPC inverter topologies with more than three levels. Although the three-level NPC operates with high power factor, the multilevel NPC inverter is mainly used in compensation circuits. This is due to the capacitor balancing issue.[6]

### 1.5.2 Cascaded H-Bridge converter

The first model of inverter was the H-bridge inverter. A progress in multilevel inverters was due to the cascaded H-bridge model. The first application of the H-bridge inverter was for plasma stabilization. The outputs of the H-bridge inverters are connected in series so that the synthesized voltage waveform is the sum of the output voltages. The major advantage of this approach is that the number of steps in the output voltage waveform can be increased without adding new components. The use of power conversion cells in series allows for an increase in the number of voltage and power levels of the converter. However, the major drawback of this topology is the large number of isolated DC voltages required for each bridge. [6]

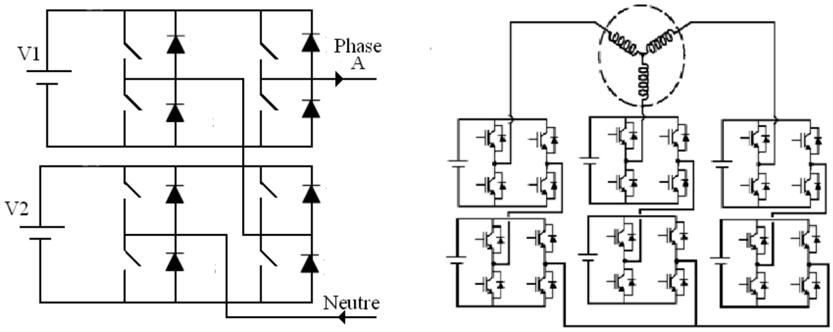


Figure 1.7. *H bridge converter*

**Advantages:**

- The blocking voltage of the switches is the same everywhere.
- Its modularity allows for easy extension and adaptation of control strategies to a high number of levels.
- For a high number of levels, the use of a filter is unnecessary.[7]

**Disadvantages:**

- The main drawback of this topology lies in the required number of capacitors, which can represent a prohibitive volume.
- Control becomes complicated to track voltage levels for all capacitors.
- System control becomes difficult with increasing number of levels.[7]

### 1.5.3 Flying capacitor converter

The Flying Capacitor Multilevel Inverter, or multicell inverter, is an energy conversion topology based on series-connected controlled switches. It emerged in the early 1990s following a patent filed by Meynard and Foch. This inverter is obtained by connecting flying capacitor cells. The primary advantage of this topology is the absence of freewheeling diodes found in NPC and MPC inverter topologies. Additionally, voltage stresses imposed on power components are naturally limited: there is a low dv/dt value across the components. 'Redundancies' in the switching sequences introduce states that can be used to maintain capacitor voltage balance. Thus, only one DC source is needed per phase. FC inverters can have even or odd numbers of levels, as shown in Fig 12. [6]

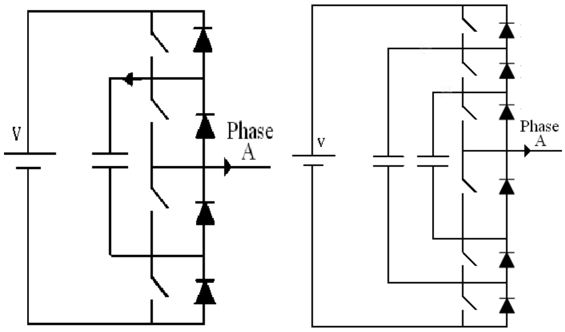


Figure 1.8. *Flying capacitor converter*

**Advantages:**

- To achieve the same number of voltage levels, this type of converter requires fewer components.
- Unlike the freewheeling diode and floating capacitor inverter, no additional diode is needed.
- Small DC sources are typically involved, resulting in fewer safety issues.[7]

**Disadvantages:**

- The capacitor charge controller increases the complexity of controlling the entire circuit.
- It requires capacitors connected in parallel, through which high currents may flow.
- There is a potential for parasitic resonance between the decoupled capacitors. [6]

## 1.6 Comparison between topologies

Topologies such as NPC inverters and cascaded H-bridge inverters divide their supply voltage: the output voltage is smaller or equal to the input DC voltage. They are capable of operating from a single DC supply.

On the other hand, structures such as series-connected cell inverters raise their supply voltage, so the maximum output voltage is greater than each of the input voltages; it is smaller or equal to the sum of the input voltages. Unlike other topologies, the cell supplies cannot be obtained from a single DC supply without additional converters. In most cases, transformers are required to obtain the necessary supplies. Parallel coupling of transformers on the "supply side" and adding voltages on the "load side" leads to a voltage increase.

Although the choice of multilevel topology is directly related to the application and feature set, in order to minimize losses, volume, and costs, usually the number of components plays the most important role. [8]

## 1.7 Application of multilevel converter

Multi-level converters are receiving significant attention in both industry and academia as one of the preferred choices for high-power applications. They have successfully made their way into industrial settings and can therefore be considered a mature and proven technology. Currently, they are standardized and operate a wide range of applications, such as compressors, extruders, pumps, fans, milling machines, rolling mills, conveyors, crushers, furnace blowers, gas turbine starters, mixers, elevators, reactive power compensation, maritime propulsion, high-voltage direct current gearboxes, pumped hydro storage, photovoltaic and wind power, and railway traction. Converters for these applications are commercially available from a growing number of companies in the field, such as ABB, SIEMENS, Schneider-Electric, Alstom, TMEIC-GE, among others. [9]

### 1.7.1 Solar energy

In order to improve the efficiency of the photovoltaic (PV) system, i.e., to maximize the power delivered to the load connected to the terminals of the photovoltaic generator, several optimization methods have been applied, and techniques followed to achieve good adaptation and high efficiency. Among these methods, improving the quality of the output voltage of the inverter by using multilevel inverters. Multilevel inverter-based structures have brought significant benefits to DC-AC conversion, especially in high-power applications. However, most photovoltaic systems have low-voltage loads.[10]

### 1.7.2 Wind energy

As the production of renewable energies, particularly wind turbines, takes up space, the use of multilevel converters helps improve the waveform by utilizing the different voltage levels injected at the common connection point for variable-speed wind turbines to prevent disconnection of the wind turbine from the grid. These converters help to mitigate harmonics, which are associated with filters (active or passive filtering).[11]

## 1.8 Conclusion

In this chapter, we have presented the different basic structures of multi-level voltage inverters. The study aims to describe the characteristics related to each of the topologies from the perspective of topology, properties (advantages and disadvantages). Thus, the various application areas: are PV and wind energies. Applying these topologies in the industrial domain differs from one domain to another and from one topology to another. Each structure is advantageous in one domain and presents disadvantages in another, there is no versatile topology, and each structure has its application domain.

Finally, this chapter compares multi-level topologies regarding the number of components and source of DC voltage.

# 2. Modular Multilevel Converter

## 2.1 Modular Multilevel Converter

A Modular Multilevel Converter (MMC) is a type of power electronic converter architecture that consists of multiple submodules (or cells) arranged in a modular and scalable manner to convert electric power between AC and DC forms.

Each submodule typically contains a capacitor and a pair of power semiconductor switches, allowing the converter to generate a multi-level voltage waveform with high quality and low harmonic distortion.

The MMC architecture is widely used in high-voltage direct current (HVDC) transmission systems, flexible AC transmission systems (FACTS), and other applications requiring efficient and reliable high-power conversion. The key advantages of MMCs include their modularity, scalability, high efficiency, redundancy, and fault tolerance.

## 2.2 Structure of MMC

A Modular Multilevel Converter (MMC) has a distinctive structure composed of numerous submodules and arm inductors, arranged to form a highly flexible and scalable power conversion system. Here’s a detailed description of its structure:

**1. Submodules (SMs)**

- **Composition:** Each submodule typically consists of a capacitor and two power semiconductor switches (often implemented as Insulated Gate Bipolar Transistors (IGBTs) or other types of transistors).

- **Configuration:** The submodules can be of different configurations, such as half-bridge or full-bridge circuits, depending on the specific design requirements.

- **Operation:** Each submodule can insert or bypass its capacitor in the circuit, allowing the converter to generate multiple voltage levels by combining the voltages of the capacitors.

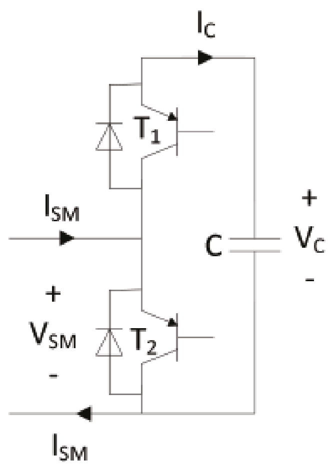


Figure 2.9. *Submodule structure.*

**2. Arms**

- **Upper and Lower Arms:** The converter is divided into three phases, with each phase containing two arms: an upper arm and a lower arm.

- **Arm Inductors:** Each arm includes an inductor to limit the circulating currents and to smooth the current waveform.

**3. Phase Legs**

- **Composition:** Each phase leg of the converter is composed of the upper and lower arms connected in series.

- **Connection:** The midpoint of each phase leg is connected to the AC terminal, while the ends of the arms are connected to the DC bus.

**4. DC Bus**

- **Role:** The DC bus provides the connection for the DC side of the converter, carrying the direct current that is converted to AC, or vice versa.

- **Configuration:** The positive and negative terminals of the DC bus are connected to the ends of the arms in each phase.

**5. Control System**

- **Functions:** The control system manages the switching of the submodules and the overall operation of the converter. It ensures proper voltage balancing of the capacitors, regulates the current, and maintains the desired output voltage and frequency.

- **Methods:** Advanced modulation techniques such as Pulse Width Modulation (PWM) and Nearest Level Control (NLC) are used to control the switches and generate the multi-level voltage waveforms.

6. **Cooling System**

- **Purpose:** Due to the significant power handled by MMCs, an efficient cooling system is necessary to dissipate the heat generated by the power semiconductors and other components.

- **Types:** Cooling methods can include air cooling, liquid cooling, or other advanced thermal management techniques.

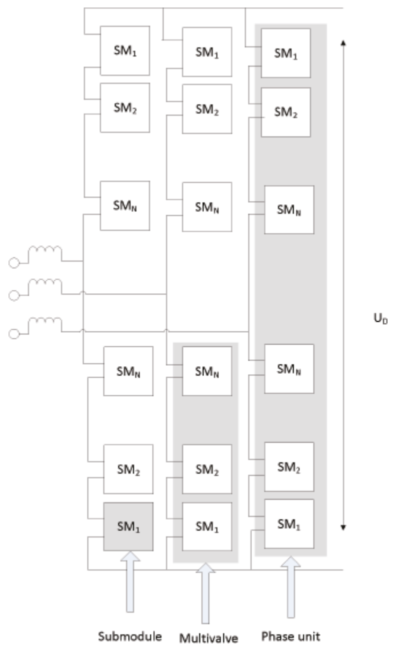


Figure 2.10. *3 phases MMC structure.*

**Example of MMC Structure:**

For a three-phase MMC, the structure includes six arms (two per phase) with a series of submodules in each arm. The upper arm of each phase connects to the positive terminal of the DC bus, while the lower arm connects to the negative terminal. The AC terminals are connected to the midpoint of the upper and lower arms of each phase. This arrangement allows for flexible and efficient conversion of power between AC and DC forms with high-quality output.

