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Par

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**Contribution à la commande avancée des convertisseurs matriciels multi-niveaux modulaires**

**Contribution to advanced control of modular multilevel matrix converters**

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# Dedication

I have the honor of dedicating this work:

To my very dear parents, may Allah keep them and protect them for their moral and financial support, for their encouragement and the sacrifices they have endured.

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# List of Nomenclature

Symbol	Definition
MC	Matrix Converter
MMC	Modular Multilevel Converter
MMMC	Modular Multilevel Matrix Converter
MMMC-FC	Modular Multilevel Matrix Converter with Three Flying Capacitors
$I_o$	Output load current
$p$	Number of cells per output phase
$f_{sw}$	Switching frequency
$\Delta V_c$	Voltage ripple of the capacitor clamped
$V_{c1}, V_{c2}, \dots, V_{c9}$	Voltage across capacitors C1 to C9 in the flying capacitor
$T_{sw}$	Carrier switching period ( $1/f_{sw}$ )
$\Delta V$	Voltage deviation or ripple
SVM	Space vector modulation
$C_1, C_2, \dots, C_9$	Flying capacitors
$R_f, L_f, C_f$	Parameters of the RLC output filter (Resistance, Inductance, Capacitance)
$V_{im}$	Input voltage
$f_i$	Input frequency
$f_o$	Output frequency
$q$	ratios
$\theta$	Angle used in modulation functions
pwm	Pulse width modulation signal used for switch control
IAB, IAC	Input currents for different phases
$t_{Aa1}, t_{Aa2}$	Switching time for the bidirectional switches in the first group
$V_{saw1}, V_{saw2}$	Sawtooth carrier signals used for modulation
$S_{ij1}, S_{ij2}$	Groups of switches used in phase control
M	Modulation function

# **General Introduction**

## General Introduction

The growing need for efficient, reliable, and scalable power conversion systems has driven significant advancements in power electronics. One of the most promising technologies in this field is the modular multilevel matrix converter (MMMC)[1]. This converter integrates the benefits of matrix converters (MC), known for direct AC-AC conversion without intermediate energy storage, and MMC, which excel in scalability and harmonic reduction. These features make MMMCs ideal for high-performance applications, such as renewable energy systems, industrial motor drives, and transportation [2].

Despite their advantages, MMMCs face several challenges, including complex control strategies, harmonic distortion, and reliability concerns due to the increased number of components [3]. This thesis aims to address these challenges by proposing advanced control strategies. By focusing on enhancing power quality, operational efficiency, and system reliability, this work contributes to the advancement of MMMCs for modern industrial and energy systems.

The field of power electronics has revolutionized energy conversion technologies, enabling efficient power management across diverse applications. Among the innovations, matrix converters (MCs) introduced direct AC-AC conversion, eliminating the need for bulky intermediate DC-link capacitors. This compact and efficient design makes MC a preferred choice for applications requiring bidirectional power flow and high-quality sinusoidal output[4]. Building upon this, MMMC brought scalability and harmonic reduction, particularly for medium- and high-voltage applications.

The MMMC combines the advantages of both technologies. Its modular structure allows for increased voltage levels, improved power quality, and reduced voltage stress on components. However, the complex control requirements, harmonic issues, and reliability challenges demand innovative solutions. This thesis explores these aspects by developing advanced control strategies that enhance the performance of MMMC in high-power applications [5].

## Background

## General Introduction

Matrix converters, introduced in the 1970s, provided a groundbreaking approach to direct AC-AC conversion. Unlike conventional converters, matrix converters achieve bidirectional power flow without intermediate energy storage, reducing size and improving efficiency. Over the years, MMC extended this concept, enabling multilevel voltage outputs with superior harmonic performance. The integration of MMC with matrix converters gave rise to MMMC, which are now pivotal in applications like renewable energy systems, industrial drives, and grid-level energy management.[6]

MMMCs have gained popularity for their ability to deliver high-quality power, improve efficiency, and operate in high-voltage environments. However, challenges such as harmonic distortions, complex modulation, and control strategies have limited their widespread adoption. Addressing these challenges is crucial to unlocking the full potential of MMMC in modern power systems.

### Research Problem

While MMMC exhibit significant advantages over traditional converters MC, their deployment in real-world scenarios faces several critical challenges:

1. **Harmonic Distortion:** High-frequency switching introduces harmonic distortions that degrade power quality and may cause interference with connected devices.
2. **Control Complexity:** The need for precise modulation and switching control across multiple levels of MMMC increases computational and algorithmic complexity.
3. **Thermal Management:** The large number of components operating at high power levels generates considerable heat, necessitating efficient cooling mechanisms.
4. **System Reliability:** The modular design increases the risk of component failure, which can compromise overall system stability and reliability.

## General Introduction

This research focuses on overcoming these challenges by designing advanced control algorithms that improve harmonic performance, simplify control processes, the thesis aims to make MMCs more practical for industrial and renewable energy applications.

### Objectives of the Research

The primary objectives of this research are:

1. **Develop Advanced Control Algorithms:** Design improved control strategies to address harmonic distortion and ensure voltage balancing across submodules.
2. **Enhance Power Quality:** Minimize total harmonic distortion (THD) to achieve clean and stable sinusoidal output waveforms.
3. **Improve Efficiency:** Reduce switching losses and optimize thermal management to enhance overall system efficiency, because of the use of low frequency .
4. **Validate Proposed Strategies:** Use simulation tools like MATLAB/Simulink to test and validate the proposed control algorithms under various operational conditions.

These objectives align with the overarching goal of advancing MMC technology to meet the demands of modern energy systems.

### Methodology Overview

The research methodology follows a structured and systematic approach to achieve the outlined objectives:

#### Literature Review

A comprehensive review of existing matrix and modular multilevel converter technologies is conducted to identify their strengths, limitations, and gaps. Special attention is given to modulation techniques, control strategies, and harmonic reduction methods.

### Mathematical Modeling

Detailed mathematical models of MMCs are developed to describe their behavior under various operating conditions. These models incorporate advanced control algorithms to ensure accurate simulation and analysis.

### Control Design

The control strategies, focus on reducing harmonic distortion, balancing voltages, and improving overall efficiency. Techniques like space vector modulation (SVM) and enhanced sliding mode control (ESMC) are adapted to MMC systems.

### Simulation and Analysis

The models and control strategies are implemented in MATLAB/Simulink. Simulations are conducted to evaluate performance metrics such as THD, efficiency, and voltage balancing under different scenarios.

### Comparative Analysis

The proposed control methods are compared against existing techniques to highlight improvements in efficiency, reliability, and power quality.

### Significance of the Study

This research is significant for several reasons:

1. **Industrial Relevance:** The proposed solutions improve the efficiency and reliability of MMCs, making them suitable for high-performance industrial applications.
2. **Renewable Energy Integration:** Enhanced power converters facilitate the seamless integration of renewable energy sources into existing grids, supporting global sustainability goals.
3. **Technological Innovation:** The control strategies contribute to the advancement of power electronics, paving the way for future innovations in the field.

4. **Global Impact:** By addressing harmonic distortion and improving efficiency, this research supports efforts to develop sustainable energy systems with minimal environmental impact.

## **Thesis Structure**

The thesis is structured as follows:

### **General Introduction**

Provides an overview of the research, its significance, and the challenges addressed.

### **Chapter 1: Generalities of Modular Multilevel Matrix Converters**

Details the structure, principles, and applications of MMHCs, highlighting their advantages and limitations.

### **Chapter 2: A Comprehensive Study of Matrix Converters and a Comparative Analysis of Control Strategies**

Explores existing control and modulation techniques, analyzing their performance and limitations in MMHC systems.

### **Chapter 3: Modulation and Control Strategy of a Modular Multilevel Matrix Converter with three Flying Capacitor**

Presents the novel control algorithms developed in this research, emphasizing their design, implementation, and benefits.

### **Chapter 4: Advanced Techniques for Enhanced Performance of Modular Multilevel Matrix Converters with Flying Capacitors.**

Discusses the results of simulations conducted to validate the proposed strategies, comparing them with existing methods.

.

# **Chapter I: Generalities of MMMMC**

### I.1 Introduction

Matrix converters have emerged as a transformative innovation in direct power conversion (AC/AC), offering an advanced alternative to traditional converters. Unlike conventional designs, matrix converters are composed entirely of semiconductor devices and are often referred to as Direct Frequency Converters (DFC). These converters enable bidirectional power flow between the grid and the load, while providing precise control over the amplitude and frequency of the output voltage. This is achieved through a matrix configuration of bidirectional power switches, which directly connect  $n$  input phases to  $m$  output phases without the need for intermediate energy storage components, such as capacitors [2].

The MC has gained considerable attention in applications such as drive systems and variable-speed generation [4]. This is due to its numerous advantages, including compact design, high efficiency, reduced component count, and the capability for seamless bidirectional power exchange.

To address the increasing demand for higher performance, researchers have also developed MMMC, an extension of the classic topology. MMMC enhance the capabilities of conventional designs by introducing multiple voltage levels at the output, improving power quality, and reducing harmonic distortion. These multilevel topologies are particularly well-suited for high-power and high-voltage applications, where their ability to produce smoother waveforms and reduce switching losses provides significant advantages.

In this chapter, we provide a comprehensive overview of direct matrix converters, examining both the classic topology and the multilevel topology. We explore their fundamental operating principles, advantages, and key applications. Furthermore, we identify the specific configurations selected for detailed study in this work, focusing on a representative design from the classic topology and another from the multilevel topology.

## I.2 State of the art

In 1980, M. Venturini and A. Alesina first mentioned the term "matrix converter." They described the converter circuit, analyzed it, and defined the concept of the modulation matrix. They developed a control algorithm to calculate the conduction times of the switches based on the desired output waveform [2].

Starting in 1983, a series of works on the analysis and control of the MC was published. J. Rodriguez introduced the concept of a fictitious DC link to introduce MLI-based controls [3], which are widely used in the control of conventional AC-DC/DC-AC converters. Methods based on the fictitious link approach are called "indirect methods."

In 1985, J. Rodriguez and G. Kastner presented the analysis of the matrix converter using the concept of space vectors [3]. L. Huber and D. Borjovic developed a space vector modulation control four years later [4].

In parallel, in 1987 and 1989, G. Roy and G. E. April developed a new scalar control algorithm. More practical than Venturini's, it yields substantially similar results [5]. The determination of closing times, based on instantaneous values measured at the converter input and output, leads to a more robust modulation but requires a fast processing unit [5], [6].

Other work on the development of control algorithms has also been carried out [7] [8] and can be classified into two families: scalar algorithms and vector algorithms.

Since 1990, studies have primarily focused on optimizing the performance of electromechanical systems powered by a MC [9], [10], reducing the number of switch used in the converter [11], and providing solutions to the drawbacks of a matrix converter, namely the limitation of the voltage ratio [12], and operation in unbalanced conditions [13].

One of the determining factors for ensuring the commercial future of the MC lies in solving the problems encountered during switching between two cells. To ensure reliable and robust operation, so-called "step-by-step" methods have emerged. By

modifying the control algorithm, these methods achieve switching by passing through states that do not involve short circuits or open circuits [7], [14].

Currently, MC are still in a development phase and are attracting increasing interest in AC/AC conversion due to the high power density of the device and the adaptability of its control.

The next steps in its evolution will focus on improving its reliability, reducing manufacturing costs, and developing a true bidirectional semiconductor device [15].

### I.3 Matrix converter

A matrix converter is a direct AC-AC power converter made up of bidirectional semiconductor switches. The matrix structure of these bidirectional switches allows each output phase to be connected to any input phase.

The output waveforms vary in both frequency and amplitude and are constructed based on a principle of sampling the input signals.

The matrix converter possesses several operational qualities, some of which are highlighted. The load current is sinusoidal and the source current contains only high-order harmonics, multiples of the sampling frequency [16].

There are two types of matrix converters: the direct converter, which we will develop and study later, and the indirect converter. The use of bidirectional switches allows power flow from the source to the load and vice versa from the load to the source.

#### I.3.1 Indirect MC

The indirect converter is composed of a rectifier, an inverter, and an intermediate circuit, where an inductor or capacitor acts as an energy storage element. This type of circuit, widely used since the 1970s, is very common [17].

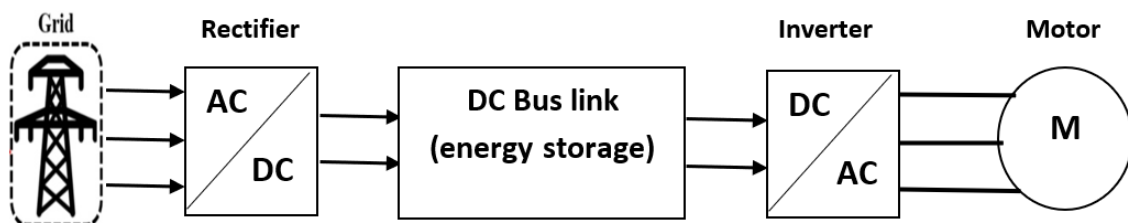


Figure I. 1: structure of an indirect converter

### I.3.2 Direct matrix converter

The conversion is carried out in a single stage as we convert an alternating input quantity into an alternating output quantity. An energy storage element is not necessary

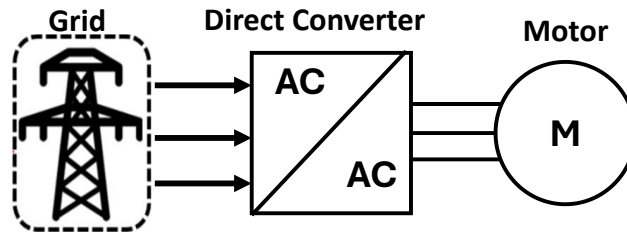


Figure I. 2: Structure of a direct converter

### I.4 Structure of the matrix converter

Most matrix converters are three-phase to three-phase, typically connecting a three-phase network voltage source to current load. They are therefore composed of nine bidirectional current and voltage switches connected in such a way that any phase of the source can be connected to any phase of the load, as shown in Figure 1-3.

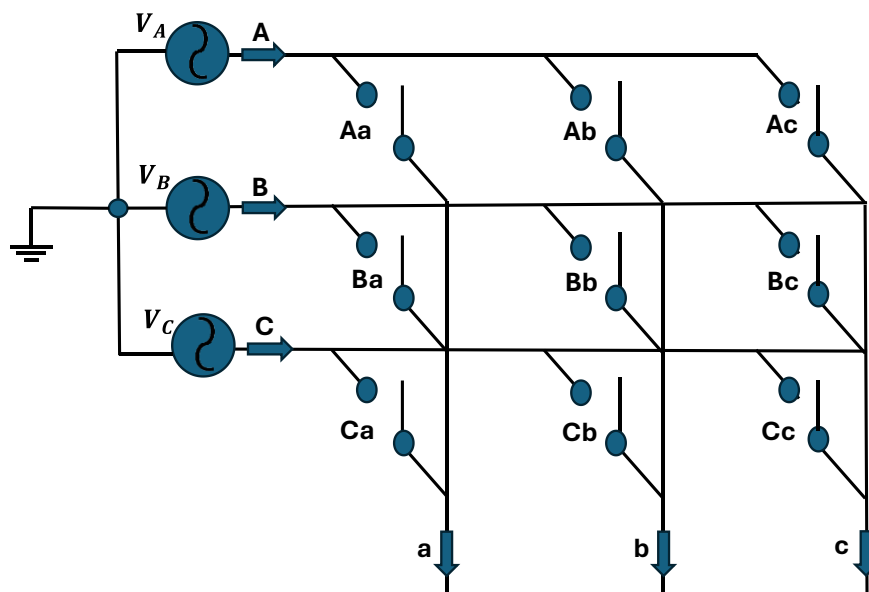


Figure I. 3: ideal three-phase-three-phase matrix converter

## I.5 Matrix Converter circuit

### I.5.1 Single-phase matrix Converter

The structure of the single-phase matrix converter is presented in Figures 1-4 and 1-5.

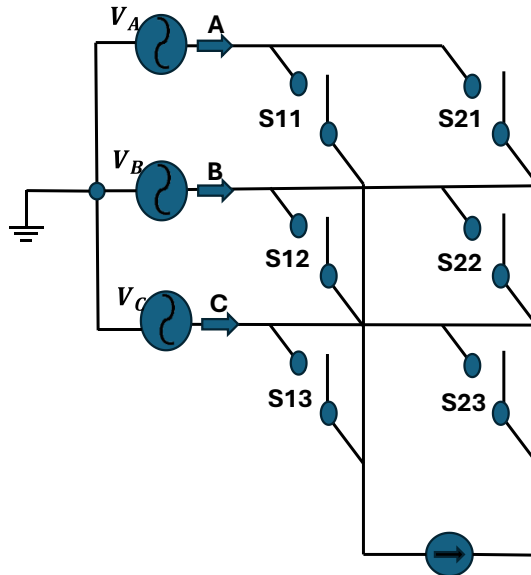


Figure I. 4: Single-Phase Matrix Converter without Midpoint

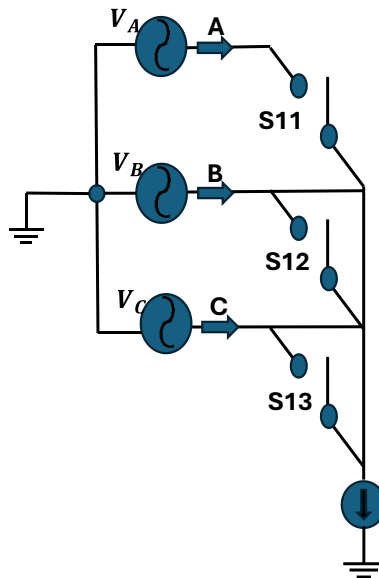
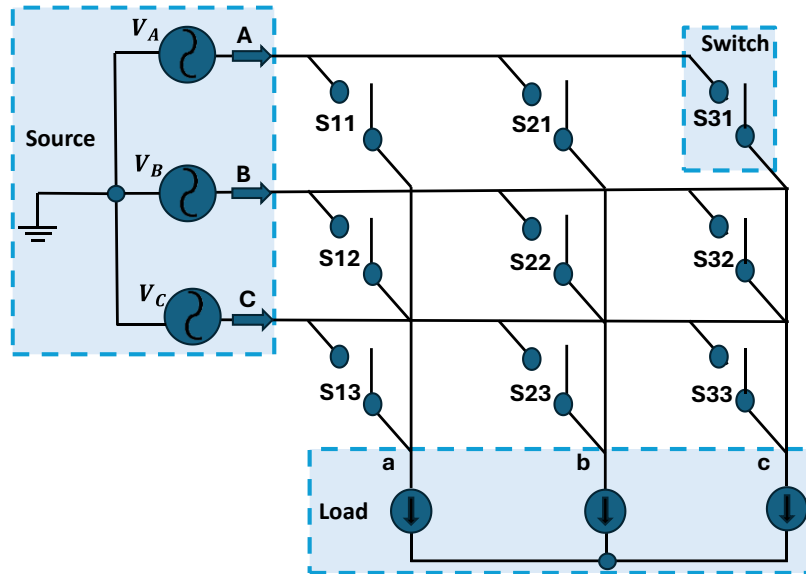


Figure I. 5: Single-Phase Matrix Converter with one Output Branch

### I.5.2 Three-phase matrix converter

Figure (I.6) shows the structure of the three-phase matrix converter.



**Figure I. 6: Three-Phase Matrix Converter**

In this work, we have focused on the three-phase converter, and therefore we make the following two assumptions:

1. The three-phase voltage source is balanced.

$$V_{in} = \begin{bmatrix} V_A(t) \\ V_B(t) \\ V_C(t) \end{bmatrix} = \begin{bmatrix} |V_{in}| \cdot \cos(\omega_i \cdot t) \\ |V_{in}| \cdot \cos\left(\omega_i \cdot t - \frac{2 \cdot \pi}{3}\right) \\ |V_{in}| \cdot \cos\left(\omega_i \cdot t - \frac{4 \cdot \pi}{3}\right) \end{bmatrix} \quad (I.1)$$

2. The load is considered as a current load (inductive load) in order to respect the source alternation rule. In practice, most loads in electrical engineering applications are inductive or can become so by adding an inductance.

The source alternation rule also imposes the following two switching conditions on the operation of power converters:

A voltage source must never be short-circuited.

The load, being inductive, must be considered as a current source and must never have its circuit open-circuited.

$h_{ij} = 1$  If the switch  $S_{ij}$  is closed.

$h_{ij} = 0$  If the switch  $S_{ij}$  is open.

With:

$h_{ij}$ : Existence function;  $S_{ij}$ : switch;

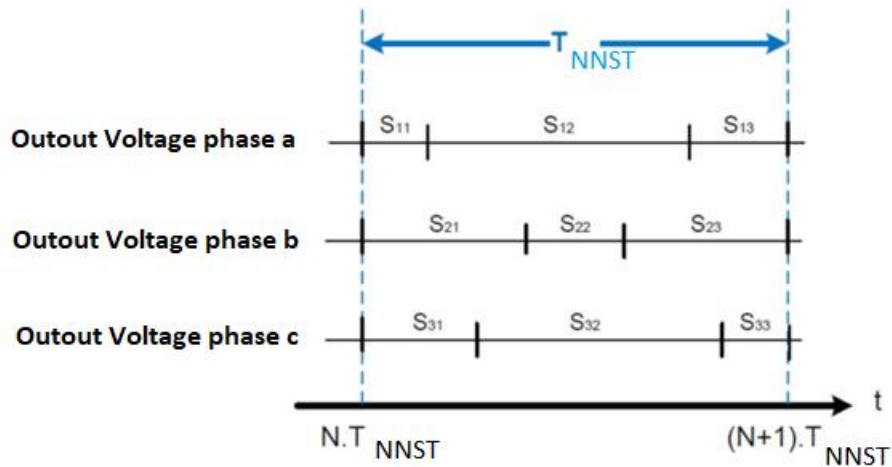
i: output phases; j: input phase.

The two switching conditions allow us to write the following mathematical model:

$$\begin{cases} h_{11} + h_{12} + h_{13} = 1 \\ h_{21} + h_{22} + h_{23} = 1 \\ h_{31} + h_{32} + h_{33} = 1 \end{cases} \quad (\text{I.2})$$

Subsequently, it can be concluded that it is necessary to ensure the closure of only one switch at a time for each output phase.

Figure (I.7) provides a timing diagram example of the operation of the nine switches in a three-phase matrix converter.



**Figure I. 7: Example of a timing diagram of the operation of the switches S<sub>ij</sub> [18.19]**

For each sampling period, there are  $3^3 = 27$  possible connection configurations. By applying Kirchhoff's laws, we express the output voltage equation (I.3) and the input current equation (I.4) as a function of  $h_{ij}$ .

$$\begin{bmatrix} V_a \\ V_b \\ V_c \end{bmatrix} = \begin{bmatrix} h_{11} & h_{12} & h_{13} \\ h_{21} & h_{22} & h_{23} \\ h_{31} & h_{32} & h_{33} \end{bmatrix} \begin{bmatrix} V_A \\ V_B \\ V_C \end{bmatrix} = [H] \cdot \begin{bmatrix} V_A \\ V_B \\ V_C \end{bmatrix} \quad (\text{I.3})$$

$$\begin{bmatrix} I_A \\ I_B \\ I_C \end{bmatrix} = \begin{bmatrix} h_{11}h_{21}h_{31} \\ h_{12}h_{22}h_{32} \\ h_{13}h_{23}h_{33} \end{bmatrix} = \begin{bmatrix} I_a \\ I_b \\ I_c \end{bmatrix} = [H]^T \cdot \begin{bmatrix} I_a \\ I_b \\ I_c \end{bmatrix} \quad (\text{I.4})$$

### I.5.2.1 Calculation of the duty cycles of the switches

For the converter to function properly, the sampling rate must be very high compared to the frequency of the input and output signals.

$$\left( T_{NNST} = \frac{1}{f_{NNST}} \right) \ll T \quad (\text{I.5})$$

The average output voltage over a sampling period is given by equation (1.6).

$$V_{o,T_{NNST}} = \frac{1}{T_{NNST}} \cdot (t_A \cdot V_A + t_B \cdot V_B + t_C \cdot V_C) \quad (\text{I.6})$$

With:

$t_A$ : closing time of the switch connecting input phase "A" to the desired output phase ( $t_{11}, t_{21}, t_{C31}$ ).

$t_B$ : closing time of the switch connecting input phase "B" to the desired output phase ( $t_{12}, t_{22}, t_{C32}$ ).

$t_C$ : closing time of the switch connecting input phase "C" to the desired output phase ( $t_{13}, t_{23}, t_{C33}$ ).

The duty cycles of each switch  $S_i$  are defined as follows:

$$m_{ij} = \frac{t_{ij}}{T_{NNST}} \quad (\text{I.7})$$

$$0 < m_{ij} < 1$$

The output voltages over a sampling period are then defined by equation (I.8):

$$\begin{bmatrix} V_{a,T_{NNST}} \\ V_{b,T_{NNST}} \\ V_{c,T_{NNST}} \end{bmatrix} = \begin{bmatrix} m_{11}m_{12}m_{13} \\ m_{21}m_{22}m_{23} \\ m_{31}m_{32}m_{33} \end{bmatrix} = \begin{bmatrix} V_A \\ V_B \\ V_C \end{bmatrix} = [M] \cdot \begin{bmatrix} V_A \\ V_B \\ V_C \end{bmatrix} \quad (\text{I.8})$$

The input currents are defined by equation (I.9)

$$\begin{bmatrix} I_{A,T_{NNST}} \\ I_{B,T_{NNST}} \\ I_{C,T_{NNST}} \end{bmatrix} = \begin{bmatrix} m_{11} & m_{21} & m_{31} \\ m_{12} & m_{22} & m_{32} \\ m_{13} & m_{23} & m_{33} \end{bmatrix} = \begin{bmatrix} I_a \\ I_b \\ I_c \end{bmatrix} = [M]^T \cdot \begin{bmatrix} I_a \\ I_b \\ I_c \end{bmatrix} \quad (I.9)$$

### I.6 Switch characteristics and their role in MC.

By definition, a switch is a two-terminal device that allows for a binary connection (open or closed) within the electrical circuit where it is inserted.

The voltage across its terminals in the open state and the current flowing through it in the closed state characterize its static operation and its bidirectional capabilities.

The conditions for its state changes characterize its dynamic operation and its controllability.

The MC requires the use of nine switches, whose static characteristic is represented by figure (I.8). These switches are controllable and conduct current regardless of its sign.

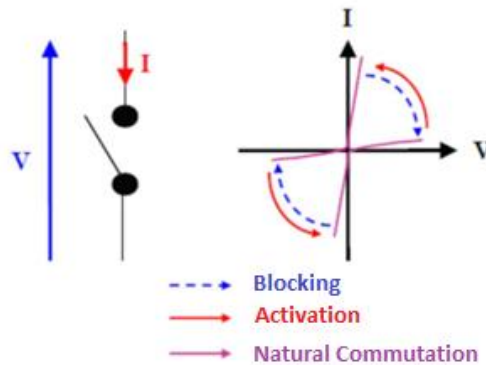


Figure I. 8: Static Characteristic of the Bidirectional Switch[18.19]

#### I.6.1 Semiconductor switch used in MC

Bidirectional voltage and current switches (capable of conducting current in both directions and blocking voltage regardless of its polarity) are devices made by assembling diodes, transistors, IGBTs, or other power switching devices.

The main switch topologies used in matrix converters are:

1. Diode-transistor hybrid topology.
2. Transistor-only topology.

### I.6.1.1 Topology with transistor connected to a diode bridge

The first proposed topology is the simplest possible. It consists of a transistor connected to the center of a diode bridge (Figure I-9) [18], [19]. These diodes are included to provide the reverse voltage blocking capability that the transistor lacks.

The main advantage of this topology is that it has only one unique component. This feature reduces both the cost of the assembly and the complexity of the control, as well as the number of isolated power supplies required to power the driver circuits, which provide the gate control signals.

The disadvantage of this switch is that three components (two diodes and one transistor) are conducting when it is activated, producing a significant voltage drop across its terminals. This voltage drop therefore generates significant conduction losses, limiting the efficiency of the converter.

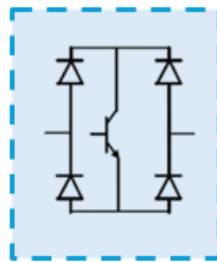


Figure I. 9: Topology of a Transistor Connected to a Diode Bridge

### I.6.1.2 Transistor topology

#### Head-to-tail transistor and diode topology

The switches used consist of a transistor connected in anti-parallel with a diode. They are bidirectional in current and unidirectional in voltage. Two configurations are possible to design a four-quadrant switch based on this configuration [18], [19]

#### Common emitter four segment switch

This switch is composed of two diodes and two transistors connected as shown in Figure I-10. The diodes serve to provide reverse voltage blocking capability.

The advantage of this structure is that it offers an additional degree of freedom for switch commutation management, and conduction losses are also reduced because only two elements (a transistor and a diode) conduct.

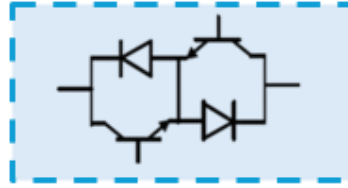


Figure I. 10: Common Emitter Topology

### Common Collector Bidirectional Switch

This switch has the same characteristics as the previous switch. The difference is that the transistors are arranged in a common collector configuration (Figure I-10). Conduction losses are strictly identical to those of the common emitter configuration. Since the emitters of the two transistors are not common, the four-quadrant switch requires two isolated power supplies

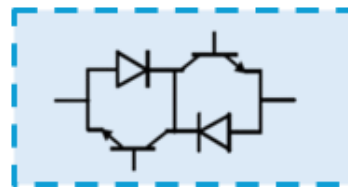


Figure I. 11: Common Collector Topology

### Series transistor and diode topology

Two other possible configurations are created from a transistor in series with a diode, resulting in a component that is bidirectional in voltage but unidirectional in current. The Bidirectional switch is composed of two components arranged in anti-parallel (Figure I-12) [18]. Possibility (a) leads to the same number of isolated power supplies as the common collector topology in Figure I-11.

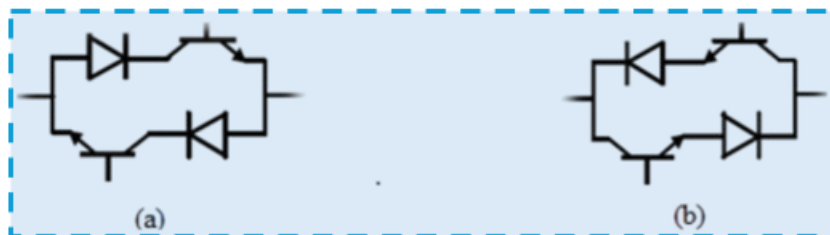


Figure I. 12: Topology without Central Connection

### I.6.1.3 RB-IGBT topologies

The last possible switch structure is the RB-IGBT, which is based on an N.P.T (Non-Punch-Through) IGBT technology (Figure I-13). This new switch allows the creation of a controllable bidirectional voltage component.

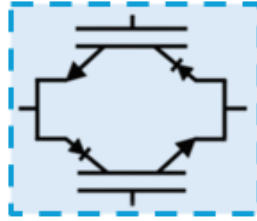


Figure I. 13: Structure of RB-IGBT Technology

### I.6.1.4 Advantages and disadvantages of each of these four-segment switches

Four-segment switches offer distinct characteristics, making them suitable for various applications [9]. Their advantages include improved control flexibility, enhanced fault tolerance due to segmented operation, and the ability to achieve better voltage and current balancing in modular systems. Additionally, these switches often enable more compact designs, reducing overall system size and weight. However, their disadvantages include increased complexity in control algorithms, higher costs due to additional components, and potential reliability concerns if segments fail individually. These trade-offs are summarized in the following table (I.1) for clarity

Table I. 1 : Summary of Switches

Semi-conductor Association	Ease of Control	Voltage Drop in Conduction	Isolated Power Supplies Required for CM
Transistor and Diode Bridge	Simple	High	9
Transistor and Diode in Anti-parallel	More complex	Medium	6 or 9
Transistor and Diodes in Series	More complex	Medium	6 or 18
RB-IGBT	More complex	Low	6

The most commonly used semiconductor connection for matrix converters is the common collector configuration [20].

### **I.7 Input filter**

Matrix converters produce output voltages and input currents with high-frequency harmonics. These harmonics are likely to generate undesirable high-frequency disturbances that can affect other electronic systems. Consequently, it is necessary to add one or more filters to the converter.

The role of the filtering device placed upstream of the matrix converter is to reduce the harmonic currents returning to the grid by providing them with a low impedance path.

The filtering device must also meet a number of criteria, namely:

Have good attenuation at the cutoff frequency, Introduce a minimum phase shift at the input, Be low-cost, Have a low weight and small dimensions, Allow for stable operation of the overall system...etc.

Figure (1.17) shows the circuits of the filters used for the matrix converter. The most common filter used for matrix converters is the L-C low-pass filter [21].

$$q = \frac{V_o}{V_i} = \frac{i_i}{i_o} \quad (\text{I.10})$$

### **I.8 Matrix converter protection**

The occurrence of switching faults, caused by the non-ideal behavior of the switches, can lead to significant overvoltages at the input and output ports of the converter. For this reason, a clamping circuit, as shown in Figure (I-14), is connected between the converter ports. This circuit protects the converter semiconductors from overvoltages produced by the momentary opening of all three switches in the same output branch or by the sudden connection of the load. The clamping circuit capacitor initially charges through the first rectifier connected to the mains; the capacitor's resting voltage is equal to the peak value of the mains line voltage. In the event of an

overvoltage, the second rectifier connects the capacitor to the output phases and limits the output line voltages to the peak value of the capacitor.

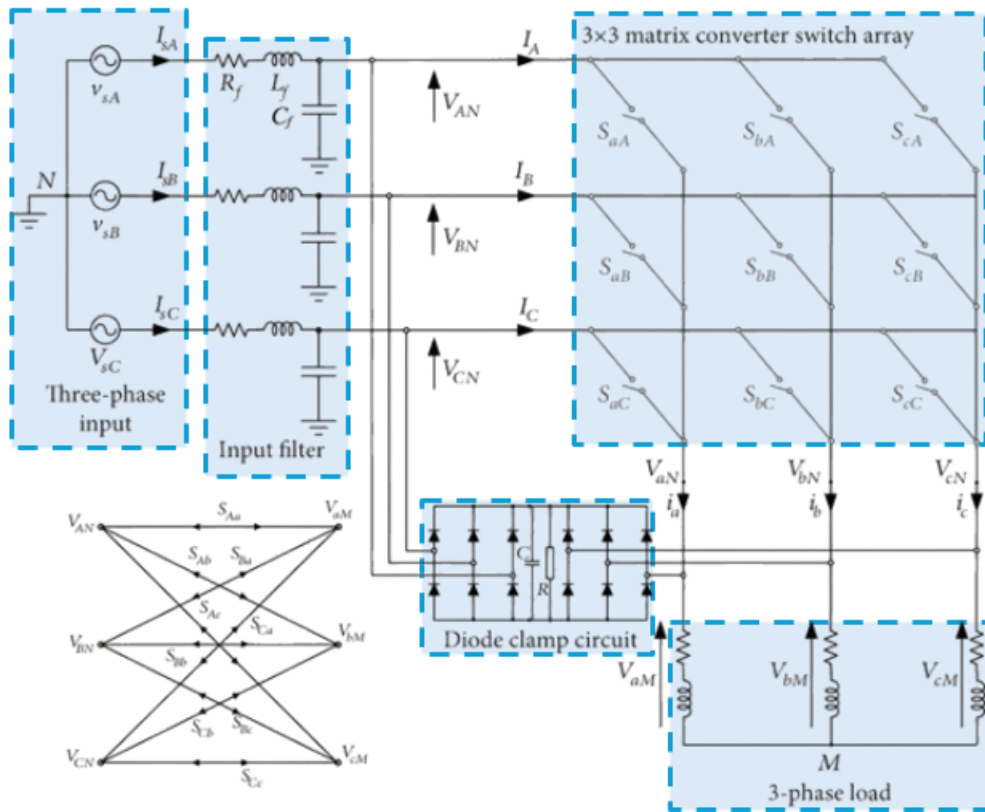


Figure I. 14: Protection circuit of a MC [18.19]

## I.9 Advantages and disadvantages of the MC

### Advantages

- A wide range of frequency variation.
- A low frequency spectrum for both input and output quantities.
- The input power factor can be improved, and moreover, it can be imposed by the control system.
- Ability to operate in both directions, thus in all bidirectional of the voltage-current plane, allowing both motor and generator operation.