## 2.3 Use of MMC

Modular Multilevel Converters (MMCs) are used in various high-power applications due to their modularity, efficiency, and flexibility. They are essential in HVDC transmission for efficient long-distance power transfer and in Flexible AC Transmission Systems (FACTS) to enhance grid stability and power quality. MMCs facilitate the integration of renewable energy sources like wind and solar into the grid and power high-power motor drives in industrial applications and electric vehicles. They are also used in energy storage systems to manage and convert stored energy, improve power quality by reducing harmonic distortion, and support reactive power. Additionally, MMCs are crucial in railway electrification for powering electric trains and in marine and offshore applications for powering ships and offshore platforms. Their key advantages include high efficiency, low harmonic distortion, fault tolerance, and flexible control.

## 2.4 Modulation of MMC

As shown in Fig. 6, the modulation techniques employed in MMC can be categorized based on their switching frequencies. Several power semiconductor commutations occur during a single period of the fundamental output voltage in high-frequency modulation techniques. A popular technique in industrial settings is the basic carrier-based sinusoidal PWM (SPWM), which reduces harmonics in the load voltage by using phase-shifting. The Space Vector Modulation (SVM) technique is another noteworthy substitute that is frequently used in three-level inverters.

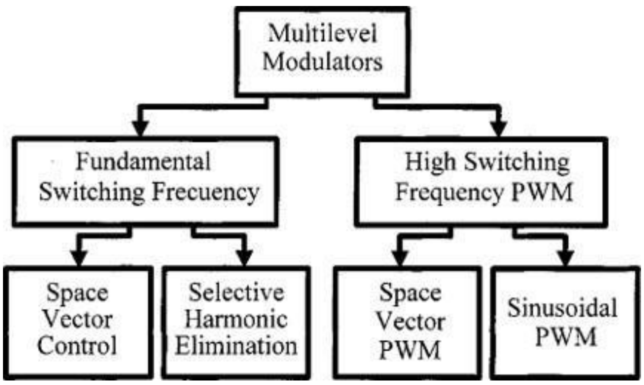


Figure 2.11. *Classification of modulation strategies.*

On the other hand, low-frequency modulation methods typically involve one or two power semiconductor commutations over the course of one output voltage cycle, producing a staircase waveform. Space Vector Control (SVC) and multilevel selective harmonic elimination are two examples of this methodology. For this project we will use the SPWM modulation technique.[12]

## 2.5 PWM high frequency switching

The PWM technique involves generating an output signal formed by several pulses with varying widths and an amplitude equal to the supply voltage. The opening and closing commands of the switches are determined by the intersection of a triangular signal (carrier) with a reference signal according to the chosen strategy.[13]

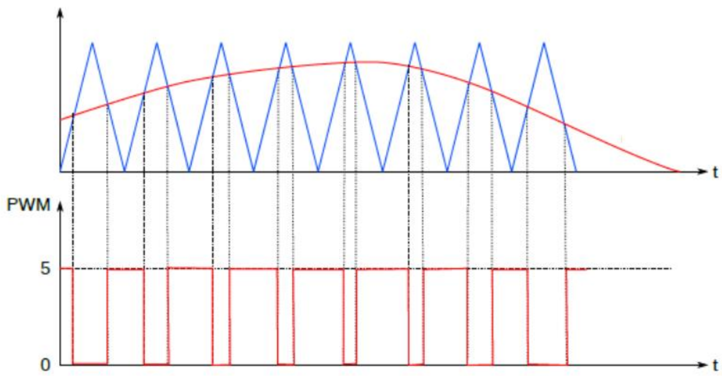


Figure 2.12. *Realization of the PWM signal.*

### 2.5.1 The characteristics of PWM

The important parameters in PWM control are:

- The modulation frequency $f_p$.
- The frequency modulation index m: which is defined as the ratio of the carrier frequency to themodulating frequency.

$$m = \frac{f_p}{f_r} \tag{2.1}$$

  It should be noted that when the modulation index is large, it means that harmonic neutralization is effective.

- The adjustment coefficient A: is defined as the ratio of the amplitude of the modulating signal to the amplitude of the unmodulated carrier.

$$A = \frac{A_r}{A_p} \tag{2.2}$$

The adjustment coefficient should never be equal to "1"; there should always be sufficient time for the conduction and blocking intervals of the switches in the same arm.[13]

### 2.5.2 Advantages of PWM

- Effective harmonic elimination compared to other control methods.
- With the same DC source, PWM allows the power supply of multiple inverter sets, asynchronous motors.
- Variation of the output voltage fundamental value.
- PWM enables the shifting of output voltage harmonics to higher frequencies (filtering).

### 2.5.3 Disadvantages of PWM

- The harmonic content generated by a PWM wave causes losses in the network (iron losses in the transformer, Joule losses, and losses due to Foucault currents).
- It generates acoustic noise and electromechanical resonances in rotating machines, causing torque oscillations.
- It destabilizes the system due to noise injection into the control.

### 2.5.4 Bipolar Pulse-Width Modulation

A set of typical waveforms for an H-bridge inverter with bipolar modulation is shown in Figure 8. The sinusoidal modulating wave $V_m$, the triangular carrier wave $V_{cr}$, and the gate signals for the upper switches $S_1$ and $S_3$, respectively, are denoted by $V_{g1}$ and $V_{g3}$. With one switch turned on and the other off, the upper and lower switches in the same inverter leg function in tandem. As a result, we only need to take into account the two separate gate signals that result from comparing $V_m$ with $V_{cr}$: $V_{g1}$ and $V_{g3}$. By using the same processes, the waveforms of $V_{bn}$ and $V_{an}$, the inverter terminal voltages, may be obtained. From there, $V_{ab} = V_{an} - V_{bn}$ can be used to find the inverter output voltage. This approach is called bipolar modulation because the waveform of $V_{ab}$ alternates between the positive and negative dc voltages $\pm V_d$. As $V_{ab}$ represents the rms value of the nth-order harmonic voltage, the harmonic spectrum of the inverter output voltage $V_{ab}$ normalized to its dc voltage $V_d$ is displayed in Fig. 8(b). Around the frequency modulation index $m_f$ and its multiples, $2m_f$ and $3m_f$, the harmonics manifest as sidebands. If the order of the voltage harmonics is less than ($m_f - 2$), they are either removed or very tiny. The carrierfrequency $f_{cr}$ is equal to the switching frequency of the IGBT device, which is called device switching frequency $f_{sw,dev}$. The harmonic content of $V_{ab}$ is plotted against the amplitude modulation index $m_a$ in Figure 9. With $m_a$, the basic voltage $V_{ab1(rms)}$ rises linearly. With $m_a$ < 0.8, the magnitude of the dominant harmonic $m_f$ is much larger than $V_{ab1}$. The unipolar pulse width modulation technique can remove this harmonic and its sidebands.[13]

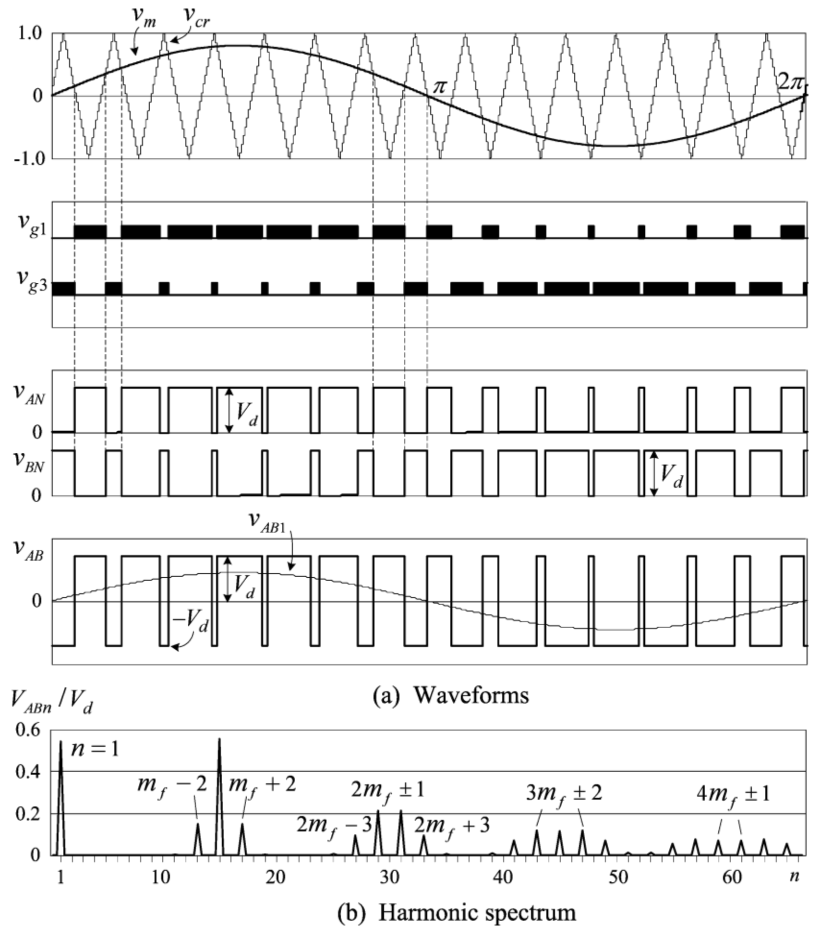


Figure 2.13. *Bipolar PWM for the H-bridge inverter.*

### 2.5.5 Sinusoidal pulse width modulation (SPWM)

One of the most widely used modulation techniques for multilevel inverters is the SPWM technique. To create the trigger signals for the inverter switches in SPWM, a triangular wave known as the carrier and a sinusoidal voltage wave termed the reference are compared. One of the most crucial problems in high-power applications is energy dissipation. To reduce switching losses, the SPWM control approach at fundamental frequency has been suggested. In order to enhance the performance of multi-level inverters, multi-carrier SPWM control techniques are also used. These techniques are categorized based on whether the carrier signal is arranged vertically or horizontally.[13]

**Level-Shifted Multicarrier Modulation:**

Similar to the phase-shifted modulation, an m-level CHB inverter using level-shifted multicarrier modulation scheme requires (m – 1) triangular carriers, all having the same frequency and amplitude. The (m – 1) triangular carriers are vertically disposed such that the bands they occupy are contiguous. The frequency modulation index is given by $m_f = f_{cr}/f_m$, which remains the same as that for the phase-shifted modulation scheme whereas the amplitude modulation index is defined as:[13]

$$m_a = \frac{V_m}{V_{cr}(m-1)} \qquad (2.3)$$

where $V_m$ is the peak amplitude of the modulating wave $v_m$ and $V_{cr}$ is the peak amplitude of each carrier wave. Three schemes for the level-shifted multicarrier modulation are depicted in Figure 9: (a) phase opposite disposition (POD), where all carriers are in phase but opposite of those below the zero reference; (b) alternative phase opposite disposition (APOD), where all carriers are opposite of each other in an alternative manner; and (c) phase opposite disposition (IPD), where all carriers are in phase. Out of the three modulation methods, only the IPD modulation scheme is examined in the following because it offers the best harmonic profile. [13]