### Disadvantages

The main drawback is that it generates large harmonic currents at the input and harmonic voltages at the output, which cannot be easily eliminated by filters[4]. This problem was solved by Mr. Venturini in 1980 who proposed a new MLI control

algorithm. This algorithm allows for sinusoidal input currents and output voltages. The drawback of this algorithm is that the output voltage ratio is limited to 0.5. In 1989, Venturini published a mathematical demonstration regarding the improvement of the voltage ratio after modifying the original algorithm.

### **I.10 Multilevel matrix converter**

#### **I.10.1. Research motivations**

In the context of multilevel power converter topologies, they have been widely investigated for their ability to achieve higher output voltages while reducing voltage stress on semiconductor switches. This allows for the use of lower voltage-rated switching devices, ultimately leading to cost savings. The introduction of Multilevel Direct Matrix Converters (DMCs) by Erickson and Al-Naseem in 2001 marked a significant advancement, where nine H-bridges were used in place of the traditional nine bidirectional switches in a matrix configuration [22]. Additionally, a capacitor-clamped multilevel matrix converter was explored in detail in [40], demonstrating superior performance in terms of output voltage harmonics, while halving the stress per switch. However, this improvement comes at the cost of increased complexity due to the additional number of switches and capacitors, which also raises concerns about the overall system reliability.

Further work on suppressing common mode voltage (CMV) has been discussed in [23], while studies presented in [24–33, 34] introduce an incremental version of the multilevel DMC. This topology is achieved by incorporating multiple H-bridges in each line connecting the input to the output, resulting in a lower ripple in the output voltage. However, the trade-off for this benefit lies in the increased number of switches and the complexity of the control strategies, making this configuration more suitable for specialized applications. Additional research into multilevel matrix converters, such as fault detection, can be found in [35].

Notably, the Modular Multilevel Matrix Converter (MMC) does not fit the traditional Venturini Matrix Converter category, as the latter does not incorporate capacitor storage elements. Regarding the  $3 \times 3$  MMC employing bidirectional

semiconductor switches, Yong Shi et al. proposed a capacitor-clamped topology, utilizing two flying capacitors per output phase [36]. However, this configuration introduces a non-uniform path impedance for the load current across the three output phases under different switching combinations. A potential solution to this issue, involving the use of three flying capacitors per output phase, was proposed by Janina Rzasas [37], offering improved impedance uniformity for the load current across the three output phases.

This research highlights the ongoing advancements in multilevel matrix converter topologies, each presenting specific advantages and challenges, particularly with respect to the balance between performance improvements and system complexity.

Multilevel technology offers an effective approach for converting medium- and high-voltage power [23, 36–39]. There are three primary types of multilevel converters: diode clamped, capacitor clamped, and cascade [37]. Of these, the capacitor-clamped multilevel converter is particularly well-suited for direct AC to AC conversion [38, 39]. This chapter focuses on the MMMC utilizing the capacitor clamped, flying capacitor, or multilevel topology [23, 36]. The Venturini algorithm is employed to generate gate pulses for the MMC, differing from the applications seen in traditional single-cell matrix converters.

### **I.10.2. Overview of MMMC**

The MMC is a type of multilevel converter that utilizes multiple submodules to synthesize output voltages. Each submodule can be independently controlled, enabling the converter to achieve a wide range of output voltage levels while maintaining high efficiency. The modular design allows for scalability, making it suitable for various applications, including renewable energy systems, electric vehicles, and industrial drives

### I.11 MMC Topologies

Multilevel converters are a class of power electronic converters that offer significant advantages over traditional two-level converters. They are particularly well-suited for high-power, low-harmonic, and efficient applications.

There are three primary types of multilevel converters:

#### I.11.1 Diode-Clamped Multilevel Converter (DCM)

This topology utilizes diodes to clamp the output voltage to a predetermined number of levels. The DCM is characterized by its simple structure and ease of control. However, it suffers from increased conduction losses due to the presence of diodes.

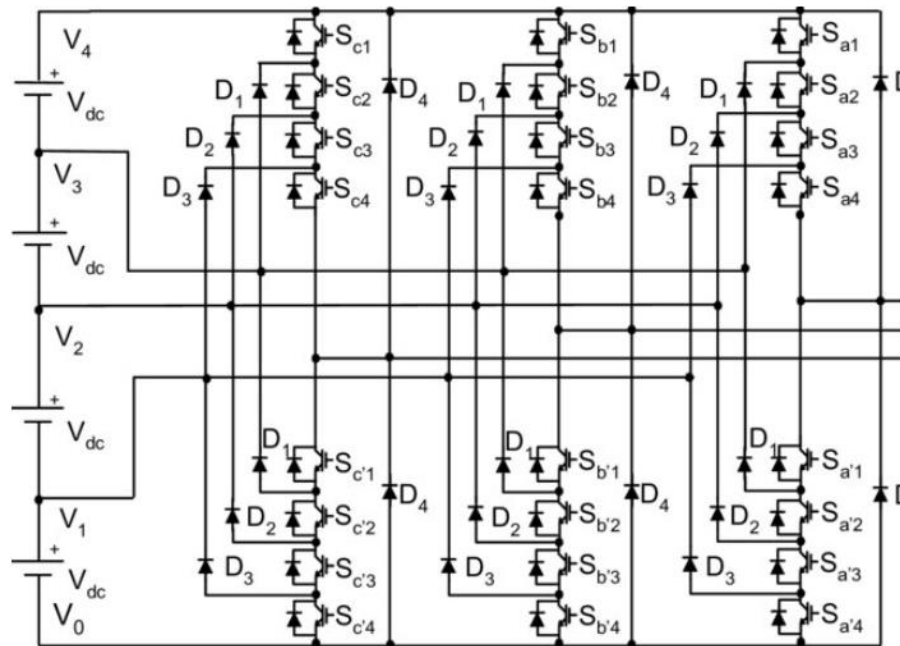


Figure I. 15 Diode-Clamped Multilevel Converter [22]

#### I.11.2 Cascade Multilevel Converter (CMC)

The CMC is composed of multiple two-level converters connected in series. This topology provides a high number of output levels and can achieve lower harmonic distortion. However, it can be complex to control and may suffer from increased switching losses.

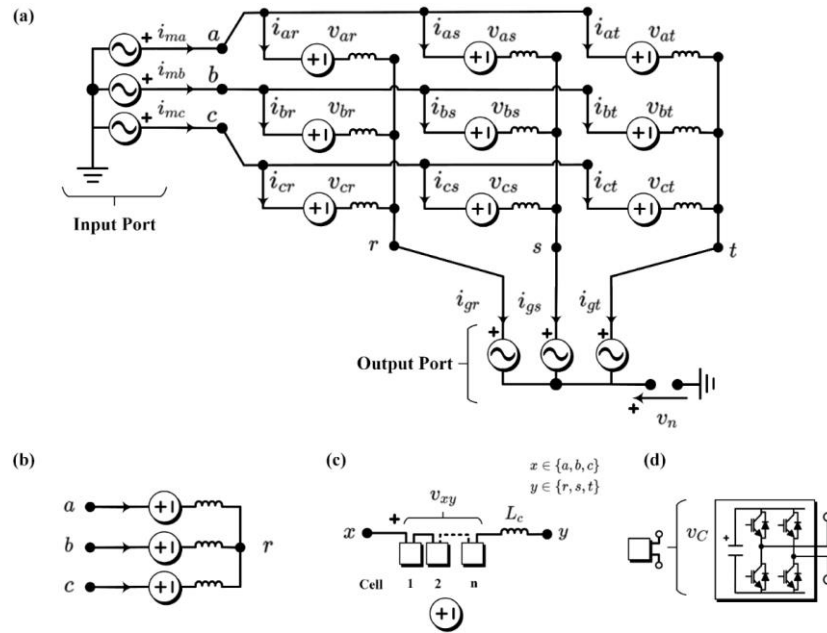


Figure I. 16 : Cascaded H-bridge Multilevel Converter [25]

### I.11.3 Capacitor-Clamped Multilevel Converter (CCMC)

In this topology, capacitors are used to generate the intermediate voltage levels. The CCMC offers a higher number of output levels compared to the DCM, resulting in lower harmonic distortion. However, it requires more complex control strategies to ensure balanced capacitor voltages.

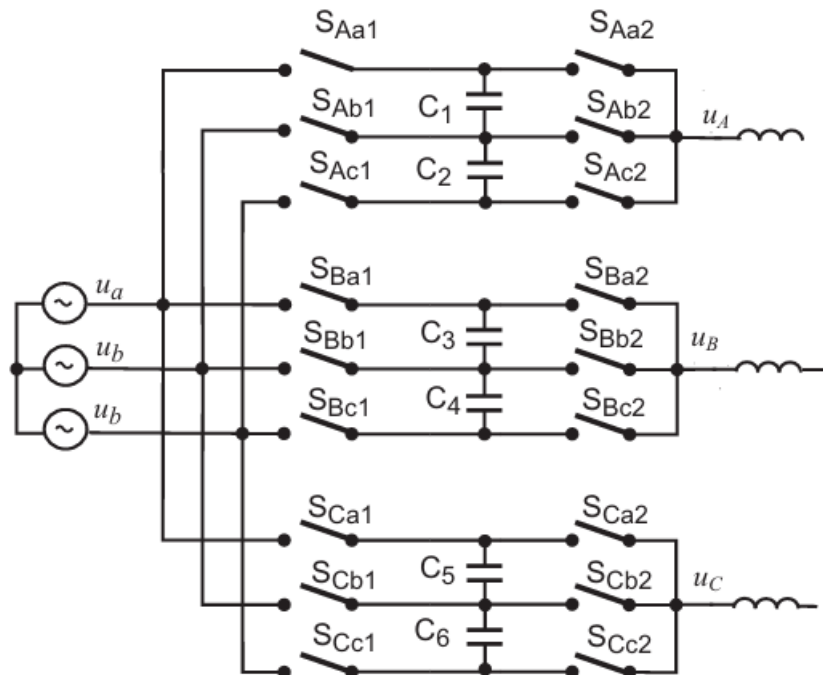


Figure I. 17 : Multilevel Converter with Two Capacitor clamped [23]

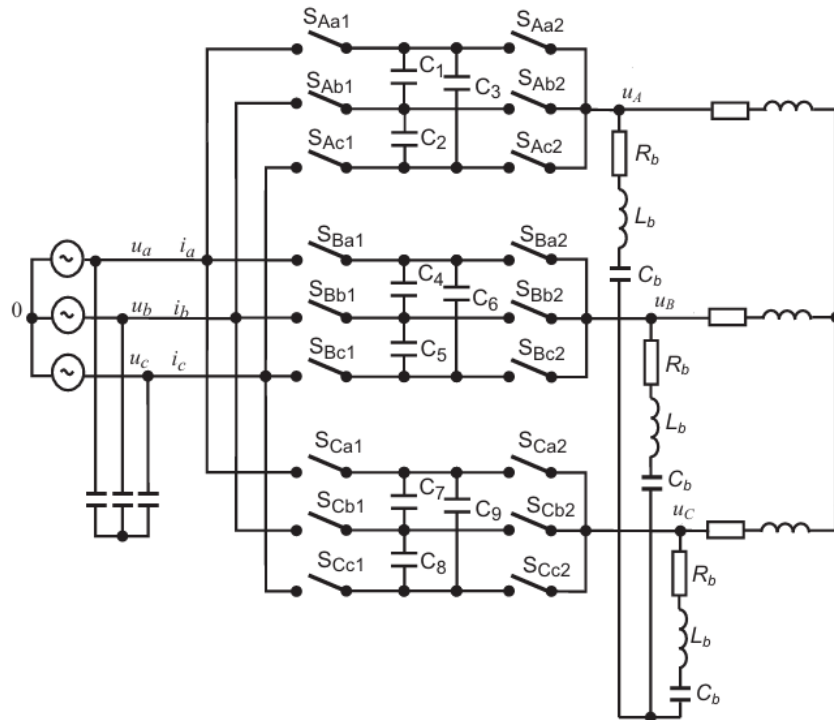


Figure I. 18 : Multilevel Converter with Three Capacitor clamped [49]

## I.12 Applications of MMC

Multilevel converters have found widespread applications in various fields, including:

**High-Voltage Direct Current (HVDC) Transmission:** Multilevel converters are used in HVDC systems to transmit large amounts of power over long distances with minimal losses.

**Wind Power Generation:** Multilevel converters are used in wind turbine systems to convert the variable DC output of the generator into a fixed AC voltage for grid connection.

**Motor Drives:** Multilevel converters can be used to drive high-power motors in industrial applications, such as electric vehicles, cranes, and elevators.

**Static Var Compensators (SVCs):** Multilevel converters are employed in SVCs to provide reactive power compensation and improve power quality in electrical grids.

### I.13 Control Strategies for MMMC-FC

The control strategies for the MMMC with three flying capacitors, as discussed in the provided chapter, are integral to achieving efficient operation and high-quality output. These strategies ensure proper modulation, voltage balancing, and feedback control, while advanced simulation tools allow for detailed performance evaluation. Here's an in-depth exploration of the key components that define the control strategies for this sophisticated converter:

**Modulation Function:** One of the core aspects of controlling the MMC is the modulation function, which generates the switching signals for the bidirectional switches. The modulation function ensures that the switches within the converter are triggered in a manner that effectively controls the output voltage. In the specific case of three flying capacitors, the modulation function assumes a unity input phase displacement factor. This mathematical representation allows for precise control over the converter's output voltage by adjusting the timing of the switch transitions, ensuring that the voltage levels generated by the MMC remain consistent with the desired output. The modified modulation function plays a crucial role in shaping the output waveform, especially in minimizing harmonic distortion. By carefully adjusting the switching signals, the modulation function enables the converter to produce multiple voltage levels that closely approximate a sinusoidal waveform, improving power quality and reducing the need for extensive filtering.

**Switch control:** Switch control in the MMMC involves managing the bidirectional switches located within each switching cell. The strategy for controlling these switches includes shifting the control signals of the switches in each cell by an angle of  $2\pi/p$ , where "p" represents the number of switching cells. This phase-shifting ensures that the switches do not operate simultaneously, which would increase switching losses and reduce efficiency. Instead, by staggering the control signals, the MMC can achieve smoother transitions between voltage levels. This approach also helps in reducing harmonic distortion by ensuring that the voltage levels in each phase are balanced over time. By carefully managing the duty cycles for each group of

switches, the converter can minimize the abrupt changes in voltage, resulting in a smoother, more refined output waveform.

**Voltage Balancing:** A critical aspect of controlling the MMC, particularly when using flying capacitors, is maintaining voltage balance across the submodules. Voltage balancing is vital to ensure that the flying capacitors do not experience overvoltage conditions, which could lead to component damage or failure. To address this, the control strategy includes specific mechanisms that adjust the switching states of the submodules to maintain a consistent voltage level across the capacitors. This balancing is achieved through careful management of the charge and discharge cycles of the flying capacitors. By controlling how the capacitors interact with the switches, the system can ensure that the voltage across each capacitor remains stable, contributing to the overall reliability and performance of the converter. The ability to maintain voltage balance also allows the MMC to handle higher power levels without risking overvoltage conditions, which is essential for applications such as renewable energy systems and industrial drives.

**Feedback Control:** Another key element of the MMC control strategy is the implementation of feedback control mechanisms. Feedback control allows for real-time monitoring of the converter's output voltages and currents. This data is then used to make dynamic adjustments to the control signals, ensuring that the converter responds quickly to changes in load conditions or input variations. For instance, in applications where the load characteristics might change rapidly, such as electric vehicle charging or variable industrial loads, the feedback control system can adjust the switching signals in real-time to maintain optimal performance. This ensures that the output voltage remains stable, and the power delivered to the load is of high quality, even in fluctuating conditions. The feedback control strategy also plays a role in maintaining the voltage balance across the flying capacitors. By constantly monitoring the voltage levels, the system can make fine adjustments to the switching states, ensuring that the capacitors are balanced and the converter operates within its safe voltage limits.

### I.15 Advantages and disadvantages of MMC

MMC are advanced power electronic converters widely used in various high-voltage and high-power applications, such as industrial systems, renewable energy integration, and high-voltage direct current (HVDC) transmission. They offer several advantages, particularly in terms of voltage capabilities, harmonic reduction, and efficiency, but also come with some drawbacks related to complexity, cost, and thermal management. Here's a detailed exploration of the advantages and disadvantages of MMCs:

#### I.15.1 Advantages of MMC

**High Voltage Capability:** MMCs are highly suited for medium- to high-voltage applications, which makes them ideal for a wide range of industries, including power generation, transmission, and renewable energy systems such as wind farms and solar plants. Their modular structure allows them to handle significantly higher voltages than traditional converters without needing bulky components like transformers. This capability is especially beneficial in applications requiring efficient power transmission over long distances, such as HVDC systems.