The IPD modulation principle for a seven-level CHB inverter working with $m_f = 15$, $m_a = 0.8, f_m = 60Hz$, and $f_{cr} = f_m * m_f = 900Hz$ is shown in Figure 29. Power cell $H1$ uses the uppermost and lowermost carrier pair, $V_{cr1}$ and $-V_{cr1}$, to generate the gatings for switches $S_{11}$ and $S_{31}$. Gatings for $S_{13}$ and $S_{33}$ in $H3$ are produced by the innermost carrier pair, $V_{cr3}$ and $-V_{cr3}$. For $S_{12}$ and $S_{22}$ in $H2$, the final carrier pair are $V_{cr2}$ and $-V_{cr2}$. The switches $S_{11}$, $S_{12}$, and $S_{13}$ are activated for the carriers above the zero reference ($V_{cr1}$, $V_{cr2}$, and $V_{cr3}$) when the phase A modulating signal $V_{ma}$ is greater

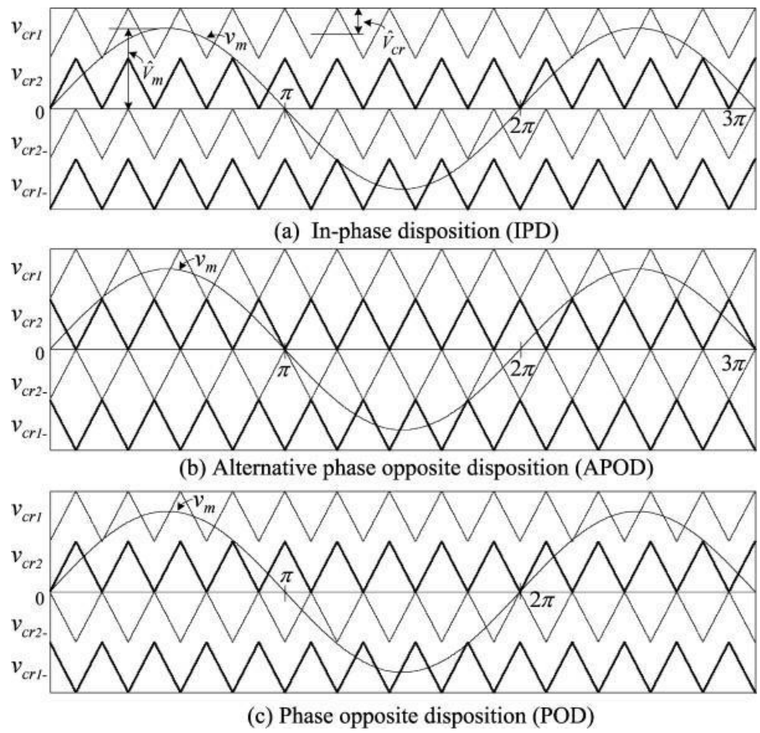


Figure 2.14. *Level-shifted multicarrier modulation for five-level inverters.*

than the corresponding carriers. When $V_{ma}$ is less than the carrier waves, $S_{31}$, $S_{32}$, and $S_{33}$ are turned on for the carriers below the zero reference ($-V_{cr1}$, $-V_{cr2}$, and $-V_{cr3}$). For the sake of simplicity, the gate signals for each H-bridge's bottom switches are omitted since they are complementary to the corresponding upper switches. As illustrated in Fig. 10, the resulting H-bridge output voltage waveforms $V_{H1}$, $V_{H2}$, and $V_{H3}$ are all unipolar. Seven voltage levels combine to generate the inverter phase voltage waveform $V_{an}$. [13]

The device switching frequency in phase-shifted modulation is the same as the carrier frequency. For the IPD modulation, however, this link is no longer valid. For instance, the switching frequency of the devices in H1, with a carrier frequency of 900 Hz in Fig. 10, is only 180 Hz. This is determined by multiplying the frequency of the modulating wave (60 Hz) by the number of gating pulses per cycle. Additionally, the devices in various H-bridge cells have varying switching frequencies. H3 switches have a switching frequency of 60 Hz so they are only turned on and off once every cycle. In general, the switching frequency of the inverter using the level-shifted modulation is equal to the carrier frequency, that is:[13]

$$f_{sw,inv} = f_{cr} \tag{2.4}$$

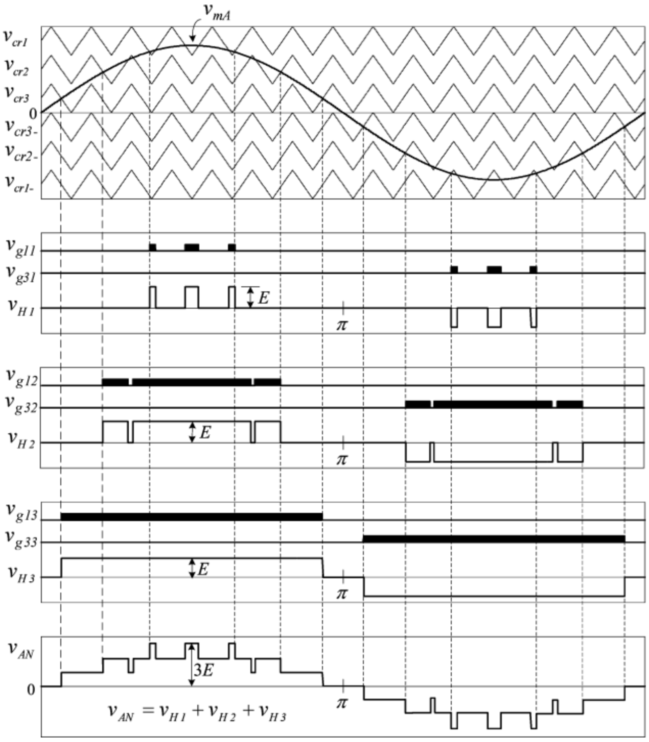


Figure 2.15. *Level-shifted PWM for a seven-level CHB inverter.*

From which the average device switching frequency is:

$$f_{sw,dev} = \frac{f_{cr}}{(m-1)} \tag{2.5}$$

The devices' conduction times are not spread equally in addition to their differential switching frequencies. For instance, $S_{11}$ in $H1$ conducts for a lot less time per fundamental frequency cycle than $S_{13}$ in $H3$. Rotating the switching pattern among the H-bridge cellsis necessary to disperse the switching and conduction losses equally. The simulated waveforms for a seven-level inverter with the following parameters: $f_m = 60Hz$, $m_a = 1.0$,$m_f = 60$, and $f_{cr} = 3600Hz$ are displayed in Figure 11. The typical device switching frequency is just 600 Hz, despite the fact that the carrier frequency of 3600 Hz appears high for high-power converters. The output voltages of the H-bridge cells, $V_{H1}$, $V_{H2}$, and $V_{H3}$, are all different, signifying that the IGBTs operate at different switching frequencieswith various conduction times. [13]

Similar to the voltage waveforms produced by the phase-shifted modulation,the inverter phase voltage $V_{an}$ is composed of seven voltage levels while the lineto-line voltage $V_{ab}$ has13 voltage levels. The dominant harmonics in $V_{an}$ and $V_{ab}$ appear as sidebands centered around $m_f$. The inverter phase voltage contains triplen harmonics, such as $m_f$ and $m_f \pm 6$,

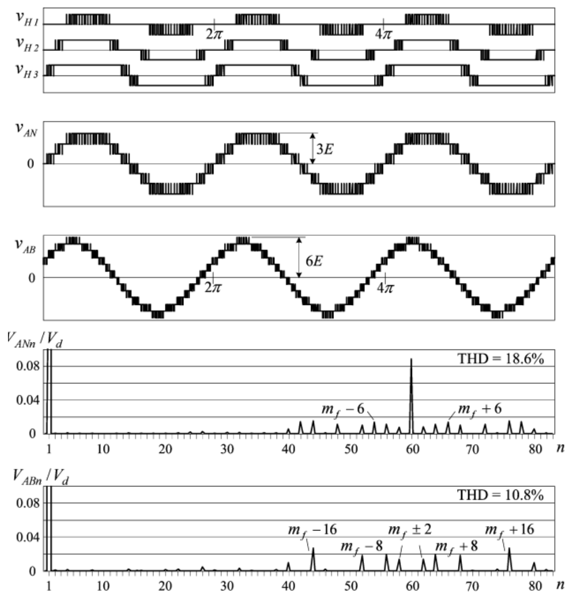


Figure 2.16. *Simulated waveforms for a seven-level CHB inverter with IPD modulation.*

with $m_f$ being a dominant harmonic. Since these harmonics do not appear in the line-to-line voltage, the THD of $V_{ab}$ is only 10.8% in comparison to 18.6% for $V_{an}$. The spectra of $V_{ab}$ at other modulation indices ma are shown in Fig. 12. The THD of $V_{ab}$ decreases from 48.8% at $m_a = 0.2$ to 13.1% at $m_a = 0.8$.

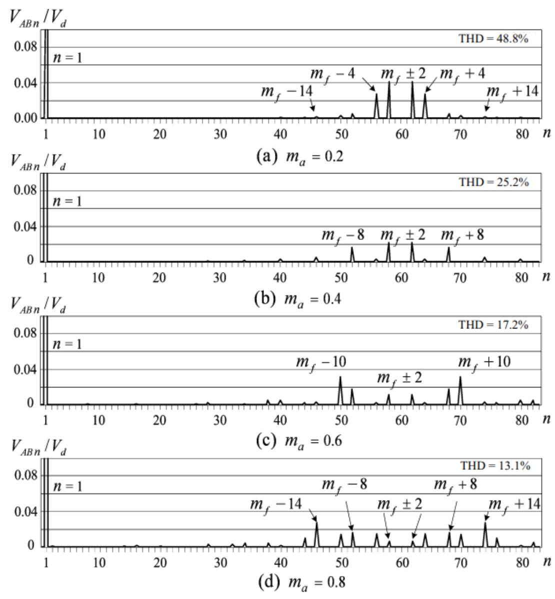


Figure 2.17. *Harmonic content of Vab produced by a seven-level CHB inverter with IPD.*

Fig. 13 shows the $V_{an}$ and $V_{ab}$ waveforms obtained from a seven-level CHB inverter in the lab. If $m_f = 60$, $m_a = 1.0$, $f_m = 60Hz$, and $f_{cr} = 3600Hz$, then the inverter will function. The simulation findings displayed in Fig. 12 are in agreement with the measured waveforms and their harmonic spectra. [13]

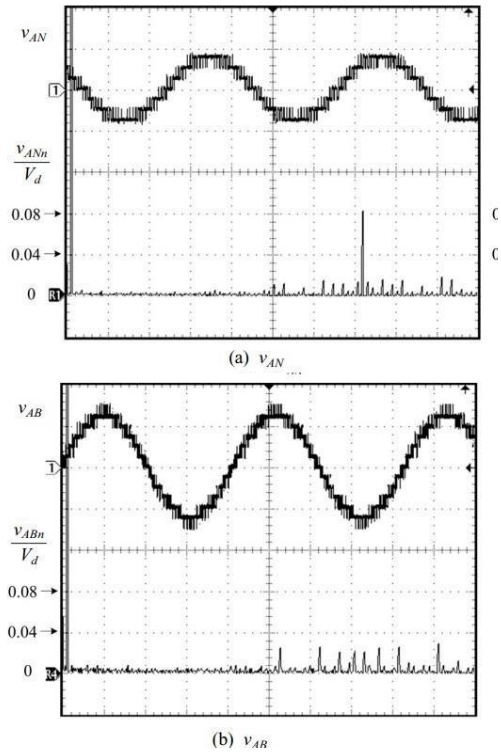


Figure 2.18. *Waveforms measured from a laboratory seven-level CHB inverter with IPD modulation.*

## 2.6 Conclusion

In this chapter, we have presented the main control strategies for multi-level inverters. Several strategies exist for controlling multi-level inverters. However, sinusoidal modulation and vector modulation (only for three-phase applications) are currently the most commonly used methods in industrial applications.