**Reduced Harmonics:** One of the most significant advantages of MMCs is their ability to reduce harmonic distortion in the output voltage. The multilevel nature of MMCs allows for the generation of a smoother voltage waveform, which greatly reduces harmonic content compared to traditional two-level or three-level converters. This leads to cleaner power output, minimizing electromagnetic interference and reducing the stress on connected equipment such as motors and transformers. The improved power quality also translates to increased system reliability and longer equipment lifespan.

**Flexible Topology:** The modular design of MMCs provides excellent flexibility and scalability. MMCs consist of multiple submodules or cells, each contributing to the overall voltage output. This modularity means that adding more cells can increase the voltage levels or power capacity without significant redesign or restructuring of the converter. This flexibility makes MMCs adaptable to a wide range of applications,

from low to high power requirements, ensuring that they remain future-proof and capable of handling growing energy demands.

**Bidirectional Power Flow:** Another advantage of MMCs is their ability to handle bidirectional power flow, allowing energy to flow in both directions. This capability makes MMCs highly suitable for applications involving energy storage systems, electric vehicle charging, and grid integration of renewable energy sources like solar and wind power. The ability to switch between powering loads and feeding energy back into the grid enhances system flexibility, enabling better energy management and integration of intermittent renewable energy sources.

**Improved Efficiency:** MMCs offer improved efficiency compared to traditional converters. One key factor is the use of flying capacitors, which help reduce switching losses by softening voltage transitions during switching events. This results in less heat generation and higher overall efficiency, making MMCs attractive in energy-critical applications. The modular structure also allows for more efficient handling of power conversion, with each module processing a smaller portion of the total voltage, thereby reducing stress on individual components and further enhancing efficiency.

**Voltage Balancing:** Voltage balancing across the submodules, particularly the flying capacitors, is critical to the operation of MMCs. Sophisticated control strategies are implemented to ensure that the voltage across each capacitor remains balanced. This balancing is essential for maintaining converter stability, reliability, and preventing component failures due to overvoltage conditions. Proper voltage balancing improves the overall durability and longevity of the MMC, reducing the likelihood of breakdowns and minimizing maintenance needs.

**Modulation Flexibility:** MMCs allow for the use of various modulation techniques, such as the Venturini algorithm or pulse-width modulation (PWM). This flexibility in modulation provides precise control over the output voltage and current, enabling the converter to adapt to different operating conditions. The ability to tailor the modulation strategy to specific applications enhances system performance and efficiency, making MMCs versatile in a broad range of power conversion scenarios.

### I.15.2 Disadvantages of MMMC

**Complex Control Strategies:** While MMCs offer superior performance, they require highly sophisticated control strategies to manage their operation effectively. The increased number of submodules and switches introduces greater complexity in the control system, requiring real-time feedback mechanisms and advanced algorithms to ensure proper modulation, voltage balancing, and fault management. Developing and implementing these control strategies can be challenging, especially in large-scale systems, and may demand significant computational resources[25].

**Higher Component Count:** The modular nature of MMCs leads to a higher number of components, including switches, capacitors, and other control elements. This increase in component count adds to the complexity of the system and can drive up both the initial cost and the ongoing maintenance requirements. A higher number of components also raises the risk of component failure, which could compromise the overall reliability of the converter. Ensuring that all components function correctly and in harmony is crucial for the smooth operation of MMCs.

**Size and Weight:** Due to the large number of submodules and associated components, MMCs tend to be bulkier and heavier than conventional two- or three-level converters. This can be a disadvantage in applications where space and weight are critical, such as in marine or aerospace systems. The increased size and weight may also pose challenges in terms of installation and integration, particularly in environments where space is limited or where compactness is a key requirement.

**Capacitor Voltage Management:** Managing the voltage across the flying capacitors is one of the most challenging aspects of MMC operation. If the voltage is not balanced properly, it can lead to overvoltage conditions, which may result in capacitor failure or degraded system performance. Sophisticated voltage balancing techniques are required to ensure that the voltage across each capacitor remains within safe operating limits, but improper implementation or control failure could lead to significant issues, including system instability or damage.

**Thermal Management:** The large number of components in MMCs can lead to increased thermal stress, especially during high-power operation. Effective thermal management solutions, such as advanced cooling systems, are necessary to prevent overheating and ensure the reliable operation of the converter. Poor thermal management could result in component degradation or failure, reducing the lifespan of the converter and increasing maintenance costs.

**Cost:** The complexity of MMCs, combined with their higher component count and advanced control systems, leads to increased overall costs. The initial investment for an MMC system is typically higher than that for conventional converters, which may deter some users, particularly in cost-sensitive applications. Additionally, the ongoing maintenance and operational costs associated with managing a complex system with numerous components can add to the total cost of ownership over time.

### I.16 Conclusion

Matrix converters are a groundbreaking innovation in direct power conversion (AC/AC), offering a compact, efficient, and advanced alternative to traditional converters. Their design eliminates the need for intermediate energy storage components like capacitors or inductors, enabling bidirectional power flow and precise control of output voltage amplitude and frequency. These advantages make matrix converters a preferred choice for applications such as drive systems and variable-speed generation. In this work, we focus specifically on direct matrix converters and multilevel matrix converters, with particular attention to the three-capacitor clamped topology, which enhances power quality and reduces harmonic distortion.

This chapter has provided a detailed of MC and MMMC, comparing the classic and multilevel topologies. By delving into their fundamental principles, design advantages, and potential applications, this study lays the groundwork for a deeper understanding of these converters. The selected representative designs for both the classic and multilevel topologies will serve as a foundation for further exploration

and analysis in subsequent sections, highlighting their role in advancing energy conversion technologies for modern and future applications.

In the subsequent chapters, we will explore the control strategies and performance analysis of matrix converters in greater detail. We will delve into various control techniques, including space vector modulation (SVM) and pulse width modulation (PWM), Vonturini modulation (VM) and their impact on the overall performance of matrix converters. Additionally, we will examine the challenges associated with matrix converter control and explore potential solutions to address these issues. These investigations will provide a comprehensive understanding of the capabilities and limitations of matrix converters, paving the way for their continued development and integration into advanced power systems.

**Chapter II: A  
Comprehensive Study  
of Matrix Converters  
and a Comparative  
Analysis of Control  
Strategies**

## **II.1 Introduction**

In this chapter, we study the matrix converter and analyze its operation using various control and modulation methods to understand its performance and limitations. The problem of controlling a matrix converter lies in finding the appropriate pulse sequences such that the moving average of the phase voltages at the output is sinusoidally modulated. The amplitude and frequency of the fundamental wave of the voltage must be variable, making control a challenging task.

To address this challenge, we will study three modulation methods that enable pulse-width modulation control of the matrix converter switches. The first method focuses on the Venturini Modulation (VM), known for its simplicity and ability to achieve near-optimal modulation. The second method examines space vector modulation (SVM), widely recognized for its superior performance and flexibility in matrix converter applications. Lastly, we explore (MLI) modulation with three intervals for the matrix converter, offering advanced control capabilities for improved harmonic performance.

Following a comprehensive simulation of these methods, we compare their results to evaluate the performance, efficiency, and power quality achieved by each approach. Based on these findings, we conclude the next stage of development and identify the steps required to address the inherent limitations of the matrix converter, paving the way for advancements such as the adoption of multilevel matrix converters.

## **II.2 Control strategy of a Direct Matrix Converter**

### **II.2.1 Venturini modulation algorithm**

Venturini proposed a high-frequency switching strategy for matrix converters. This method was subsequently modified in order to increase the transformation ratio between the output voltage and the input voltage from 0.5 to 0.866. Similarly, it provides sinusoidal input currents to the matrix converter with a power factor independent of the load [42]. The choice of each input phase during a period forms the output signals of the converter for well-defined time periods (output voltage and

input current). The output voltage is obtained from segments of the three input voltages. The output current is obtained from segments of the three input currents. In order to determine the behavior of the matrix converter for output frequencies lower than the switching frequency.

A switching cycle ( $\frac{1}{t_{seq}}$ ) can be defined for each switch [42, 43]. The balanced three-phase voltages at the converter input are expressed by the following formula:

$$v_i(t) = \begin{bmatrix} v_a(t) \\ v_b(t) \\ v_c(t) \end{bmatrix} = V_{im} \begin{bmatrix} \cos(\omega_i t) \\ \cos\left(\omega_i t + \frac{2\pi}{3}\right) \\ \cos\left(\omega_i t + \frac{4\pi}{3}\right) \end{bmatrix} \quad (\text{II.1})$$

On the other hand, the balanced three-phase currents at the converter output are expressed by the following expression:

$$i_o(t) = \begin{bmatrix} i_A(t) \\ i_B(t) \\ i_C(t) \end{bmatrix} = I_{om} \begin{bmatrix} \cos(\omega_o t + \varphi_o) \\ \cos\left(\omega_o t + \varphi_o + \frac{2\pi}{3}\right) \\ \cos\left(\omega_o t + \varphi_o + \frac{4\pi}{3}\right) \end{bmatrix} \quad (\text{II.2})$$

Where:  $V_{im}, I_{om}, \omega_i$  and  $\omega_o$  are the peak values and angular frequencies of the converter's input voltage and output current, respectively, and  $\varphi_s$  is the phase angle between the output voltage and current [43]

Considering the ratio between the output voltage and the input voltage of the matrix converter

$$q = \frac{V_o}{V_i} = \frac{i_i}{i_o} \quad (\text{II.3})$$

We obtain:

$$v_o(t) = \begin{bmatrix} v_A(t) \\ v_B(t) \\ v_C(t) \end{bmatrix} = qv_{om} \begin{bmatrix} \cos(\omega_o t) \\ \cos\left(\omega_o t + \frac{2\pi}{3}\right) \\ \cos\left(\omega_o t + \frac{4\pi}{3}\right) \end{bmatrix} \quad (\text{II.4})$$

$$i_i(t) = \begin{bmatrix} i_A(t) \\ i_B(t) \\ i_C(t) \end{bmatrix} = q\cos(\varphi_o)i_{om} \begin{bmatrix} \cos(\omega_o t + \varphi_i) \\ \cos\left(\omega_o t + \varphi_i + \frac{2\pi}{3}\right) \\ \cos\left(\omega_o t + \varphi_i + \frac{4\pi}{3}\right) \end{bmatrix} \quad (\text{II.5})$$

If we replace  $V_i, V_o, i_i$  and  $i_o$  in expressions (I.6) and (I.8) and (I.13) in chapter I, the modulation matrix admits the following two solutions [44, 45].

For  $\varphi_i = \varphi_o$  and  $\omega_{oi} = \omega_o - \omega_i$  we obtain:

$$M_1(t) = \frac{1}{3} \begin{bmatrix} 1 + 2q\cos(\omega_{oi}t) & 1 + 2q\cos\left(\omega_{oi}t - \frac{2\pi}{3}\right) & 1 + 2q\cos\left(\omega_{oi}t - \frac{4\pi}{3}\right) \\ 1 + 2q\cos\left(\omega_{oi}t - \frac{4\pi}{3}\right) & 1 + 2q\cos(\omega_{oi}t) & 1 + 2q\cos\left(\omega_{oi}t - \frac{2\pi}{3}\right) \\ 1 + 2q\cos\left(\omega_{oi}t - \frac{2\pi}{3}\right) & 1 + 2q\cos\left(\omega_{oi}t - \frac{4\pi}{3}\right) & 1 + 2q\cos(\omega_{oi}t) \end{bmatrix} \quad (\text{II.6})$$

For  $\varphi_i = -\varphi_o$  and  $\omega_{oi} = -(\omega_o + \omega_i)$  we obtain:

$$M_2(t) = \frac{1}{3} \begin{bmatrix} 1 + 2q\cos(\omega_{oi}t) & 1 + 2q\cos\left(\omega_{oi}t - \frac{2\pi}{3}\right) & 1 + 2q\cos\left(\omega_{oi}t - \frac{4\pi}{3}\right) \\ 1 + 2q\cos\left(\omega_{oi}t - \frac{2\pi}{3}\right) & 1 + 2q\cos\left(\omega_{oi}t - \frac{4\pi}{3}\right) & 1 + 2q\cos(\omega_{oi}t) \\ 1 + 2q\cos\left(\omega_{oi}t - \frac{4\pi}{3}\right) & 1 + 2q\cos(\omega_{oi}t) & 1 + 2q\cos\left(\omega_{oi}t - \frac{2\pi}{3}\right) \end{bmatrix} \quad (\text{II.7})$$

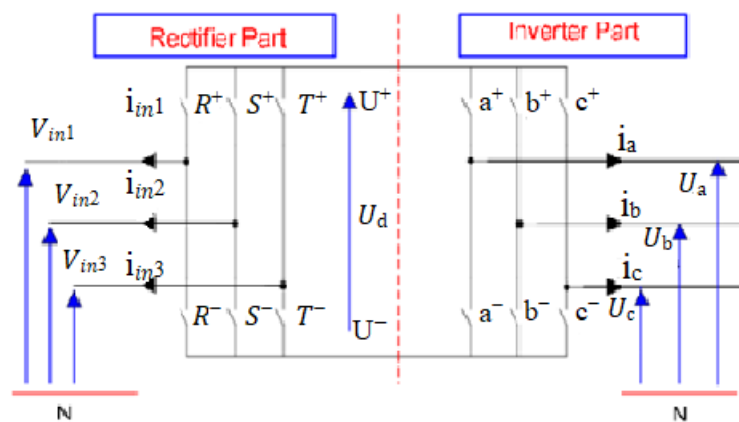
Solution (II.6) is obtained for an input phase shift equal to that of the output ( $\varphi_i = \varphi_0$ ) just as the solution (II.7) is obtained for an input phase shift in opposition to that of the output ( $\varphi_i = -\varphi_0$ )

The Venturini modulation method, based on expressions (II.6) and (II.7), allows for a maximum ratio of 0.5 (or 50%) between the output voltage and the input voltage of the matrix converter [46].

### II.2.2 PWM three intervals control strategy:

The matrix converter's control mechanism is analogous to that of an indirect converter with an intermediate circuit (rectifier/inverter) [14]. In order to facilitate the control of the matrix converter and avoid its inherent complexity, a virtual intermediate voltage is introduced, capitalizing on the simplicity offered by conventional converters. The concept is illustrated in Figure II.1. Taking into account that the three-phase input voltage system of the power supply always comprises at least one positive phase and one negative phase relative to the neutral power supply, the virtual intermediate voltage is determined by selecting the appropriate virtual potentials.  $U^+$  and  $U^-$  so that:  $U_d = U^+ - U^-$  (12)

where:  $U_d$  intermediate virtual potential,  $U^+$  virtual positive potential,  $U^-$  virtual negative potential.



**Figure II. 1: Model of the MC with middle fictitious circuit**

1. Study of the rectifier part

The harmonic spectrum of the input current has significant importance for this component. Consequently, it is necessary to employ a modulation function that guarantees a sinusoidal current is supplied to the input while the voltage transmitted through the intermediate circuit is maintained. This modulation function's definition can be stated as follows [9,10]

$$\tau = \frac{\cos(\Phi - 2\pi/3)}{\cos(\Phi)} + 10 \leq \tau \leq 1 \quad (\text{II.8})$$

where  $\Phi = (\omega t) \bmod(\pi/3) - (\pi/6)$ . The connection between the input voltages and the virtual potential are represented follows [19]:

$$\begin{bmatrix} U^+ \\ U^- \end{bmatrix} = \begin{bmatrix} R^+ & S^+ & T^+ \\ R^- & S^- & T^- \end{bmatrix} \begin{bmatrix} V_{in1} \\ V_{in2} \\ V_{in3} \end{bmatrix} \quad (\text{II.9})$$

The value of the virtual DC-voltage  $U_d = U^+ - U^-$  will be varying as function of the line phase angle and the rectifier control functions. For example, in the interval  $\pi/3 < \omega t < 2\pi/3$ , the switches can be taken the values ( $R^+ = 1, S^+ = 0, T^+ = 0$ ) and ( $R^- = 0, S^- = 1 - \tau, T^- = 1$ ). The potential  $U^+ = R^+V_{in1} + S^+V_{in2} + T^+V_{in3}$ , and the potential  $U^- = R^-V_{in1} + S^-V_{in2} + T^-V_{in3}$ , the parameters of the connection matrix. Considering the symmetry founded in during a recovery period, six intervals can be determined as in fig. II.2

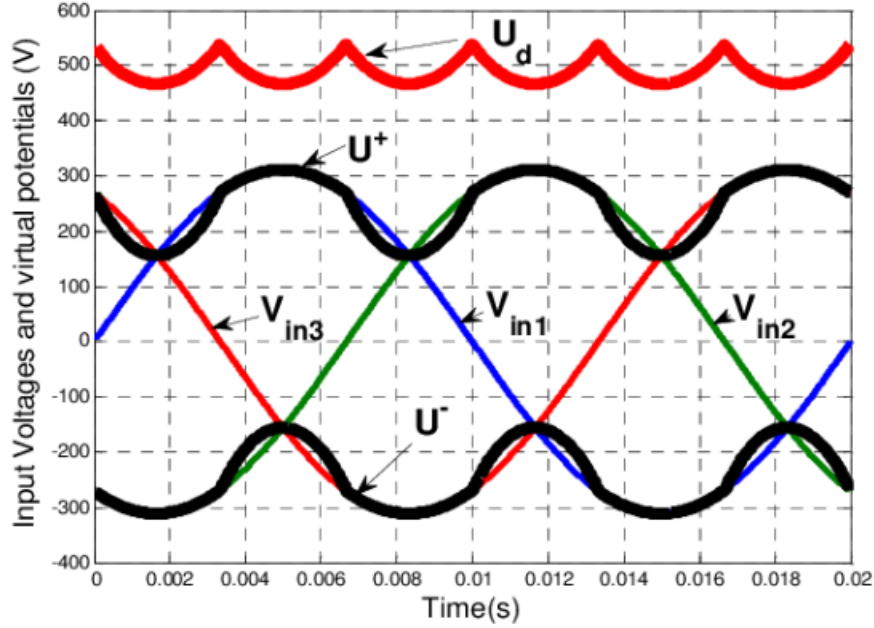


Figure II. 2: Curve of the input voltages and virtual potentials

## 2. Study of the inverter part

To establish a connection between the middle potential and the output voltages of the matrix converter, modulation capabilities  $U_{cmk}$  are introduced to define the modulation matrix  $[M_r(t)]$ . These capabilities can take on continuous values between 0 and 1. Using the following expression, this connection is made:

$$\begin{bmatrix} U_a \\ U_b \\ U_c \end{bmatrix} = \underbrace{\begin{bmatrix} U_{cm1} & 1 - U_{cm1} \\ U_{cm2} & 1 - U_{cm2} \\ U_{cm3} & 1 - U_{cm3} \end{bmatrix}}_{[M_r(t)]} \begin{bmatrix} U^+ \\ U^- \end{bmatrix} \quad (\text{II.10})$$

Taking into consideration the two rectifier-inverter blocks, the matrix  $[M_r(t)]$  can be presented as follows to define the complete algorithm function of frequency conversion:

$$\begin{bmatrix} U_a \\ U_b \\ U_c \end{bmatrix} = \underbrace{\begin{bmatrix} U_{cm1} & 1 - U_{cm1} \\ U_{cm2} & 1 - U_{cm2} \\ U_{cm3} & 1 - U_{cm3} \end{bmatrix} \begin{bmatrix} R^+ & S^+ & T^+ \\ R^- & S^- & T^- \end{bmatrix}}_{[M(t)]} \begin{bmatrix} V_{in1} \\ V_{in2} \\ V_{in3} \end{bmatrix} \quad (\text{II.11})$$

The output reference voltage phases are defined as follows:

$$U_{\text{ref}-k} = 220\sqrt{2}\sin\left(\omega_0 t - \frac{2\pi}{5}(k-1)\right) \quad (\text{II.12})$$

where:  $\omega_0 = 2\pi f_0, k = 1, 2, \dots, 5$

Determining the functions of undulation (standard reference functions) that are modulating the virtual middle voltage afore mentioned:

$$U_{cmk} = r \cos(\Phi) \sin\left(\omega_0 t - \frac{2\pi}{5}(k-1)\right) + \frac{1}{2} \quad (\text{II.13})$$

where:  $U_{cmk}$  - modulation function,  $r$  - rate of modulation,  $k = 1, 2 \dots, 5$ .

### **II.2.3 Space vector modulation method**

The space vector modulation method is based on the space vector representation of  $\vec{V}_0$  and  $\vec{I}_i$  in the reference  $d, q$ ; the space vector is obtained from the Concordia transform[47].

In the general topology of the Matrix converter as depicted in Figure II.1, which consists of 27 permissible switching combinations for each combination, the input and output line voltages can be expressed in terms of space vectors as described in [48]

$$\vec{V}_o = \frac{2}{3} \cdot (V_{o1} + a \cdot V_{o2} + a^2 \cdot V_{o3}) = V_o \cdot e^{j\alpha_o \cdot t} \quad (\text{II.14})$$

$$\vec{I}_i = \frac{2}{3} \cdot (I_{i1} + a \cdot I_{i2} + a^2 \cdot I_{i3}) = I_i \cdot e^{j\beta_1 \cdot t} \quad (\text{II.15})$$

The switching conditions outlined in Chapter 1 allow for 27 valid configurations in the three-phase direct matrix converter.

#### **II.2.3.1 Vector families**

The well-known Space Vector Modulation (SVM) approach for matrix converters leads to the definition of three families of vectors [49].

The first family consists of six vectors where each input phase is connected to a different output phase.

Second family: three null vectors which are in freewheeling mode, meaning that the switching configuration results in a zero voltage across the load denoted by  $O_i$  with  $i = 1, 2, 3$ .

Third family: 18 active vectors denoted by  $A_j$ , with a fixed angular position proportional to an input phase-to-phase voltage, where  $j$  is an integer between 1 and 18.

The first family has a time-varying vector position and therefore cannot be used to construct references for a space vector approach [50]. Consequently, only the first and second vector families are utilized in the SVM modulation of the Matrix converter [51].

The SVM algorithm is based on the concept that the DMC output line voltages for each switching combination can be represented as a voltage space vector defined by (II.14).

The modulation method involves the selection and real-time calculation of vectors. At each sampling period  $T_s$  (equal to the switching period in our case), the algorithm selects four active vectors associated with all possible combinations of output voltage and input current sectors, in addition to null vectors, to construct the desired reference voltage [52].

The amplitude of the reference voltage vector and the phase angle are calculated, and the phase angle of the desired input current vector is determined in advance [53].

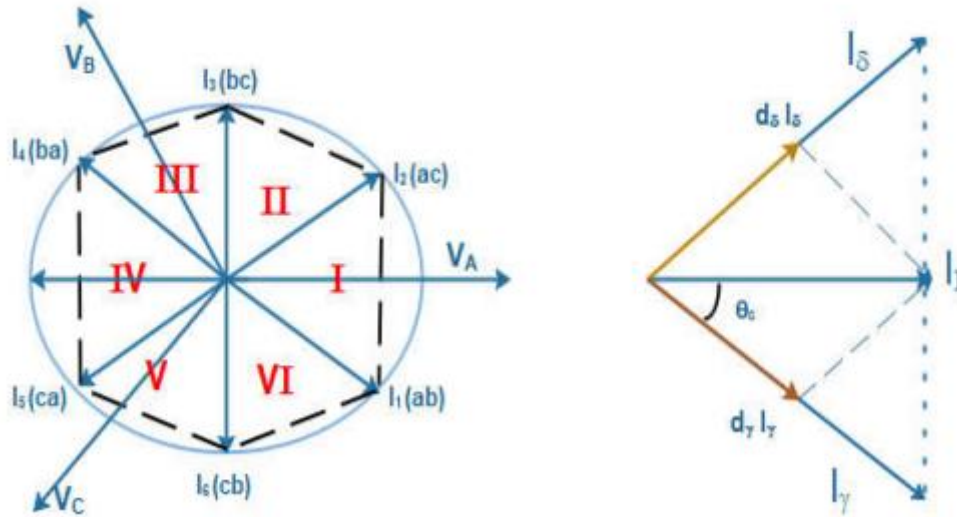


Figure II. 3 : Modulation of the input current vector[18.19]

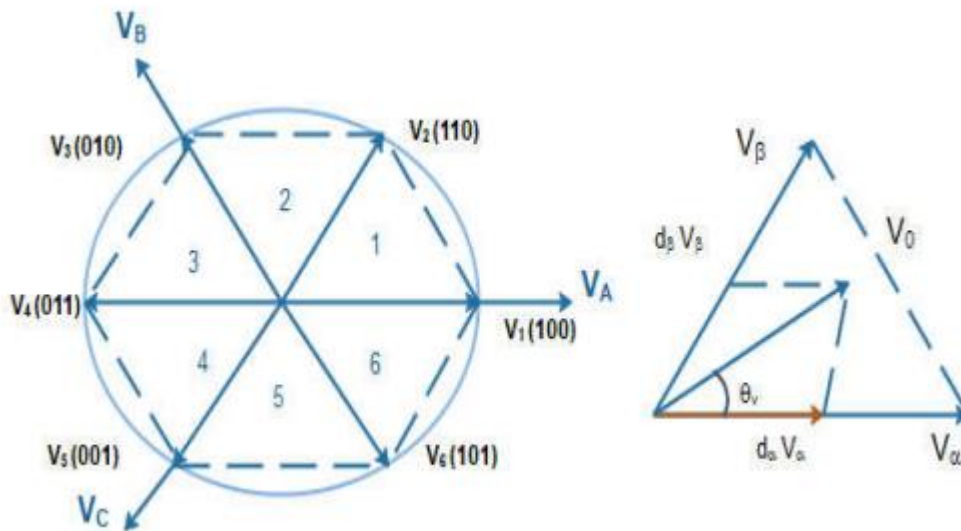


Figure II. 4 :Modulation of the output voltage vector [18.19]

To determine the real-time durations of the selected vectors, they are combined into two sets, resulting in two new adjacent vectors within the sextant that are co-directional with the reference voltage vector. Employing standard SVM theory, the general formulas derived for the real-time vectors, which simultaneously satisfy the displacement angle requirements of both the reference output voltage and the input current (as depicted in Figures II.3 and II.4), are as follows [54]:

$$\begin{aligned}
 t_1 &= \frac{2qT_s}{\sqrt{3}\cos \varphi_i} \sin \left( \frac{\pi}{3} - \theta_0 \right) \sin \left( \frac{\pi}{3} - \theta_i \right) \\
 t_2 &= \frac{2qT_s}{\sqrt{3}\cos \varphi_i} \sin \left( \frac{\pi}{3} - \theta_0 \right) \sin (\theta_i) \\
 t_3 &= \frac{2qT_s}{\sqrt{3}\cos \varphi_i} \sin (\theta_0) \sin \left( \frac{\pi}{3} - \theta_i \right) \\
 t_4 &= \frac{2qT_s}{\sqrt{3}\cos \varphi_i} \sin (\theta_0) \sin (\theta_i)
 \end{aligned} \tag{II.16}$$

Where  $q$  is the voltage transfer ratio,  $T_s$  is the switching period,  $\varphi_i$  is the input shift angle chosen to obtain the desired input power factor,  $\theta_0$  and  $\theta_i$  are the phase shift angles of the output voltage and input current vectors limited in the range  $[0, \pi/3]$  respectively. The duration of the zero vectors is given by (II.17).

$$t_0 = T_s - t_1 - t_2 - t_3 - t_4 \tag{II.17}$$

Tables II-1, II-2, and II-3 present the 27 possible configurations and their corresponding space vectors. However, the space vector method utilizes only the 18 stationary vectors presented in Table II 2 and the 3 null vectors presented in Table II.3. The rotating vectors in Table II 3 have a time-dependent phase. They are not used in the implementation of this method.

**Chapter II: A Comprehensive Study of Matrix Converters and a Comparative Analysis of Control Strategies**

**Table II. 1 :First family (rotating vectors).**

	Closed switches			Output voltages			Input current			Voltage phasor		Current phasor	
				$V_{ab}$	$V_{bc}$	$V_{ca}$	$I_A$	$I_B$	$I_C$	Ampl	Phase	Ampl	Phase
1	$S_{11}$	$S_{22}$	$S_{33}$	$V_{AB}$	$V_{BC}$	$V_{CA}$	$I_3$	$I_b$	$I_c$	$V_i$	$\omega_i t$	$I_0$	$\omega_0 t$
2	$S_{11}$	$S_{23}$	$S_{32}$	$-V_{CA}$	$-V_{BC}$	$-V_{AB}$	$I_3$	$I_c$	$I_b$	$-V_i$	$-\omega_i t + 4\pi/3$	$I_0$	$-\omega_0 t$
3	$S_{12}$	$S_{21}$	$S_{33}$	$-V_{AB}$	$-V_{CA}$	$-V_{BC}$	$I_b$	$I_3$	$I_c$	$-V_i$	$-\omega_i t$	$I_0$	$-\omega_0 t + 2\pi/3$
4	$S_{12}$	$S_{23}$	$S_{31}$	$V_{BC}$	$V_{CA}$	$V_{AB}$	$I_c$	$I_a$	$I_b$	$V_i$	$\omega_i t + 4\pi/3$	$I_0$	$\omega_0 t + 2\pi/3$
5	$S_{13}$	$S_{21}$	$S_{23}$	$V_{CA}$	$V_{AB}$	$V_{BC}$	$I_b$	$I_c$	$I_a$	$V_i$	$\omega_i t + 2\pi/3$	$I_0$	$\omega_0 t + 4\pi/3$
6	$S_{13}$	$S_{22}$	$S_3$	$-V_{BC}$	$-V_{AB}$	$-V_{CA}$	$I_c$	$I_b$	$I_a$	$-V_i$	$-\omega_i t + 2\pi/3$	$I_0$	$-\omega_0 t + 4\pi/3$

**Table II. 2 :Second family (Stationary vectors)**

		Closed switches			Output voltages			Input current			Voltage phasor		Current phasor	
IP	7	$S_{11}$	$S_{22}$	$S_{32}$	$V_{AB}$	0	$-V_{AB}$	$I_3$	$-I_a$	0	$n_v \cdot V_{AB}$	0	$n_{i,i_2}$	$\pi/6$
1 N	8	$S_{12}$	$S_{21}$	$S_{31}$	$-V_{AB}$	0	$V_{AB}$	$-I_a$	$I_a$	0	$-n_v \cdot V_{AB}$	0	$-n_{i,i_1}$	$\pi/6$
2 P	9	$S_{12}$	$S_{23}$	$S_{33}$	$V_{BC}$	0	$-V_{BC}$	0	$I_3$	$-I_a$	$n_v \cdot V_{BC}$	0	$n_{i,i_2}$	$\pi/2$
2 N	10	$S_{13}$	$S_{22}$	$S_{32}$	$-V_{BC}$	0	$V_{BC}$	0	$-I_a$	$-I_a$	$-n_v \cdot V_{BC}$	0	$-n_{i,i_1}$	$\pi/2$
3 P	11	$S_{13}$	$S_{21}$	$S_{31}$	$V_{CA}$	0	$-V_{CA}$	$-I_a$	0	$I_a$	$n_v \cdot V_{CA}$	0	$n_{i,i_2}$	$7\pi/6$
3 N	12	$S_{11}$	$S_{23}$	$S_{33}$		0	$V_{CA}$	$I_2$	0	$-I_a$	$-n_v \cdot V_{CA}$	0	$-n_{i,i_1}$	$7\pi/6$
4 P	13	$S_{12}$	$S_{21}$	$S_{32}$	$-V_{AB}$	$V_{AB}$	0	$I_b$	$-I_b$	0	$n_v \cdot V_{AB}$	$2\pi/3$	$n_{i,i_b}$	$\pi/6$

**Table II. 3: Third family (Stationary vectors)**

4 N	1 4	$S_{12}$	$S_{31}$	$S_{22}$	$V_{AB}$	$-V_{AB}$	0	$-I_b$	$I_b$	0		$\frac{2\pi}{3}$	$-n_i i_i$	$\frac{\pi}{6}$
5 P	1 5	$S_{22}$	$S_{22}$	$S_{22}$	$-V_{BC}$	$V_{BC}$	0	0	$I_b$	$-I_b$	$n_v \cdot V_{BC}$	$\frac{2\pi}{3}$	$n_i i_b$	$\frac{\pi}{2}$
5 N	1 6	$S_{22}$	$S_{22}$	$S_{22}$	$V_{BC}$	$-V_{BC}$	0	0	$-I_b$	$I_b$		$\frac{2\pi}{3}$	$-n_i i_b$	$\frac{\pi}{2}$
6 P	1 7	$S_{22}$	$S_{22}$	$S_{22}$	$-V_{CA}$	$V_{CA}$	0	$-I_b$	0	$I_b$	$n_v \cdot V_{CA}$	$\frac{2\pi}{3}$	$n_i i_b$	$\frac{7\pi}{6}$
6 N	1 8	$S_{22}$	$S_{22}$	$S_{22}$	$V_{CA}$	$-V_{CA}$	0	$I_b$	0	$-I_b$	$-n_v \cdot V_{CA}$	$\frac{2\pi}{3}$	$-n_i i_b$	$\frac{7\pi}{6}$
7 P	1 9	$S_{22}$	$S_{22}$	$S_{22}$	0	$-V_{AB}$	$V_{AB}$	$I_c$	$-I_c$	0	$n_v \cdot V_{AB}$	$\frac{4\pi}{3}$	$n_i i_c$	$\frac{\pi}{6}$
7 N	2 0	$S_{22}$	$S_{22}$	$S_{22}$	0	$V_{AB}$	$-V_{AB}$	$-I_c$	$I_c$	0	$-n_v \cdot V_{AB}$	$\frac{4\pi}{3}$	$-n_i i_c$	$\frac{\pi}{6}$
8 P	2 1	$S_{22}$	$S_{22}$	$S_{22}$	0	$-V_{BC}$	$V_{BC}$	0	$I_c$	$-I_c$	$n_v \cdot V_{BC}$	$\frac{4\pi}{3}$	$n_i i_c$	$\frac{\pi}{2}$
8 N	2 2	$S_{22}$	$S_{22}$	$S_{22}$	0	$V_{BC}$	$-V_{BC}$	0	$-I_c$	$I_c$	$-n_v \cdot V_{BC}$	$\frac{4\pi}{3}$	$-n_i i_c$	$\frac{\pi}{2}$
9 P	2 3	$S_{22}$	$S_{22}$	$S_{22}$	0	$-V_{CA}$	$V_{CA}$	$-I_c$	0	$I_c$	$n_v \cdot V_{CA}$	$\frac{4\pi}{3}$		$\frac{7\pi}{6}$
9 N	2 4	$S_{22}$	$S_{22}$	$S_{22}$	0	$V_{CA}$	$-V_{CA}$	$I_c$	0	$-I_c$	$-n_v \cdot V_{CA}$	$\frac{4\pi}{3}$	$-n_i i_c$	$\frac{7\pi}{6}$

The 18 resulting space vectors presented in Table II-2 are characterized by a variable amplitude and a constant phase. Their representations on a complex plane allow for the construction of voltage and current hexagons [55]. The first column of the table identifies the configurations based on the sign of the modulus of the calculated space vector.