# 3. Simulation and Implementation

## 3.1 Intoduction

This practical section details the simulation of a 5-level inverter using MATLAB Simulink and its subsequent implementation with real components. The objective is to validate the theoretical concepts through practical application and demonstrate the feasibility and performance of the designed inverter. The practical work involves setting up the simulation environment, designing the control system, assembling the hardware, and thoroughly testing the inverter.

### 3.1.1 Matlab

MATLAB (an abbreviation of "MATrix LABoratory") is a proprietary multi-paradigm programming language and numeric computing environment developed by MathWorks. MATLAB allows matrix manipulations, plotting of functions and data, implementation of algorithms, creation of user interfaces, and interfacing with programs written in other languages.

Although MATLAB is intended primarily for numeric computing, an optional toolbox uses the MuPAD symbolic engine allowing access to symbolic computing abilities. An additional package, Simulink, adds graphical multi-domain simulation and model-based design for dynamic and embedded systems.

### 3.1.2 Simulink

Simulink is a MATLAB-based graphical programming environment for modeling, simulating and analyzing multidomain dynamical systems. Its primary interface is a graphical block diagramming tool and a customizable set of block libraries. It offers tight integration with the rest of the MATLAB environment and can either drive MATLAB or be scripted from it. Simulink is widely used in automatic control and digital signal processing for multidomain simulation and model-based design.

## 3.2 Simulation in MATLAB Simulink setup

The simulation setup involves designing a 5-level inverter in MATLAB Simulink. The setup includes various components such as a DC power supply, submodules, a control system, and a load.

### 3.2.1 Detailed Design

- **DC Power Supply:** A stable DC voltage source is modeled to provide the input voltage necessary for the inverter operation.

- **Submodules:** Each arm of the inverter contains three submodules. Each submodule includes:
- **Capacitors:** Used for energy storage and voltage balancing.
- **IGBTs:** Serve as the switching elements.

- **Control System:** The control system employs a level-shifted PWM technique, generating switching signals for the IGBTs to produce the desired output waveform.

- **Load:** An RL load is used to test the inverter's performance under various conditions.

### 3.2.2 Pulse Width Modulation (PWM) Technique

PWM is a widely used technique in power electronics to control the output voltage of inverters. In this project, a level-shifted PWM technique is implemented to achieve a 5-level output. Setup of PWM technique includes carrier signals, mudulating signal(refrence) and switching strategy:

- **Carrier Signal:** A high-frequency triangular wave to act as the carrier signal.

- **Reference Signal:** A sinusoidal reference signal representing the desired output waveform.

- **Comparator:** A comparator block to generate PWM signals by comparing the reference signal with the carrier signal.

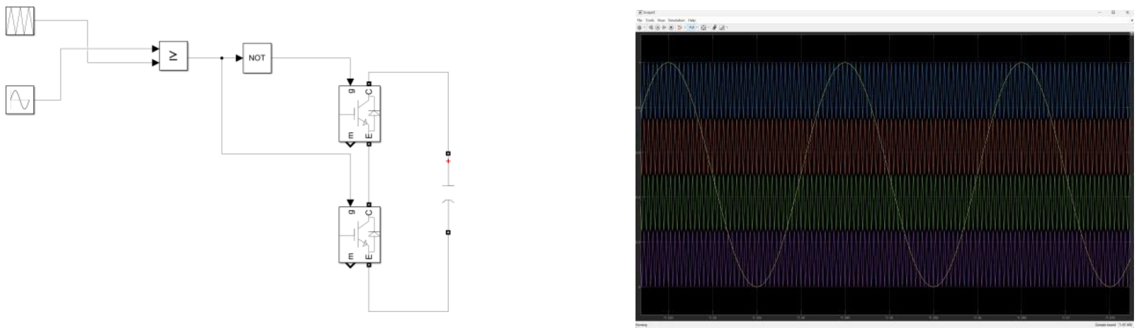


Figure 19. *Level shifted PWM technique.*

## 3.3 Pwm modulation signals

Here are the results of the Pulse Width Modulation (PWM) signals, derived from the comparison between the sinusoidal reference waveform and four carrier signals. The sinusoidal reference waveform serves as the desired output signal, while the four carrier signals, typically triangular or sawtooth waveforms, are used to generate the PWM signals.

This comparison process involves each carrier signal being compared to the sinusoidal reference at every instant in time. When the reference signal is greater than a carrier signal, a high PWM signal (1) is generated; otherwise, a low PWM signal (0) is produced.

In this setup, we have four outputs corresponding to the four carrier signals. Each output represents the PWM signal generated from the comparison of the reference waveform with one of the carriers. These four PWM signals are then used to control the switches in the power converter, enabling it to produce a multi-level voltage waveform. This multi-level approach enhances the quality of the output waveform by reducing harmonic distortion and improving the resolution of the voltage steps. As a result, the synthesized output more accurately follows the desired sinusoidal waveform, leading to better performance and efficiency in the power conversion system.

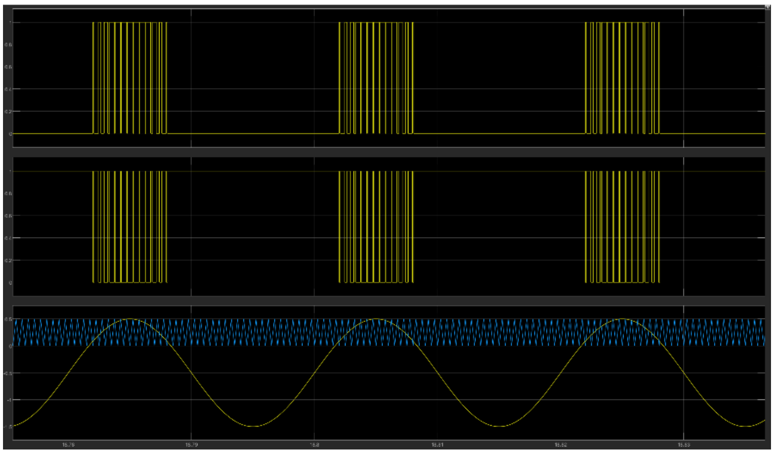

Figure 20. *PWM signal of first submodule.*

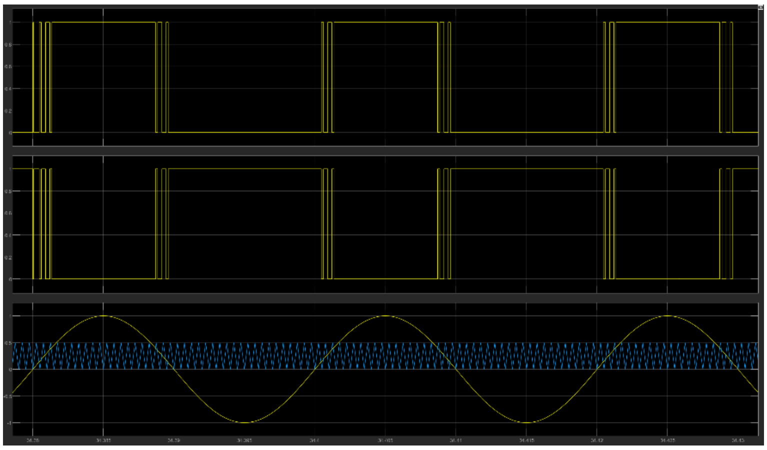

Figure 21. *PWM signal of second submodule.*

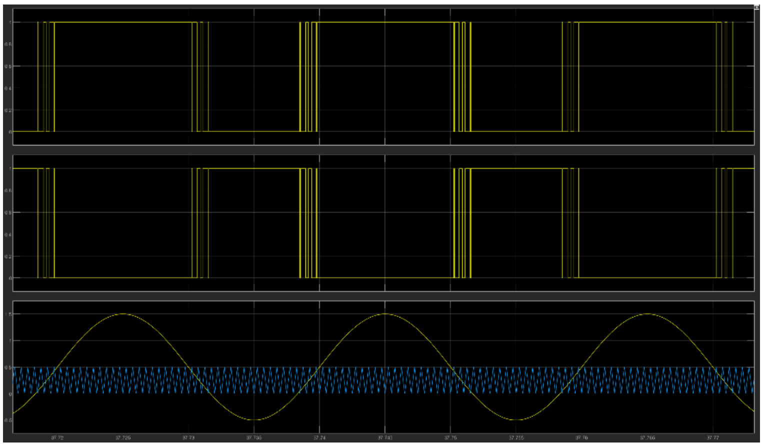

Figure 22. *PWM signal of third submodule.*

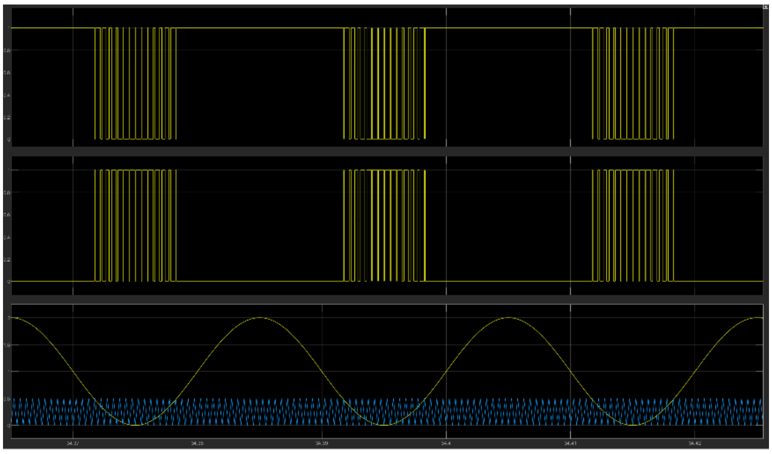

Figure 23. *PWM signal of fourth submodule.*

### 3.3.1 Parameter Settings

The simulation parameters were carefully chosen to match the real hardware specifications:

- **Switching Frequency:** Set to 10 kHz to balance efficiency and harmonic performance.
- **DC Link Voltage:** 200V, consistent with the hardware setup.
- **Capacitors:** 220 microfarad capacitors for energy storage and voltage balancing within the submodules.
- **Inductance (L_arm):** 2.5 microhenry to represent the arm inductance of the inverter.
- **Load Parameters:** Resistance (R_load) of 500 ohms to reflect typical load conditions.