**Table II. 4: family (Stationary vectors)**

	Closed switches			Output voltages			Input current			Voltage phasor		Current phasor	
	$S_{11}$	$S_{21}$	$S_{31}$										
25	$S_{11}$	$S_{21}$	$S_{31}$	0	0	0	0	0	0	0	0	0	0
26	$S_{12}$	$S_{22}$	$S_{32}$	0	0	0	0	0	0	0	0	0	0
27	$S_{13}$	$S_{23}$	$S_{33}$	0	0	0	0	0	0	0	0	0	0

### II.3 Results and discussion:

#### II.3 .1 PWM three interval result:

Figure II.5 illustrates a periodic square-wave waveform indicative of PWM controlled load voltage regulation using an Alimonte MC. The waveform's amplitude and frequency suggest effective control and a wide range of potential applications, including motor drives, power conditioning, and renewable energy systems. Further analysis considering PWM duty cycle, switching frequency, and load characteristics would provide deeper insights into the system's performance.

Figure II.6 illustrates a sinusoidal waveform representing the current drawn by a load. The waveform's amplitude and frequency indicate a typical AC load, commonly found in various applications such as motor drives, power systems, and industrial processes. Further analysis considering load power, power factor, and harmonic content would provide deeper insights into the load's characteristics and its interaction with the system.

Figure II.7 presents a harmonic spectrum that reveals a significant level of harmonic distortion in the waveform. The prominent harmonics at lower orders indicate a potential for various power quality issues. Further analysis considering waveform analysis, load characteristics, and mitigation techniques would provide deeper insights into the sources and impacts of harmonics, enabling effective measures to address these challenges.

Figure II.8 presents a quasi-square wave waveform indicative of Venturini-controlled load voltage regulation with variations in pulse widths and amplitudes. The waveform demonstrates a degree of voltage regulation, but further analysis considering Venturini modulation parameters, load characteristics, and control algorithms would provide deeper insights into the system's performance and potential applications.

Figure II.9 illustrates a sinusoidal waveform representing the current drawn by a load. The waveform's amplitude and frequency indicate a typical AC load, commonly found in various applications such as motor drives, power systems, and industrial

processes. Further analysis considering load power, power factor, and harmonic content would provide deeper insights into the load's characteristics and its interaction with the system.

Figure II.10 presents a harmonic spectrum that reveals a significant level of harmonic distortion in the waveform. The prominent harmonics at lower orders indicate a potential for various power quality issues. Further analysis considering waveform analysis, load characteristics, and mitigation techniques would provide deeper insights into the sources and impacts of harmonics, enabling effective measures to address these challenges.

Figure II.11 illustrates a square-wave waveform indicative of SVM-controlled load voltage regulation. The waveform's amplitude and frequency suggest effective control and a wide range of potential applications, including motor drives, power conditioning, and renewable energy systems. Further analysis considering SVM switching sequence, sampling frequency, and load characteristics would provide deeper insights into the system's performance.

Figure II.12: illustrates a sinusoidal waveform indicative of SVM-controlled load current regulation. The waveform's amplitude and frequency suggest effective control and a wide range of potential applications, including motor drives, power conditioning, and renewable energy systems. Further analysis considering SVM switching sequence, sampling frequency, and load characteristics would provide deeper insights into the system's performance.

Figure II.13 presents a harmonic spectrum that reveals a moderate level of harmonic distortion in the waveform. The prominent harmonics at lower orders indicate a potential for various power quality issues. Further analysis considering waveform analysis, load characteristics, and mitigation techniques would provide deeper insights into the sources and impacts of harmonics, enabling effective measures to address these challenges.

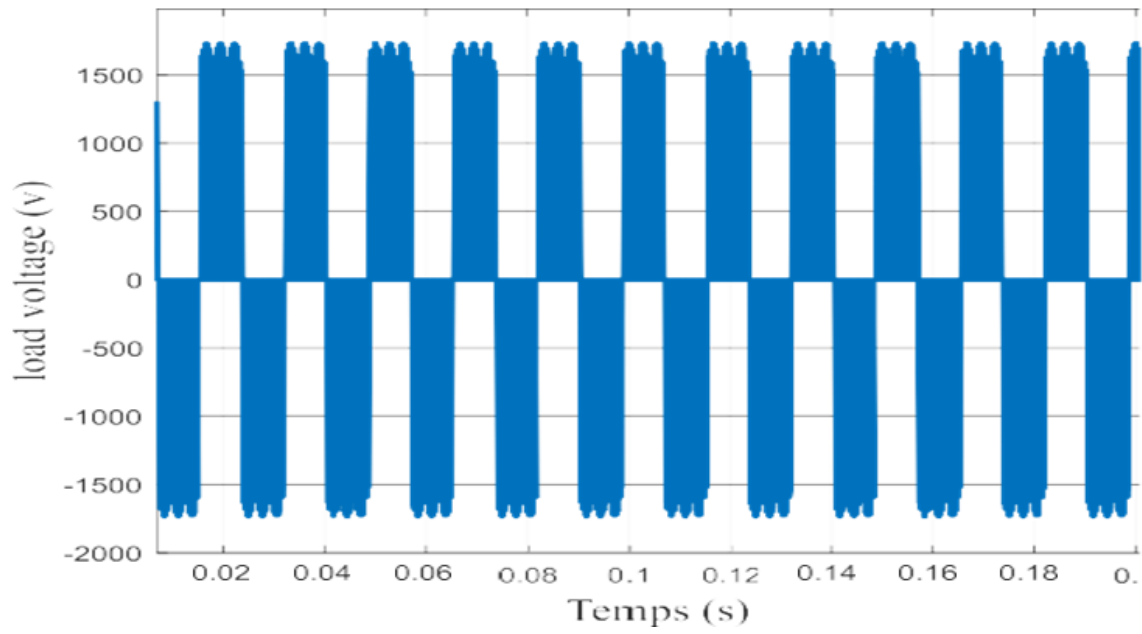


Figure II. 5:Output voltage(v)

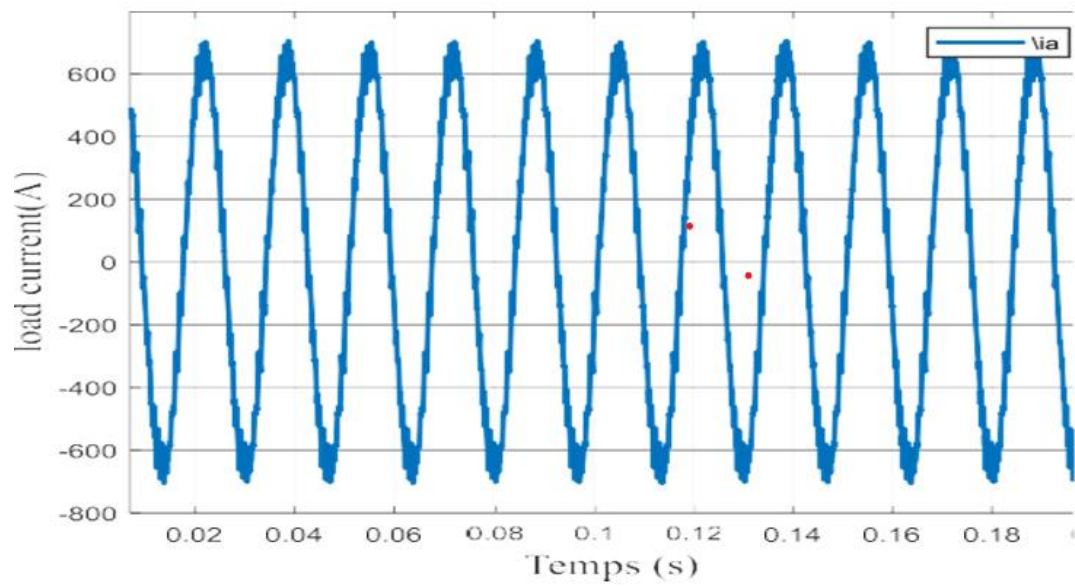


Figure II. 6:load current RL(A)

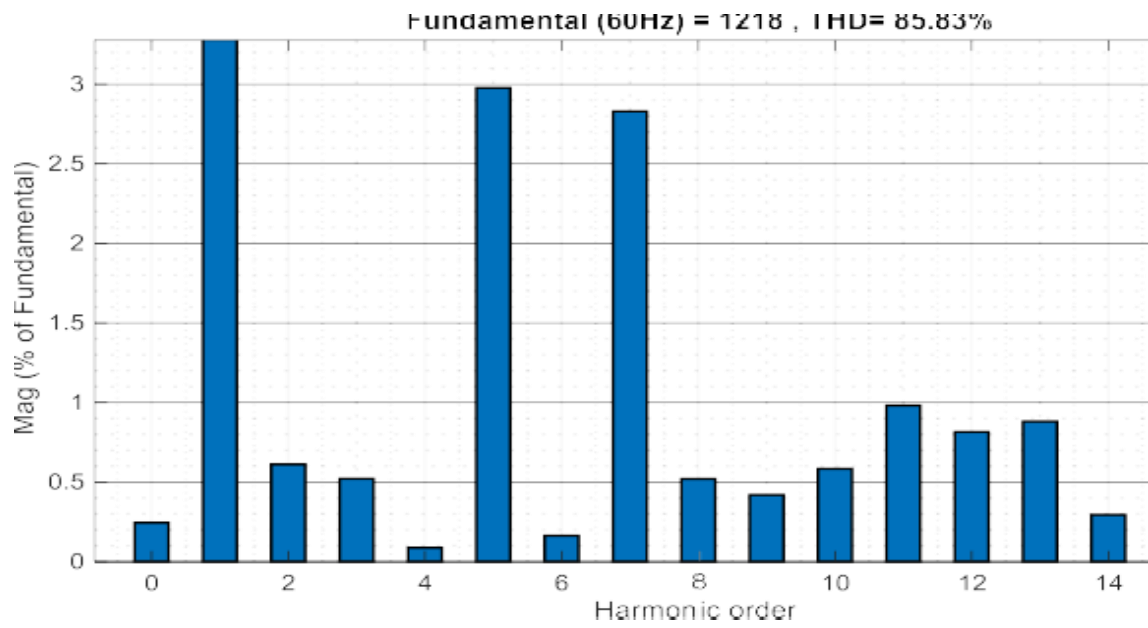


Figure II. 7:THD of output voltage

II.3 .2 Venturini result:

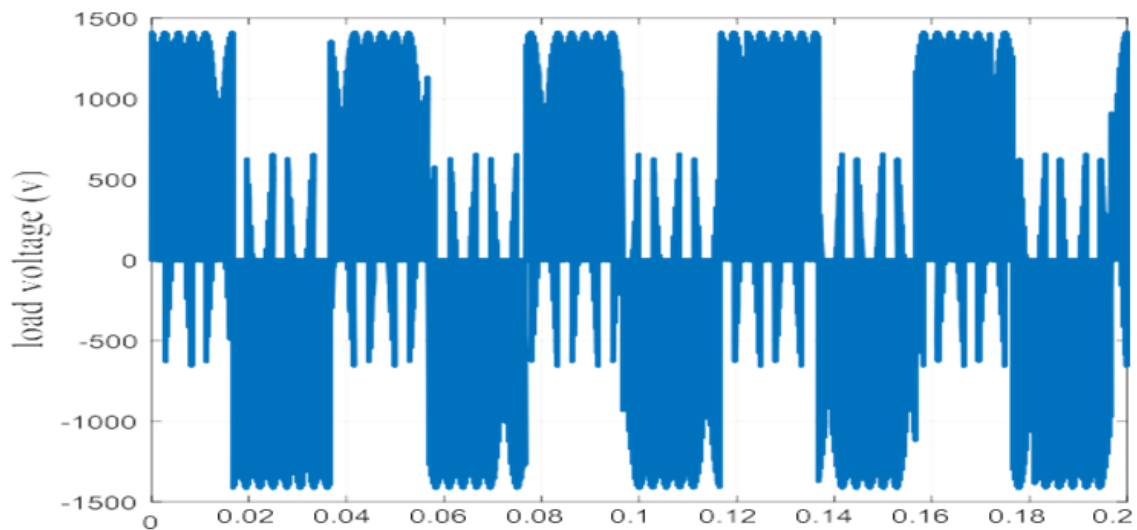
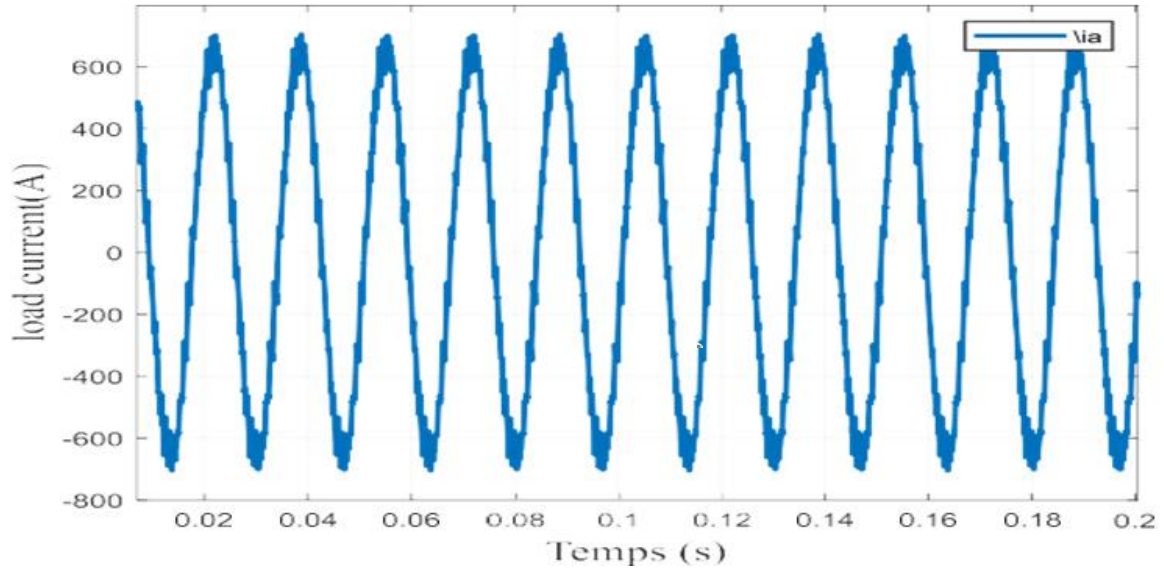
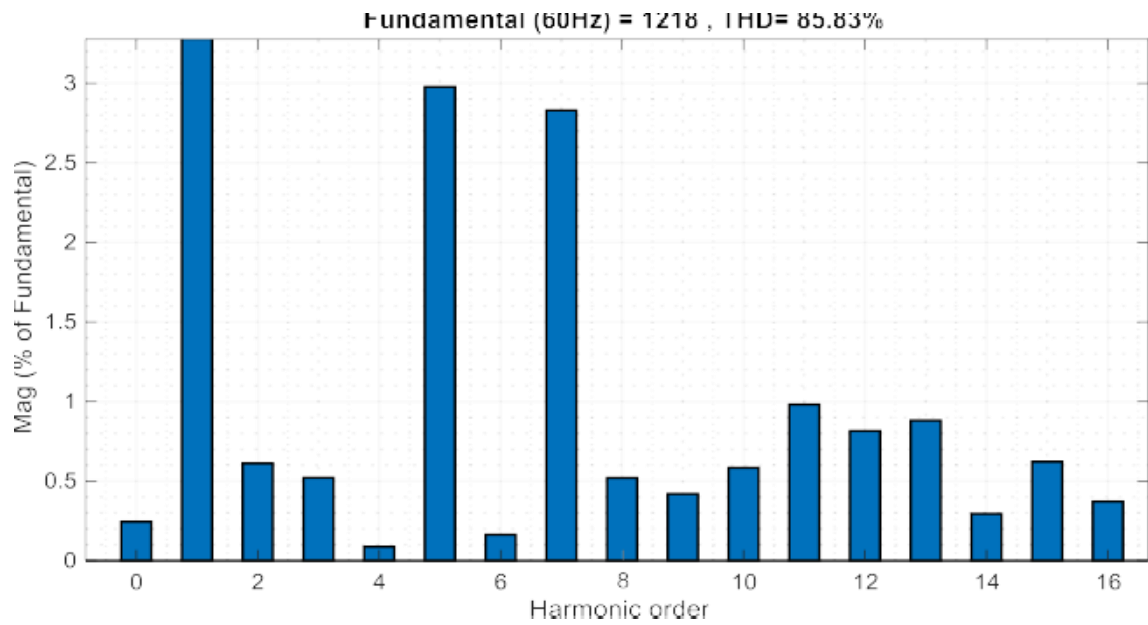


Figure II. 8 :Output voltage(v)

**Chapter II: A Comprehensive Study of Matrix Converters and a Comparative Analysis of Control Strategies**



**Figure II. 9 :load current(A)**



**Figure II. 10 :THD of output voltage**

II.3 .3. SVM method results:

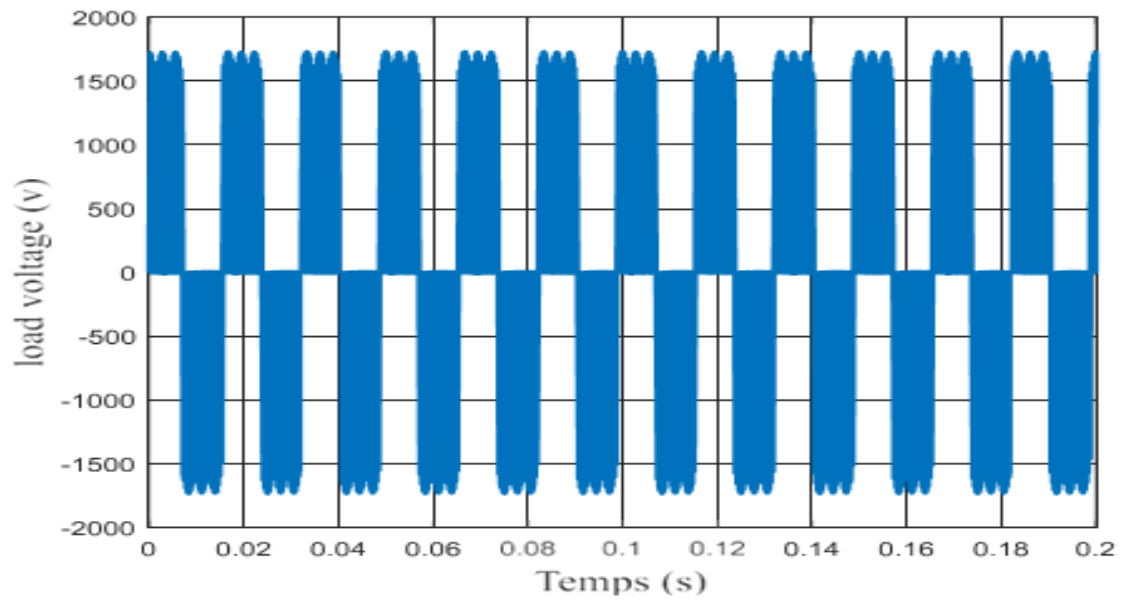


Figure II. 11 :load voltage(v)

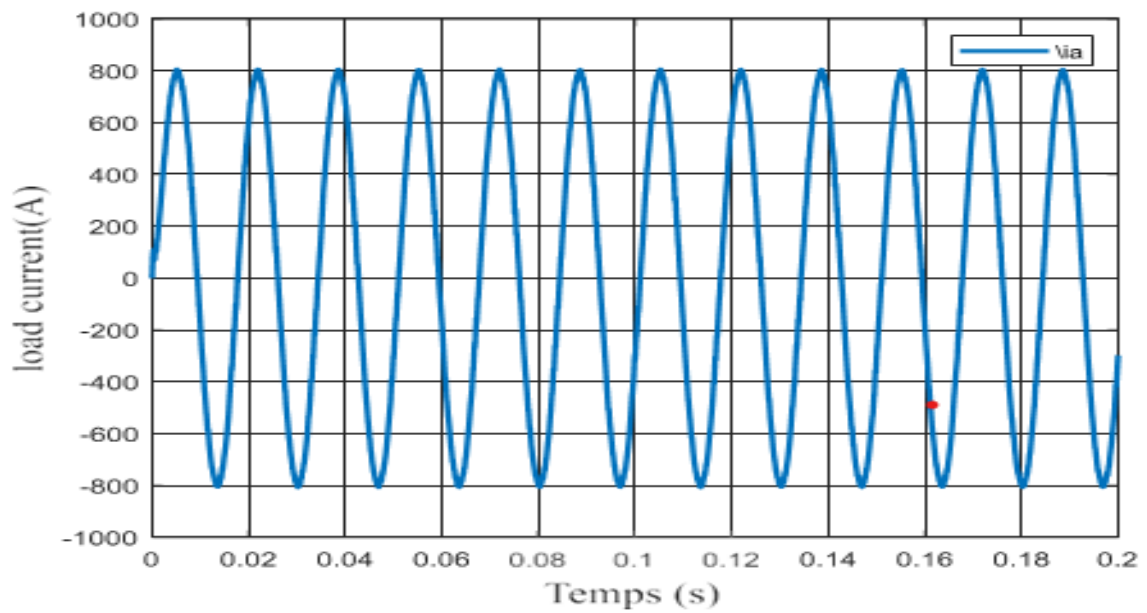


Figure II. 12 :load current RL(A)

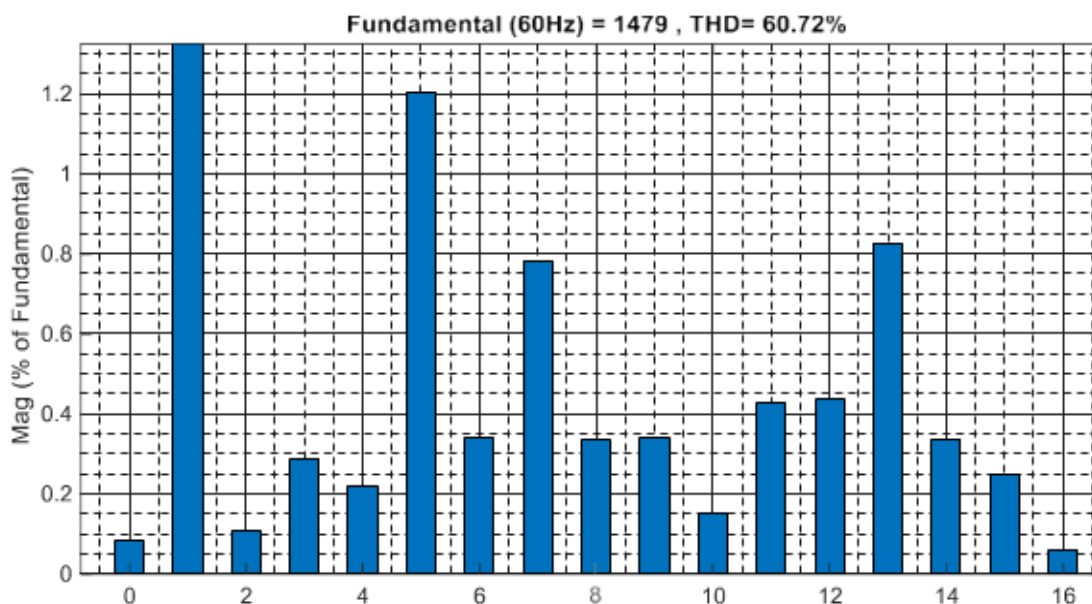


Figure II. 13:THD of output voltage

The comparative analysis examines three different techniques—Support Vector Machine (SVM), Venturini, and Pulse Width Modulation (PWM) with three intervals modulation—for controlling an AC/AC three-phase matrix converter. Each technique has its own characteristics and advantages, which are evaluated and compared in the analysis.

SVM: Support Vector Machine is a machine learning algorithm that can be utilized for control purposes. In this context, SVM is likely employed as a controller for the matrix converter. The analysis assesses the performance of SVM in terms of its ability to regulate the AC/AC converter and highlights its strengths and limitations compared to the other techniques.

Venturini: Venturini refers to the Venturini method, which is a well-known modulation technique used for controlling matrix converters. It involves a specific algorithm that determines the switching states of the converter's switches based on the desired output. The analysis examines the performance of the Venturini method and compares it with the other techniques in terms of control accuracy, efficiency, and other relevant factors. PWM with three intervals modulation: Pulse Width Modulation (PWM) is a widely used modulation technique in power electronics. In this analysis, PWM is implemented with a three-interval modulation strategy.

The analysis explores how this specific approach performs in controlling the AC/AC matrix converter, and it evaluates its advantages and disadvantages when compared to the SVM and Venturini techniques. The objective of the comparative analysis is to determine the most suitable control technique for the AC/AC three-phase matrix converter based on various criteria such as control accuracy, efficiency, complexity, implementation cost, and other relevant factors.

By comparing and contrasting the performance of SVM, Venturini, and PWM with three intervals modulation techniques, the analysis aims to provide insights into their respective strengths and limitations in the context of the matrix converter control.

#### **II.4 Exploring the Transition from MC to MMMC**

During this work with the traditional matrix converter and after the simulation result and analysis, we encountered significant limitations in achieving effective Total Harmonic Distortion (THD) reduction. Although the matrix converter is appreciated for its simple design and bidirectional power flow capability, its inherent structure posed challenges in delivering high-quality power with acceptable THD levels. The limitations were particularly evident in high-power applications, where the lack of additional voltage levels resulted in waveform distortion, leading to inefficiencies and potential issues with equipment longevity. Furthermore, developing control methods for THD minimization proved increasingly complex, as the matrix converter's design inherently restricted the degree of harmonic mitigation achievable.

These challenges highlighted the need for a more sophisticated approach, prompting a shift to the multilevel matrix converter. By incorporating multiple voltage levels, the multilevel matrix converter inherently improves the quality of output waveforms, drastically reducing THD without overly complex control strategies. This structural advancement ensures higher efficiency, better compliance with grid standards, and improved overall system performance. Additionally, the multilevel architecture provides greater flexibility in addressing grid-connected applications and renewable energy systems, making it a superior choice for modern energy conversion needs. This transition not only overcomes the drawbacks of the classic matrix converter but

also opens avenues for exploring innovative control techniques to further optimize power quality and efficiency.

## **II.5 Conclusion**

Chapter II has provided a detailed analysis of the modulation techniques used in MC, highlighting their critical role in achieving sinusoidal output voltages. The chapter examined key modulation methods, including the Venturini algorithm, space vector modulation, and vectorial MLI modulation, each contributing to the versatility and reliability of matrix converters.

The Venturini algorithm, with its unique approach to switching sequence generation, effectively mitigates low-frequency harmonics, thereby improving output voltage quality. Similarly, space vector modulation, a widely adopted technique, offers benefits such as reduced switching frequency and minimized harmonic distortion, making it an effective method for achieving high-quality sinusoidal output voltages. Moreover, vectorial MLI modulation demonstrates its potential to further enhance the performance and efficiency of matrix converters, particularly in demanding high-power applications.

Despite the advancements in modulation techniques, working with the traditional matrix converter revealed significant challenges in reducing THD, especially in high-power scenarios. The simple design and bidirectional power flow capability of the matrix converter were insufficient to overcome waveform distortions and inefficiencies caused by the lack of additional voltage levels. These limitations, coupled with the complexity of developing effective THD control strategies, underscored the need for a more advanced solution: the multilevel matrix converter. This innovative design significantly improves waveform quality, reduces THD, enhances efficiency, and provides greater adaptability for grid-connected and renewable energy systems, making it a superior choice for modern energy conversion requirements.

## **Chapter II: A Comprehensive Study of Matrix Converters and a Comparative Analysis of Control Strategies**

In conclusion, Chapter 2 has demonstrated the importance of modulation techniques in advancing the performance of matrix converters while recognizing their limitations in addressing power quality issues. This realization sets the stage for the next chapter, where we will explore the modulation and control strategies specifically designed for multilevel matrix converters, paving the way for further improvements in power quality and efficiency.

**Chapter III:  
Modulation and  
Control Strategy of a  
MMMC-FC**

### **III .1 Introduction**

In this chapter, we delve into the intricacies of the Modular Multilevel Matrix Converter (MMC) equipped with three flying capacitors (FC), a topology that has gained prominence in the field of power electronics for its ability to facilitate efficient and high-quality AC to AC conversion. The MMCFC is particularly well-suited for medium- and high-voltage applications, where its modular design allows for scalability and flexibility in operation. The use of three flying capacitors per output phase enhances the performance of the converter by improving voltage balancing and reducing harmonic distortion. This chapter aims to provide a comprehensive overview of the modeling and control strategies employed in this advanced converter topology. We begin by discussing the fundamental principles of the MMCFC, including its operational characteristics. The chapter will then explore the mathematical modeling of the MMCFC. Subsequently, we will examine the control strategies that are essential for the effective operation of the MMCFC. This includes modulation techniques for generating switching signals, voltage balancing control for the flying capacitors, and feedback mechanisms to ensure optimal performance under load conditions.

### **III .2 Overview of Modular Multilevel Matrix Converter with three flying capacitors**

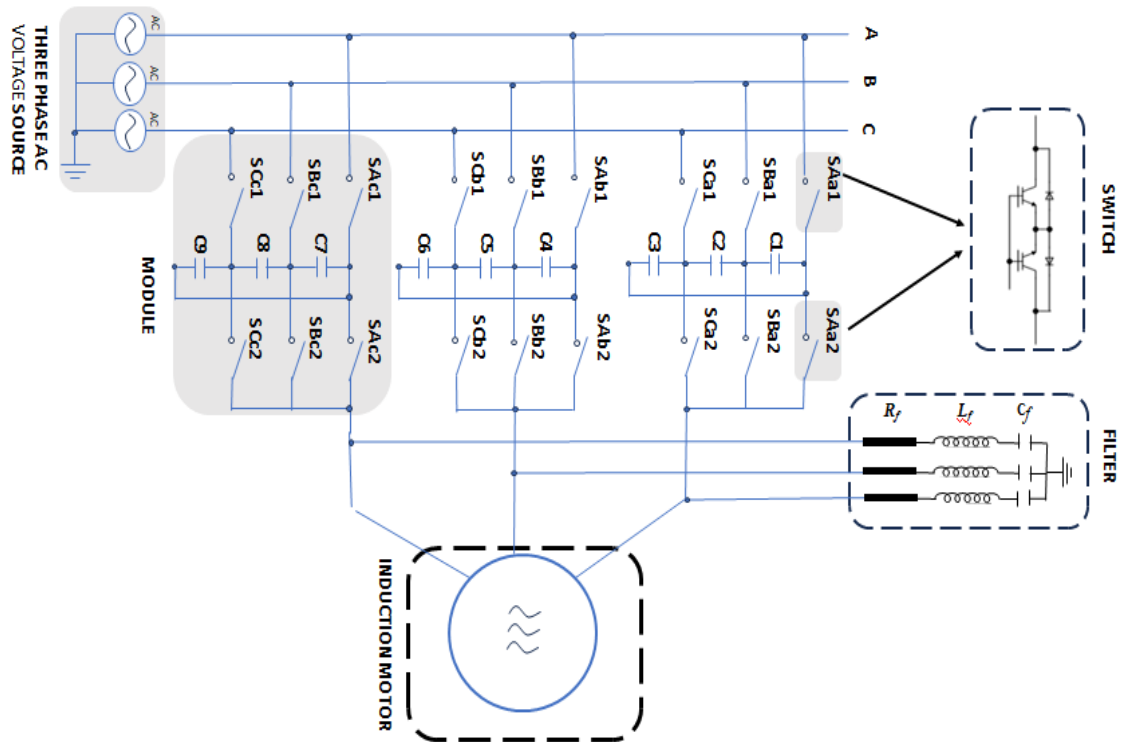
The MMC-FC is an advanced power conversion topology designed for high-power applications. It combines the principles of MMC and MC to achieve superior performance in terms of power quality, efficiency, and scalability. Integrating three flying capacitors into the design enhances its functionality, allowing for improved voltage balancing and reduced switching complexity.

#### **III .2.1 Modular Multilevel Matrix Converter with three Flying Capacitors.**

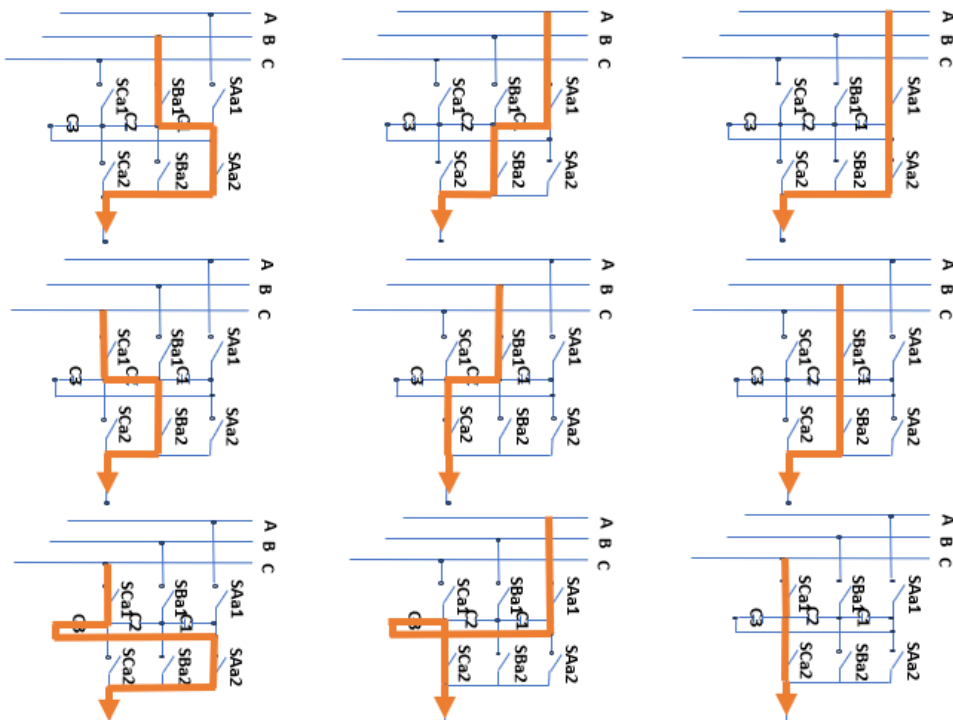
The Modular Multilevel Matrix Converter with three Flying Capacitors (MMCFC) topology, shown in Figure I.16.a [23,36], features three flying capacitors per output phase and employs bidirectional IGBT switches. The subsequent analysis examines

its

characteristics.



(a)



(b)

Figure III. 1 a. Modular Multilevel Matrix Converter with three flying capacitors. b Switching combinations of three-phase MMMCFC

Consider switches SAa1, SAa2, SBa1 and SBa2 and capacitor C1. Assuming all switches are identical with an off resistance of R<sub>off</sub>, we can apply Kirchhoff's law to the four switches while they are turned off. With C1 connected to V<sub>ab</sub> as illustrated in Figure I.20.a, the voltage V<sub>c1</sub> across C1 can be expressed as follows:

$$V_{c1} = \frac{V_{AB}}{4R_{off}} * 2R_{off} = \frac{(V_A - V_B)}{2} \quad (III.1)$$

where V<sub>c1</sub> has a positive polarity at the top plate and a negative polarity at the bottom plate. This same analysis applies to the other capacitor clamped as well C2 to C9. Thus, V<sub>c1</sub> = V<sub>c4</sub> = V<sub>c7</sub>, V<sub>c2</sub> = V<sub>c5</sub> = V<sub>c8</sub> and V<sub>c3</sub> = V<sub>c6</sub> = V<sub>c9</sub>.