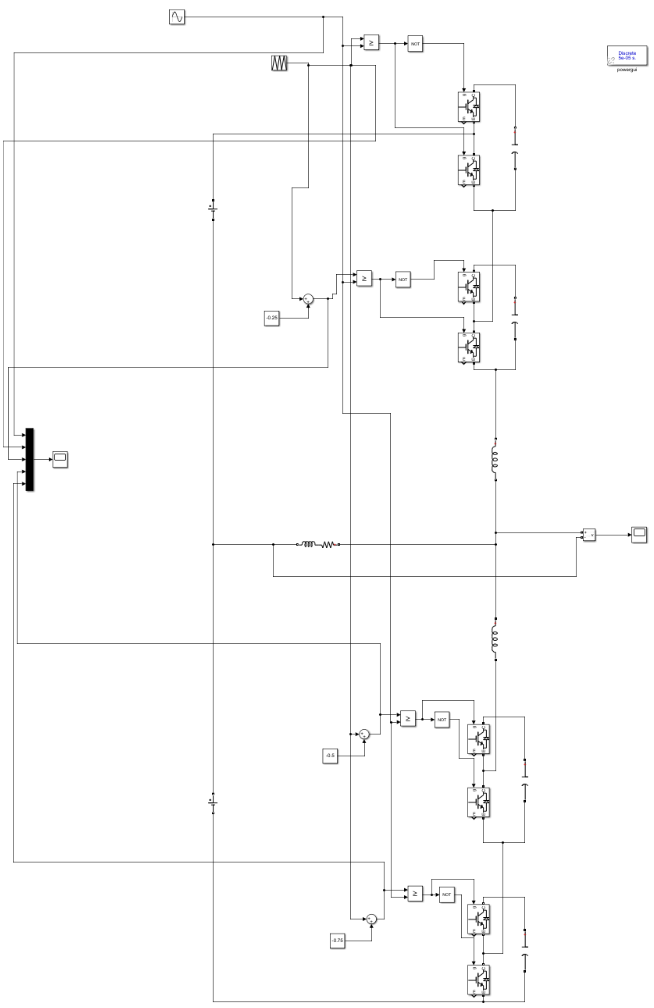

Figure 24. *Simulation of 5-level inverter.*

## 3.4 Simulation results

### 3.4.1 Output Voltage Waveform

The output voltage waveform was analyzed for different operating conditions. Key observations included:

- **Waveform Shape:** The 5-level stepped waveform closely matched the theoretical expectations, showing distinct voltage levels corresponding to the switching states.

- **Amplitude:** The peak voltage reached the expected values based on the DC link voltage and modulation technique.

- **Frequency:** The output frequency was consistent with the reference signal, ensuring proper operation of the inverter.

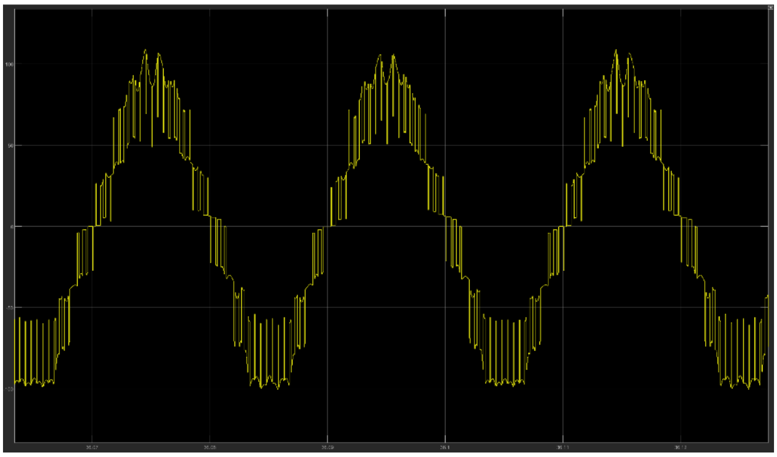

Figure 25. *Output Voltage Waveform.*

## 3.5 Implementation with Real Components

### 3.5.1 Control System

**Nucleo F429ZI development board:**

The Nucleo F429ZI development board, designed by STMicroelectronics, features the STM32F429ZI microcontroller based on the ARM Cortex-M4 core, operating at up to 180 MHz with 2 MB Flash memory and 256 KB SRAM. It is Arduino Uno V3 compatible, offering easy expansion with a wide range of shields, and includes an ST Zio connector for additional I/O options.

The board features an integrated ST-LINK/V2-1 debugger/programmer, USB OTG connector, Ethernet connectivity, and flexible power supply options. User interface elements include three LEDs, a user button, and a reset button. With multiple communication interfaces, analog inputs/outputs, and expansion headers, the Nucleo F429ZI is suitable for a variety of applications including IoT, industrial automation, and signal processing, providing a robust platform for rapid prototyping and development of embedded systems.

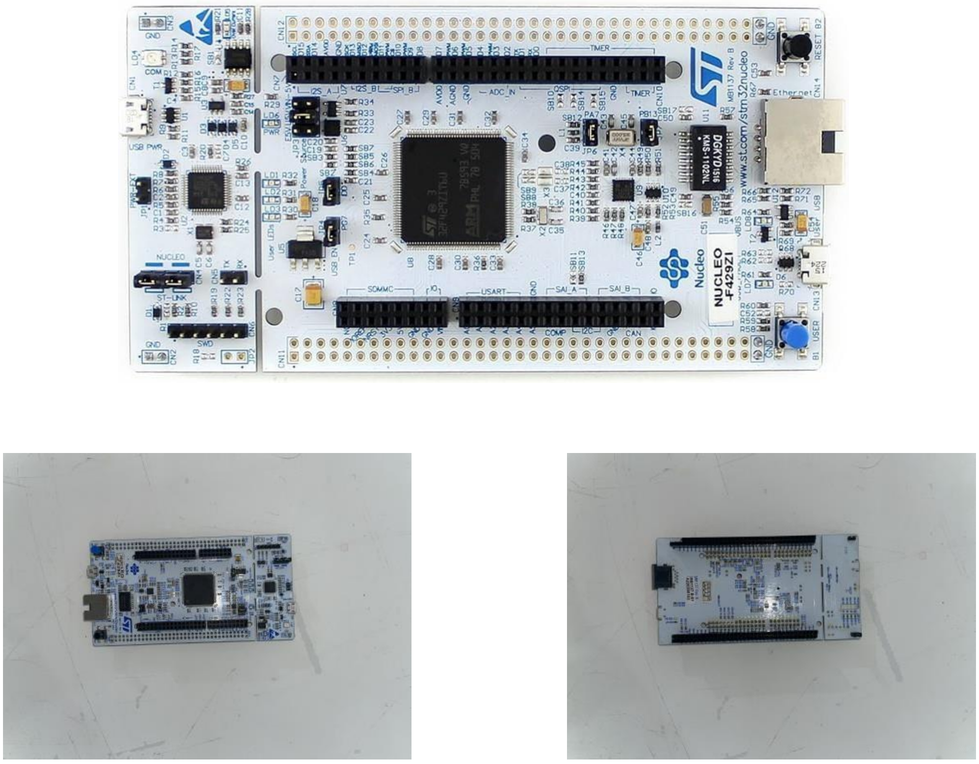

Figure 3.26. *Nucleo F429ZI microcontroller.*

**Microcontroller Programming:**

The Nucleo F429ZI microcontroller was programmed to generate the PWM signals for the IGBTs based on the desired modulation technique. The programming was done using an IDE such as STM32CubeIDE. Additionally, STM32CubeMX was used to configure the peripherals of the Nucleo F429ZI, such as timers and GPIOs, to facilitate the PWM signal generation.

For the PWM generation, channels 1, 1N, 3, and 3N of timer 1 and channels 1, 1N, 3, and 3N of timer 8 were used. The specific pins utilized were PE9, PE8, PB1, PB13, PA5, PC8, PB15, and PC8 respectively. These configurations were set in STM32CubeMX to ensure proper output for the PWM signals.

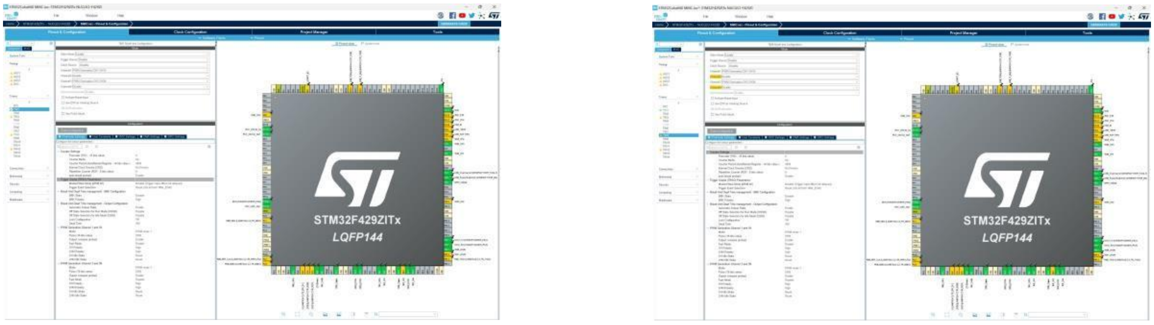


Figure 3.27. *Configuration of TIM1 and TIM8.*

**IGBT drivers:**

IGBT drivers are crucial components in power electronics, serving as the interface between control circuitry and high-power IGBTs.

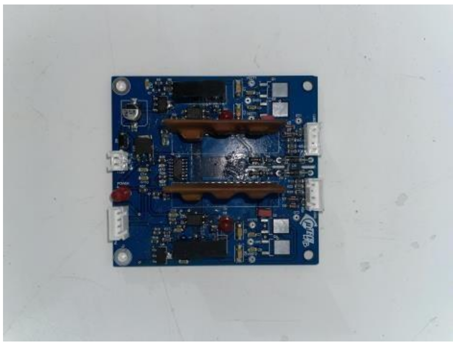

Figure 3.28. *IGBT Drivers.*

They provide the necessary signals to switch IGBTs rapidly and efficiently, converting input signals from +15V to -5V for effective IGBT control. As we can see here in IGBT driver output of a signal and its negative.This conversion is essential as IGBTs require a negative voltage to turn on and a positive voltage to turn off.

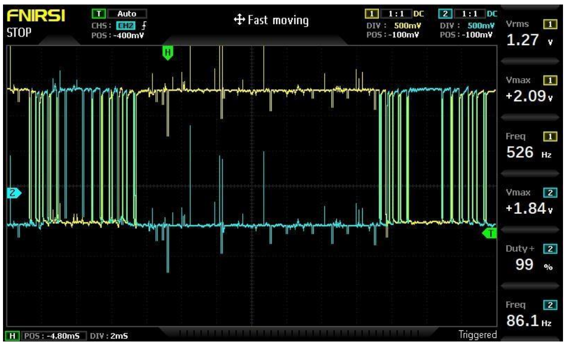


Figure 3.29. *Output voltage of IGBT Drivers.*

IGBT drivers ensure safe operation by offering electrical isolation and managing gate charge and discharge. They also include protection features like overcurrent and over-voltage protection, enhancing system reliability in applications such as motor drives, inverters, and power supplies. Overall, IGBT drivers play a critical role in improving the performance, efficiency, and reliability of power electronic systems.

**Simulink Integration:**

MATLAB Simulink was used to design the control algorithms and generate the code for the microcontroller. The workflow involved:

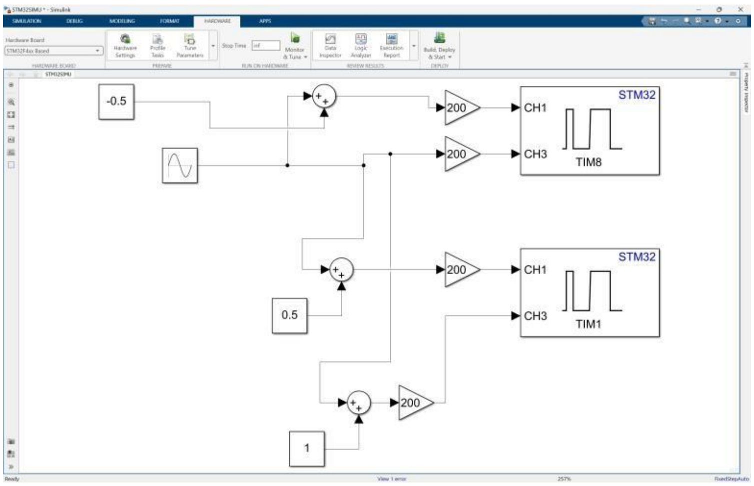


Figure 3.30. *Simulink model of the two Timers.*

- **Simulink Model:** A Simulink model was created to design the control algorithm and PWM generation logic. The model included two PWM output blocks to simulate the two timers (timer 1 and timer 8) used in the microcontroller.

- **Code Generation:** The Simulink model was used to automatically generate the C code required for the microcontroller.

- **STM32CubeMX Configuration:** STM32CubeMX was used to configure the necessary peripherals, including timers, GPIOs, and ADCs.

- **Integration:** The generated code was integrated with the STM32CubeMX project, ensuring that the PWM signals were correctly generated and controlled.

**Output signals of control system:**

From the IGBT driver, we have four sets of output signals, with each set comprising a signal and its inverse (negative). These signals are then distributed to control the eight IGBTs in the system, providing precise and synchronized switching commands for efficient power conversion.

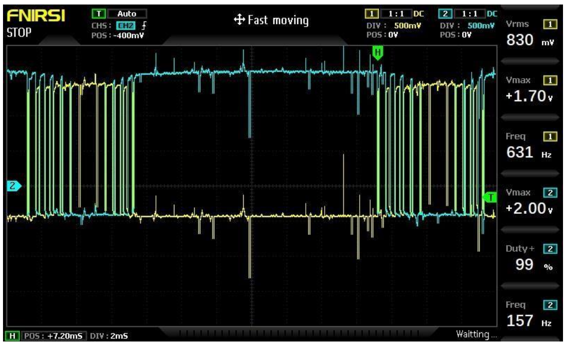


Figure 3.31. *Output voltage of IGBT driver 1.*

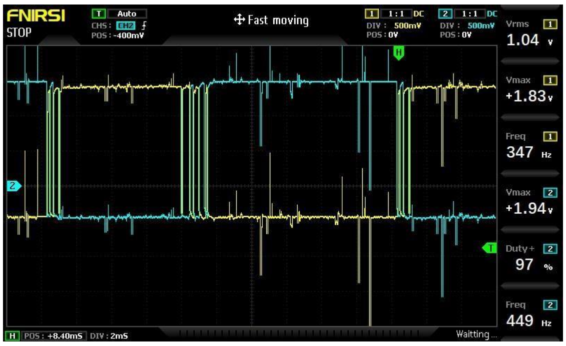


Figure 3.32. *Output voltage of IGBT driver 2.*


Figure 3.33. *Output voltage of IGBT driver 3.*

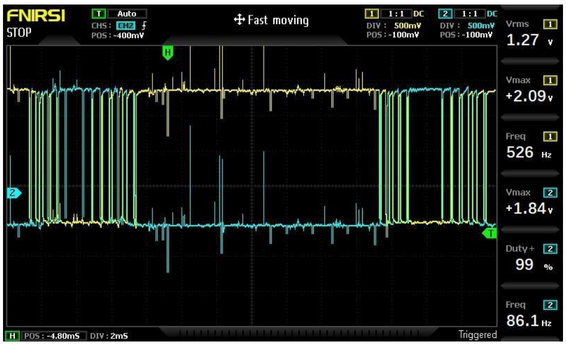


Figure 3.34. *Output voltage of IGBT driver 4.*

### 3.5.2 Hardware Design

For the hardware implementation, the following components were used:

- **IGBTs:** 8 GT60M303 IGBTs were selected for their high efficiency and reliability.

Figure 3.35. *GT60M303 IGBTs.*

- **PCB Boards:** 4 single-sided PCB boards were designed to house the submodules and control circuitry. The single-sided PCB boards were designed to accommodate the components and the wiring required for the inverter. The design ensured proper layout and spacing for minimal noise and interference.

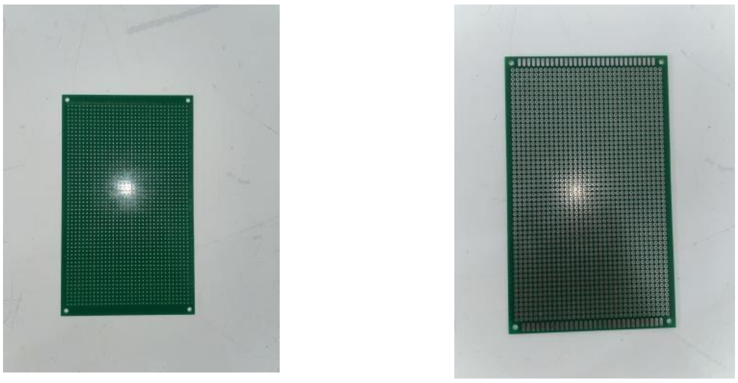

Figure 3.36. *PCB Board.*

- **Cooling System:** An aluminum cooler was employed to manage the heat dissipation of the IGBTs.

Figure 3.37. *An aluminum cooler.*

- **Oscilloscope:** An oscilloscope was used for measuring and analyzing the output voltage waveform.

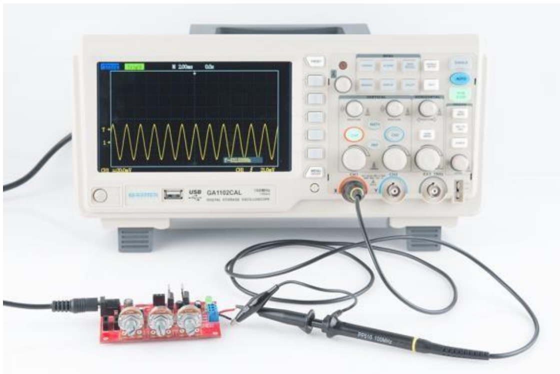

Figure 3.38. *Oscilloscope.*

- **Capacitors:** 220 microfarad capacitors rated at 500V were used for energy storage and voltage balancing within the submodules.

Figure 3.39. *220 microfarad capacitor.*

- **Inductor:** An additional inductor of 25 microhenry was added to the circuit.

Figure 3.40. *Inductor*.

- **Load:** An RL load of 50 ohms with a variable inductor was incorporated into the design.

Figure 3.41. *RL Load*.

- **DC Sources:** Two 32V DC sources were used for alimentation of the submodules, providing the necessary power for the converter's operation. Additionally, a 12V DC source was used for alimentation of the IGBT drivers, ensuring proper operation of the control circuitry.


Figure 3.42. *DC sources.*

**Implentation:**

In the implementation of the 5-level modular multilevel converter, several key steps were undertaken to assemble and integrate all components seamlessly. The IGBTs were strategically placed on an aluminum cooler to ensure efficient heat dissipation. Four submodules were meticulously designed, with each submodule comprising two IGBTs connected in series from the emitter of the first to the collector of the second, and each submodule connected to a capacitor for energy storage. The interconnection of the submodules from the two arms was carefully executed, linking the emitter of the second IGBT of submodule 1 to the collector of the second IGBT of submodule 2.

Two 32V DC sources were employed, with one connected to the collector of the first submodule and the second connected to theemitter of the second submodule of the lower arm, both sources grounded together. Additionally, two inductors were strategically placed between the two arms for current balancing and filtering purposes.

The creation of the four submodules was facilitated by PCB cards, where wires were welded to ensure secure and insulated connections.

Over- all, the implementation was conducted with meticulous attention to detail, ensuring the converter's functionality and performance under various operating conditions.

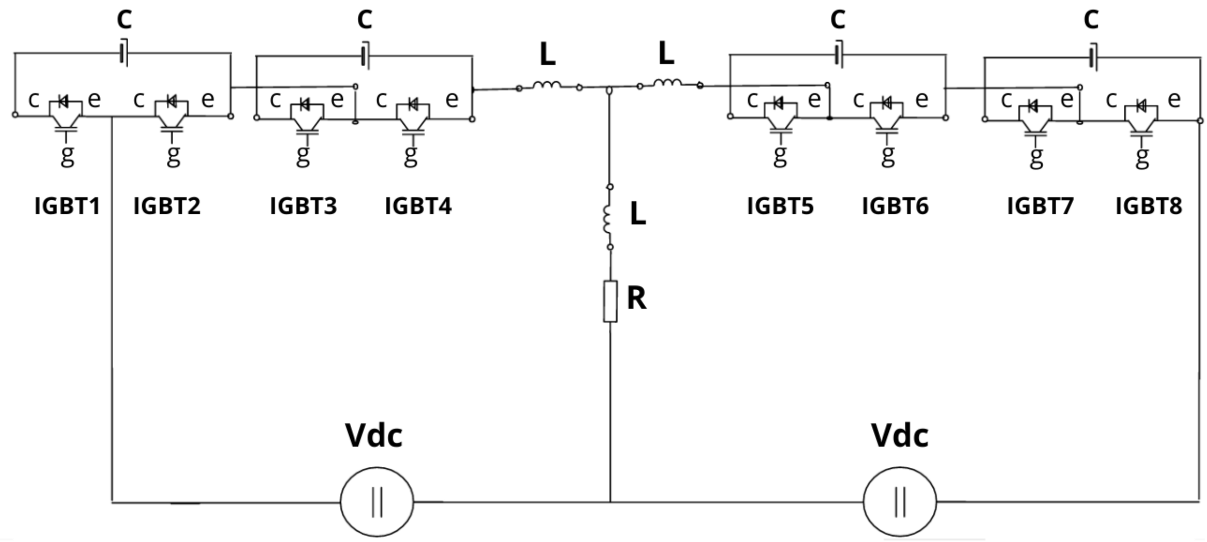


Figure 3.43. *Power circuit diagram.*

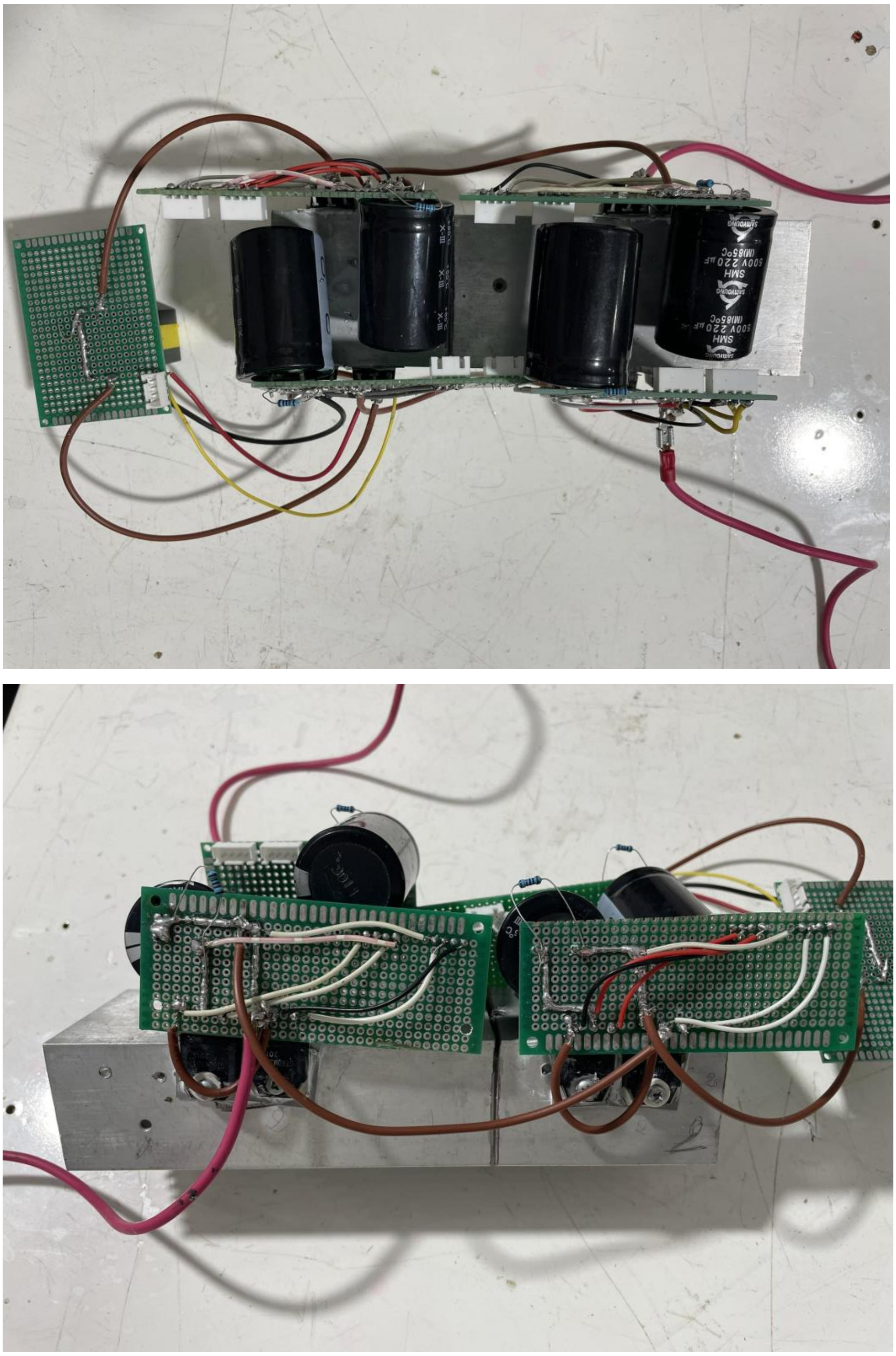

Figure 3.44. *Power circuit.*

**Outputs of the implementation:**

In the comprehensive evaluation of the 5-level modular multilevel converter, meticulous attention was given to measuring and analyzing the output voltage and current characteristics across a range of operational frequencies. The converter's performance was scrutinized at four distinct switching frequencies: 1 kHz, 2 kHz, 10 kHz, and 20 kHz.

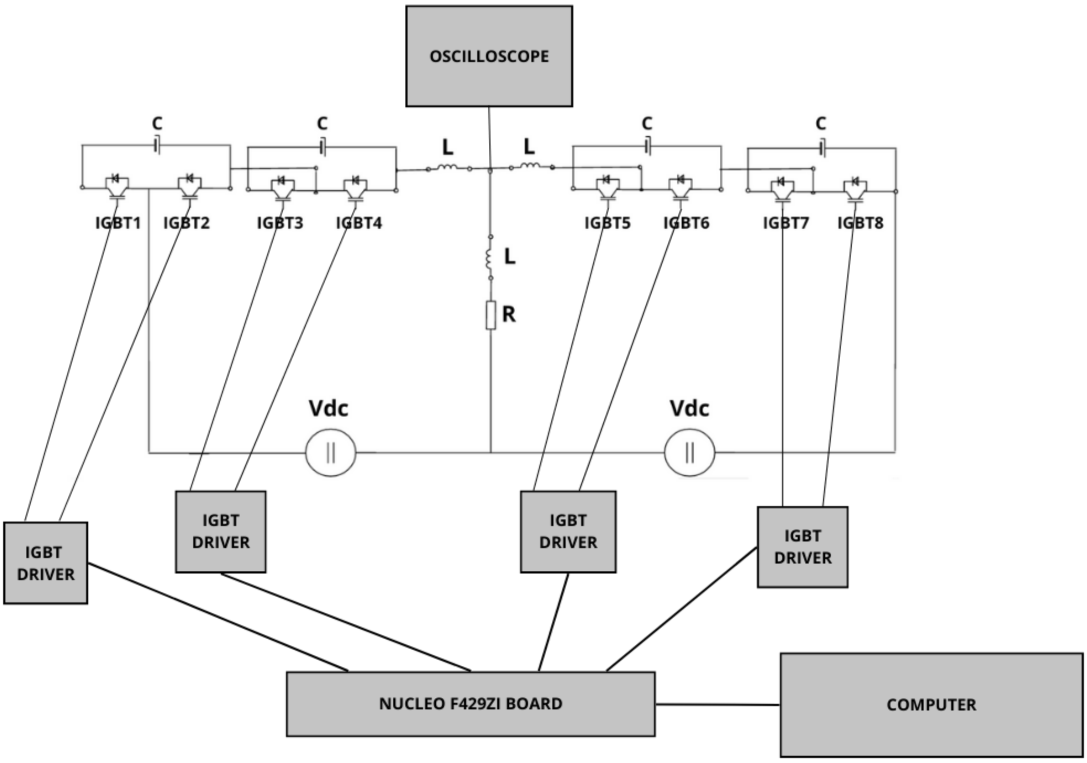


Figure 3.45. *Implementation diagram.*

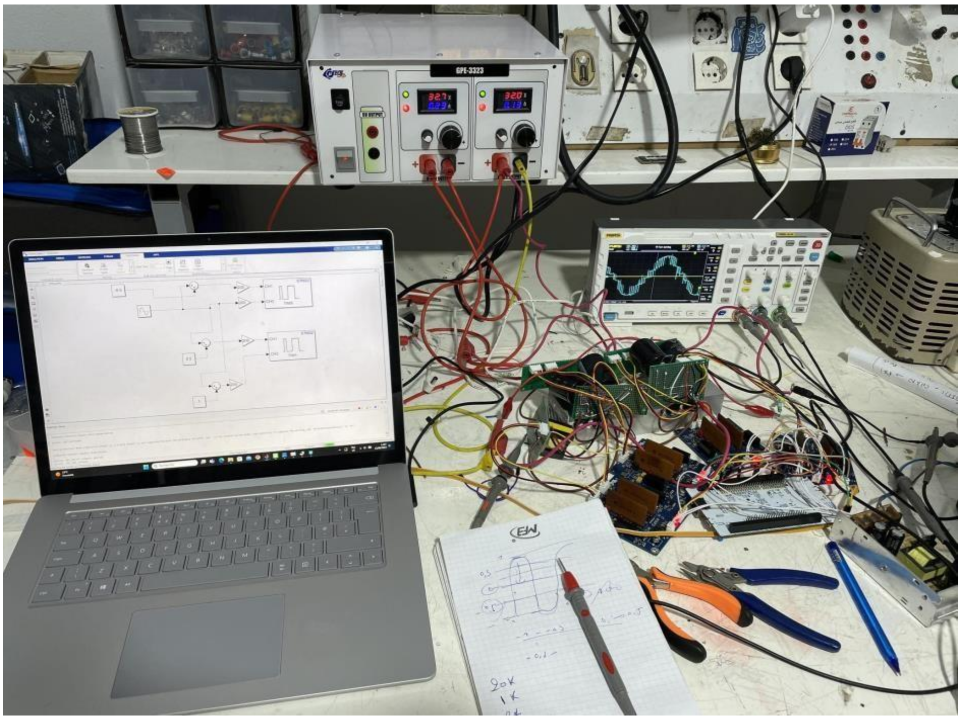

Figure 3.46. *Implementation.*

The examination revealed intriguing trends in the output voltage waveforms, showcasing a remarkable evolution as the switching frequency escalated. At lower frequencies, the waveform exhibited distinct steps, indicative of the multilevel converter's operation. However, with each increment in frequency, the waveform gradually transformed into a smoother curve, indicating enhanced voltage regulation and reduced harmonic content. This evolution underscores the converter's ability to deliver stable and precisely controlled output voltages across a broad spectrum of operational frequencies, signifying its versatility and efficiency in various power conversion applications.

Moreover, the reduction in harmonic distortion with increased switching frequency highlights the improved power quality achievable with this design. At lower frequencies, the stepped waveform can lead to significant harmonic content, causing issues like overheating, electromagnetic interference, and reduced efficiency. However, as the frequency increases, the harmonic content diminishes, resulting in a cleaner output voltage. This not only enhances performance but also minimizes potential adverse effects on connected loads and the broader power system.

Additionally, the efficiency of the converter improves with higher switching frequencies, primarily due to reduced harmonic filtering losses and more effective utilization of switching devices. The IGBTs switch more efficiently at higher frequencies, reducing switching losses and contributing to overall performance.

These findings validate the design and implementation of the 5-level modular multilevel converter, confirming its potential for high-performance power conversion in a wide range of applications. From renewable energy systems to industrial motor drives, this converter's ability to deliver clean, efficient, and stable power makes it an invaluable asset in advanced power electronics solutions.

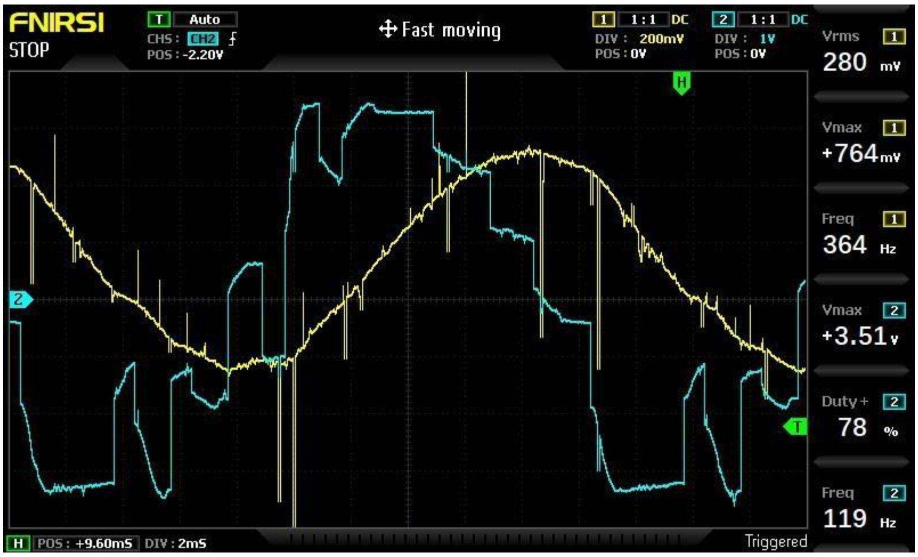

Figure 3.47. *Output voltage and current for f= 1K.*

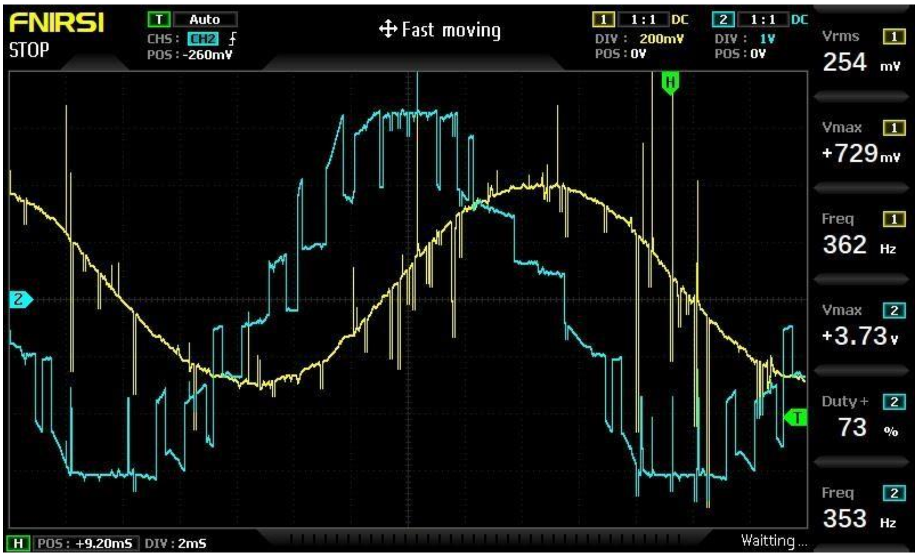


Figure 3.48. *Output voltage and current for f= 2k.*

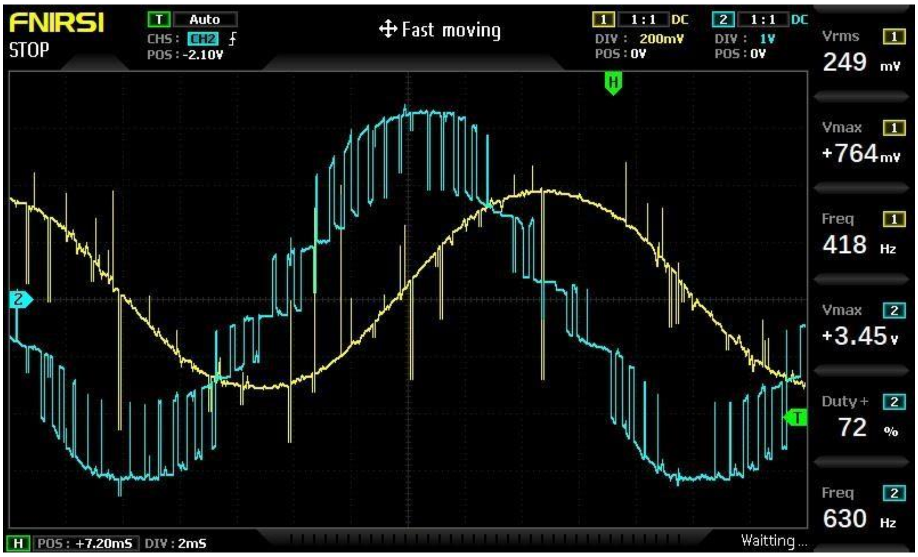


Figure 3.49. *Output voltage and current for f= 10K.*

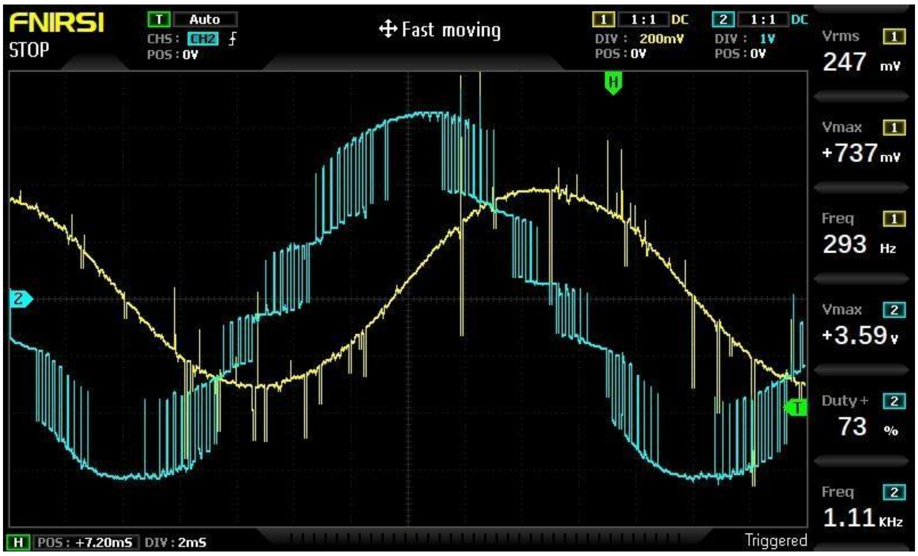


Figure 3.50. *Output voltage and current for f= 20K.*

The analysis of the output current waveforms mirrored the trends observed in the voltage waveforms, further validating the converter’s robust performance characteristics. As the switching frequency increased, the current waveforms exhibited similar smoothing effects, indicating improved current regulation and waveform quality. These findings underscore the converter’s capacity to deliver consistent and reliable output currents, essential for applications requiring precise power delivery and control. Overall, the thorough evaluation of the output voltage and current characteristics demonstrates the effectiveness and adaptability of the 5-level modular multilevel converter, positioning it as a compelling solution for diverse power conversion requirements.

# Conclusion

## 3.6 Conclusion

In conclusion, the implementation of the 5-level modular multilevel converter (MMC) has been a comprehensive and rewarding endeavor, contributing significantly to the field of power electronics. The project successfully combined theoretical knowledge with practical implementation, showcasing the importance of proper component selection, circuit design, and control strategy. Through meticulous testing and analysis, the converter demonstrated its ability to generate stable output voltages and currents at various switching frequencies. The use of advanced components such as the GT60M303 IGBTs and the Nucleo F429ZI microcontroller, along with innovative cooling solutions, has ensured the converter's reliability and efficiency. The project has not only provided valuable insights into the operation and optimization of MMCs but has also laid the foundation for future research and development in the field of power electronics. Overall, the successful implementation of the 5-level MMC highlights its potential for use in a wide range of high-power applications, underscoring its significance in the pursuit of efficient and sustainable energy solutions.

## 3.7 Future Work

While the implementation of the 5-level modular multilevel converter (MMC) has been a significant achievement, there are several areas for future exploration and improvement:

- **Higher Voltage Ratings:** Investigate the feasibility of scaling up the converter to handle higher voltage ratings, enabling its use in high-voltage applications such as renewable energy systems and electric vehicles.
- **Advanced Control Strategies:** Explore advanced control strategies, such as predictive control or model predictive control (MPC), to further enhance the converter's performance in terms of efficiency and waveform quality.
- **Fault Tolerance and Protection:** Enhance the converter's fault tolerance and protection mechanisms to ensure reliable operation under various fault conditions, improving its overall reliability and safety.
- **Modular Design:** Develop a more modular design approach for the converter, allowing for easier scalability and maintenance, as well as the ability to easily integrate with other power electronics systems.

- **Integration of Energy Storage:** Investigate the integration of energy storage devices, such as batteries or supercapacitors, to enhance the converter's performance in terms of energy efficiency and grid stability.
- **Grid Integration:** Explore the integration of the converter into smart grid systems, enabling better integration of renewable energy sources and improving grid stability and reliability.
- **Cost Optimization:** Investigate methods to optimize the cost of the converter, such as using alternative components or manufacturing techniques, without compromising its performance and reliability.

Overall, these future works aim to further enhance the performance, reliability, and efficiency of the 5-level MMC, making it a more viable and attractive solution for a wide range of high-power applications.

# References


[1] “https://elec13.wordpress.com/2016/03/05/les-convertisseurs-statiques/”. In.

[2] Wikipedia contributors. *Power inverter — Wikipedia, The Free Encyclopedia*. [Online; accessed 4-May-2024]. 2024. URL: https://en.wikipedia.org/w/index.php?title=Power_inverter&oldid=1221908941.

[3] M. Ben Ahmed B M.Chelbi F. “implémentation sur DSP F28335 des stratégies de commande des convertisseurs DC/AC)”. In: *Conference proceedings*. University of Bejaia. 2018, pp. 1–97.

[4] Surin Khomfoi and Leon M. Tolbert. “Chapter 31 : Multilevel Power Converters”. In: The University of Tennessee.

[5] Gen Li and Jun Liang. “Modular Multilevel Converters: Recent Applications [History]”. In: *IEEE Electrification Magazine* 10.3 (2022), pp. 85–92. DOI: 10.1109/MELE.2022.3187886.

[6] Kambiz Arab Tehrani. “Conception, Synthèse et Application d’une Nouvelle Commande Robuste par PID Fractionnaire pour Les Onduleurs Multiniveaux”. PhD thesis. Institut National Polytechnique de Lorraine, 2010.

[7] Taouech Soulef. “Commande et realisation d’un convertisseur multiniveaux”. In: *Conference proceedings*. Université de Blida. 2020, pp. 1–58.

[8] M.D. Manjrekar, P. Steimer, and T.A. Lipo. “Hybrid multilevel power conversion system: a competitive solution for high power applications”. In: *Conference Record of the 1999 IEEE Industry Applications Conference. Thirty-Forth IAS Annual Meeting (Cat. No.99CH36370)*. Vol. 3. 1999, 1520–1527 vol.3.

[9] M. Yaïchi A. Mammeri. “Structure des onduleurs multiniveaux asymétriques "Applications aux systèmes photovoltaïques"”. In: *Conference proceedings*. CDER, Adrar. 2011.

[10] C. De Almeida Martins. “Controle direct du couple d’une machine asynchrone alimentée par convertisseurs Multi-niveaux à fréquence imposée”. In: *Thèse de doctorat*. INPde Toulouse. 2000.

[11] R. Bayindi H. Colak E. Kabalci. “Review of multilevel voltage source inverter topologies and control schemes”. In: Elsevier. 2011.

[12] J. Rodriguez, Jih-Sheng Lai, and Fang Zheng Peng. “Multilevel inverters: a survey of topologies, controls, and applications”. In: *IEEE Transactions on Industrial Electronics* 49.4 (2002), pp. 724–738. DOI: 10.1109/TIE.2002.801052.

[13] Wu Bin. *HIGH-POWER CONVERTERS AND AC DRIVES*. 2006.