Figure I.16 a, For the aforementioned switch combinations, we can apply Kirchhoff's law, resulting in the validity of Table III.1. A detailed representation for output phase A is provided in table I.2 in chapter I [23, 36]. This table is visually represented in Figure I.16.b. The capacitance of the flying capacitor C1 is determined using the following equation:

$$C_1 = \frac{I_o}{\Delta V_c * p * f_{sw}} \quad (III.2)$$

**Table III. 1 :MMC-FC– Truth Table**

N	S <sub>Aa1</sub>	S <sub>Aa2</sub>	S <sub>Ba1</sub>	S <sub>Ba2</sub>	Output Voltage v <sub>a</sub>
1	1	1	0	0	V <sub>A</sub>
2	0	0	1	1	V <sub>B</sub>
3	1	0	0	1	(V <sub>A</sub> + V <sub>B</sub> )/2
4	0	1	1	0	(V <sub>A</sub> + V <sub>B</sub> )/2

**Table III. 2 : MMMCFC– Complete Truth Table**

N	$S_{Aa1}$	$S_{Aa2}$	$S_{Ba1}$	$S_{Ba2}$	$S_{Ca1}$	$S_{Ca2}$	Output Voltage $v_a$
1	1	1	0	0	0	0	$V_A$
2	1	0	0	1	0	0	$(V_A + V_B)/2$
3	0	1	1	0	0	0	$(V_A + V_B)/2$
4	0	0	1	1	0	0	$V_B$
5	0	0	1	0	0	1	$(V_B + V_C)/2$
6	0	0	0	1	1	0	$(V_B + V_C)/2$
7	0	0	0	0	1	1	$V_C$
8	0	1	0	0	1	0	$(V_A + V_C)/2$
9	1	0	0	0	0	1	$(V_A + V_C)/2$

where  $I_o$  represents the peak load current,  $p$  is the number of cells per output phase,  $f_{sw}$  is the switching frequency, and  $\Delta V_c$  denotes the voltage ripple of the capacitor clamped. The switching function for the bidirectional switches in Figure I.16 in chapter I expressed as follows:

$$S_{ijk} = \begin{cases} 0 & \text{when switch open} \\ 1 & \text{when switch closed} \end{cases}$$

$$S_{Ajk} + S_{Bjk} + S_{Cjk} = 1$$

$$i \in A, B, C; j \in a, b, c \text{ and } k = \text{switch column count } 1,2$$

### III.3 Mathematical Modeling

Modeling a Modular Multilevel Matrix Converter with three Flying Capacitors (MMMCFC) involves several steps, including defining the system architecture, establishing the mathematical equations governing the operation, and simulating the system using software tools like SIMULINK. Below is a general outline of the modeling process for an MMMCFC:

The modelling equation referring to table I.2 in chapter I for the output voltage can be expressed as follows:

$$\begin{bmatrix} v_a \\ v_b \\ v_c \end{bmatrix} = \begin{bmatrix} S_{AG} & S_{Ba} & S_{Ca} & S_{C1} & S_{C2} & S_{Ca} \\ S_{Ab} & S_{Bb} & S_{Cb} & S_{C4} & S_{C5} & S_{Cb} \\ S_{AC} & S_{BC} & S_{CC} & S_{C7} & S_{CB} & S_{C9} \end{bmatrix} \times \begin{bmatrix} v_A \\ v_B \\ v_C \\ (v_A + v_B)/2 \\ (v_C + v_B)/2 \\ (v_A + v_C)/2 \end{bmatrix} \quad (\text{III.3})$$

Where

$$\begin{aligned} S_{Ab} &= S_{Ab1} \cap S_{Ab2}; S_{Bb} = S_{Bb1} \cap S_{Bb2} \\ S_{Cb} &= S_{Cb1} \cap S_{Cb2} \\ S_{C4} &= S_{Ab1} \cap S_{Bb2} \cup S_{Bb1} \cap S_{Ab2}; S_{C5} = S_{Bb1} \cap S_{Cb2} \cup S_{Cb1} \cap S_{Bb2} \\ S_{C6} &= S_{Ab1} \cap S_{Cb2} \cup S_{Cb1} \cap S_{Ab2} \\ S_{AC} &= S_{Ac1} \cap S_{Ac2}; S_{BC} = S_{BC1} \cap S_{BC2}; S_{CC} = S_{Cc1} \cap S_{Cc2} \\ S_{C7} &= S_{Ac1} \cap S_{Bc2} \cup S_{Bc1} \cap S_{Ac2}; S_{CB} = S_{Bc1} \cap S_{Cc2} \cup S_{Cc1} \cap S_{Bc2} \\ S_{C9} &= S_{Ac1} \cap S_{Cc2} \cup S_{Cc1} \cap S_{Ac2} \end{aligned}$$

1= Switch closed                      0= Switch open operator

$\cap$ = AND operator                       $\cup$ = OR operator

$$\begin{bmatrix} i_A \\ i_B \\ i_C \end{bmatrix} = \begin{bmatrix} (S_{Aa} \cup S_{ABa} \cup S_{ACa}) & (S_{Ab} \cup S_{ABb} \cup S_{ACb}) & (S_{Ac} \cup S_{ABc} \cup S_{ACc}) \\ (S_{Ba} \cup S_{BAa} \cup S_{BCa}) & (S_{Bb} \cup S_{BAB} \cup S_{BCb}) & (S_{Bc} \cup S_{BAC} \cup S_{BCc}) \\ (S_{Ca} \cup S_{CAa} \cup S_{CBa}) & (S_{Cb} \cup S_{CAB} \cup S_{CBb}) & (S_{Cc} \cup S_{CAC} \cup S_{CBc}) \end{bmatrix} * \begin{bmatrix} i_a \\ i_b \\ i_c \end{bmatrix} \quad (\text{III.4})$$

Where:

$$\begin{aligned}
 S_{Aa} &= S_{Aa1} \cap S_{Aa2} S_{ABa} = S_{Aa1} \cap S_{Ba2} \\
 S_{ACa} &= S_{Aa1} \cap S_{Ca2} \\
 S_{Ba} &= S_{Ba1} \cap S_{Ba2} S_{BAa} = S_{Ba1} \cap S_{Aa2} \\
 S_{BCa} &= S_{Ba1} \cap S_{Ca2} \\
 S_{Ca} &= S_{Ca1} \cap S_{Ca2} S_{CAa} = S_{Ca1} \cap S_{Aa2} \\
 S_{CBa} &= S_{Ca1} \cap S_{Ba2} \\
 S_{Ab} &= S_{Ab1} \cap S_{Ab2} S_{ABb} = S_{Ab1} \cap S_{Bb2} \\
 S_{ACb} &= S_{Ab1} \cap S_{Cb2} \\
 S_{Bb} &= S_{Bb1} \cap S_{Bb2} S_{BAb} = S_{Bb1} \cap S_{Ab2} \\
 S_{BCb} &= S_{Bb1} \cap S_{Cb2} \\
 S_{Cb} &= S_{Cb1} \cap S_{Cb2} S_{CAb} = S_{Cb1} \cap S_{Ab2} \\
 S_{CBb} &= S_{Cb1} \cap S_{Bb2} \\
 S_{Ac} &= S_{Ac1} \cap S_{Ac2} S_{ABc} = S_{Ac1} \cap S_{Bc2} \\
 S_{ACc} &= S_{Ac1} \cap S_{Cc2} \\
 S_{Bc} &= S_{Bc1} \cap S_{Bc2} S_{BAc} = S_{Bc1} \cap S_{Ac2} \\
 S_{BCc} &= S_{Bc1} \cap S_{Cc2} \\
 S_{Cc} &= S_{Cc1} \cap S_{Cc2} S_{CAc} = S_{Cc1} \cap S_{Ac2} \\
 S_{CBc} &= S_{Cc1} \cap S_{Bc2}
 \end{aligned}$$

### III .3.1 Control of the MMC-FC by the Venturini Method

Let the (input /output) voltages be expressed using the formulas found in Chapter 2 equations II.1 and II.4, respectively. The nine modulation functions for a 3PH AC to 3Ph AC. conventional Equation III.4 provides a standard matrix converter. The following is the adjusted modulation function for the 18 bidirectional switches of the three-phase MMC seen in Figure I.16.a, assuming a unity input phase displacement factor:

$$M_{ijk} = \frac{t_{ijk}}{T_s} = \left[ \frac{1}{3} + \frac{2v_i \cdot v_j}{3 \cdot V_{im}^2} \right] \quad (\text{III .5})$$

for  $i \in A, B, C$ ; and  $j \in a,b,c$  and  $k. \in 1,2$

Signals controlling switches in individual cells of the converter should be shifted with respect to each other by an angle of  $2\pi/p$ , where  $p$  is the number of switching cells which in this case is two. Displacement of carrier signals involved in the control of switches  $S_{ij1}$  and  $S_{ij2}$  is  $T_{sw}/2$ , where  $T_{sw} = 1/f_{sw}$  is the carrier switching period. Duty cycles for switch group  $S_{ij1}$  are by comparison of modulation function with the saw-tooth carrier starting from the origin and that for switch group  $S_{ij2}$  are by

comparison of the modulation functions with the saw-tooth carrier phase shifted by  $T_{sw}/2$  or  $\pi$  rad [36]

#### III .4 Model of output filter

The output filter circuit shown in Figure 1a is an RLC circuit, where ( $R_f$ ,  $L_f$ ,  $C_f$ ) are linked in series. The resonant frequency of this circuit is designed to be equal to the carrier switching frequency  $f_{sw}$  [36], as shown below:

$$f_{siv} = \frac{1}{(2\pi*\sqrt{L_f C_f})} \quad (III.6)$$

#### III .4 Schematic and configuration of the modeled MMCFC

The modeling diagram and configuration of a Modular Multilevel Matrix Converter with three Flying Capacitors (MMCFC) illustrate its key components and operation. The MMCFC consists of multiple cells with bidirectional switches (usually IGBTs) and flying capacitors, which enable AC to AC conversion with multiple voltage levels per phase. Flying capacitors are essential for voltage balancing and refining the output waveform, minimizing harmonic distortion, and improving power quality. They distribute voltage across phases, contributing to the converter's reliability and performance.

Switching cells are arranged in a matrix, allowing independent control of the output voltage, with phase-shifted control signals minimizing switching losses and reducing stress on components. Advanced control algorithms, like the Venturini method, are employed to optimize gate pulses, ensuring efficient operation and high-quality output signals.

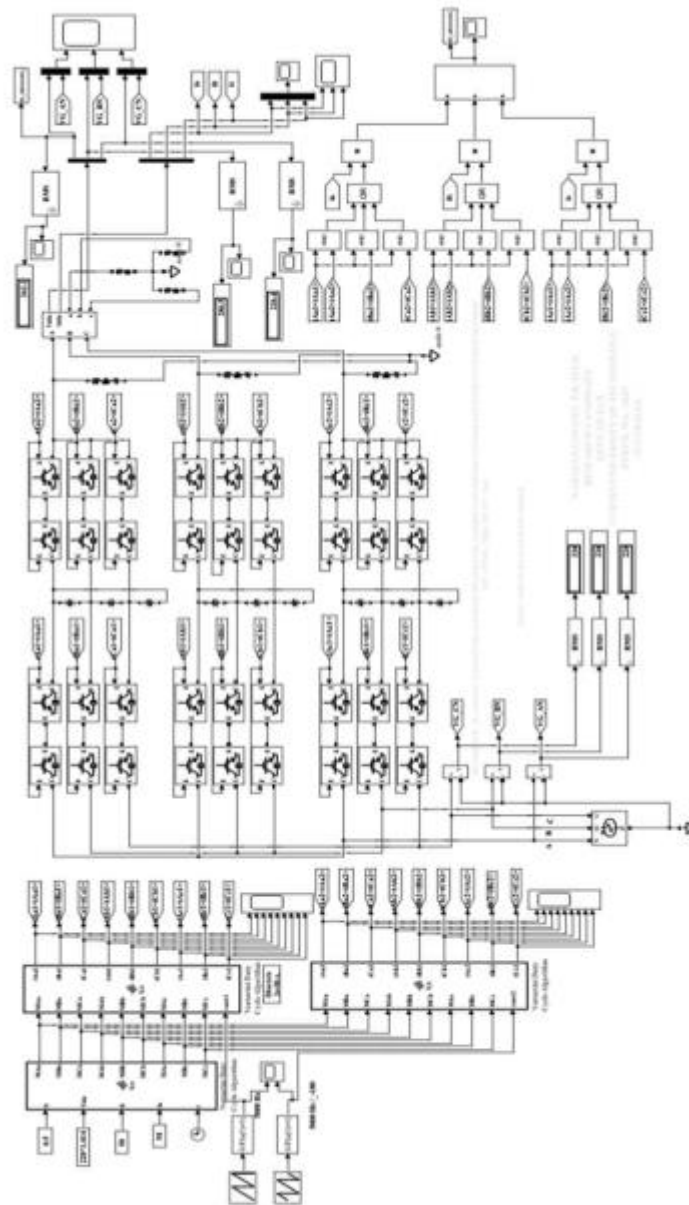
An output filter, typically an RLC circuit, is connected to smooth the waveform and reduce harmonics, with its resonant frequency matched to the carrier switching frequency. This results in a cleaner output suitable for various applications.

The MMCFC is often modeled in simulation tools like SIMULINK, where blocks represent components such as switches, capacitors, and filters. Inputs include AC

voltage and modulation functions, while outputs are analyzed for quality and performance metrics.

#### **III .4.1 Model Development**

Model of the 3PH AC/AC MMCFC using SIMULINK [41] is shown in Figure **III.2**. The model parameters are shown in **Table III.3**. The modulation function shown in equation **III .5** is used to calculate the duty cycle for the bidirectional switches. In Figure **III.1**, the Embedded MATLAB Function with the inputs  $q$ ,  $V_{im}$ ,  $f_i$ ,  $f_o$  and time module calculates the nine modulation functions for the three-phase input and output voltages defined



**Figure III. 2: Model of MMMC-FC in MATLAB**

In Equations II.1 and II.4 of Chapter 2, each phase voltage for the input and output is shifted by  $\pi/2$  radians. The source code remains the same. The switching pulses for the nine switches, from SAa1 to SCc1 in the first column of Figure III.1.a, are generated by comparing their respective modulation functions with a 5 kHz sawtooth waveform ( $V_{saw1}$ ) and applying a logic operation using a second Embedded MATLAB Function. Similarly, for the second group of bidirectional switches, from SAa2 to SCc2 in the second column of Figure III.1.a, the pulses are generated by

comparing the modulation functions with another 5 kHz sawtooth waveform ( $V_{saw2}$ ), which is phase-shifted by  $\pi$  radians, or  $T_{sw}/2$  seconds ( $1/(2*f_{sw})$ ), from  $V_{saw1}$ , followed by a logic operation via a third Embedded MATLAB Function. The source code handles the logic operation to generate gate pulses for both groups of nine bidirectional switches. The key difference is that the second Embedded MATLAB Function compares the modulation functions with  $V_{saw1}$  to create gate pulses ( $t_{Aa1}$  to  $t_{Cc1}$ ) for the first column, while the third Embedded MATLAB Function compares them with  $V_{saw2}$  to generate pulses ( $t_{Aa2}$  to  $t_{Cc2}$ ) for the second column. The output filter parameters are chosen assuming a resistance of  $10 \Omega$ , an inductance of 2 mH, and a filter capacitor determined using Equation III.6 based on the switching frequency  $f_{sw}$  in Table III.3. The three-phase AC voltage can be generated by inputting (381.04, 0, 50) into the three-phase programmable voltage source model. Phase A input current ( $i_A$ ) is derived using logic gates, multipliers, and summers, as outlined in Equation III.4. The flying capacitors (C1 to C9) in Figure III.1.a are chosen based on a peak load current of 2 A and a voltage ripple of  $\Delta V_c$  of 20%, relative to the switching frequency  $f_{sw}$  from Table III.3.

#### **III .5 Explanation of the role of Flying Capacitors in improving the quality of output signals.**

Flying capacitors play a vital role in The Modular Multilevel Matrix Converter with three Flying Capacitors (MMMCFC) by improving output signal quality through several key functions. They enable the generation of multiple voltage levels, which refine the output waveform and reduce harmonic distortion, enhancing power quality. Additionally, flying capacitors assist in voltage balancing across the converter's switches, preventing overvoltage damage and ensuring reliable operation. Their contribution to reducing switching losses further boosts efficiency by allowing fewer state transitions. Moreover, flying capacitors support advanced control strategies, such as the Venturini method, and effectively mitigate harmonics, resulting in smoother and more responsive output signals.

**III .5.1 Parameters used for simulation:**

Table IV.1 presents the parameters of MMC and the load parameters of this simulation.

**Table III. 3: paramatre of MMCFC**

Sl. No.	Parameter	Value	Units
1	RMS line-to-neutral input voltage $V_i$	220	V
2	Input frequency $f_i$	50	Hz
3	Output frequency $f_0$	0.5	Hz
4	Modulation index $q$	5	-
5	Carrier switching frequency $f_w$	10	kHz
6	Flying capacitor $C_1$ to $C_9$	$\mu$ F	
7	Series RLC output filter $R_f, L_f, C_f$	10,2e – 3,0.50712e – 6	$\Omega, H, F$
8	RL load	50,0.5	$\Omega, H$

SIMULINK is a MATLAB-based graphical programming environment used for modeling, simulating, and analyzing dynamic systems, especially in control systems, signal processing, and power electronics such as The Modular Multilevel Matrix Converter with three Flying Capacitors (MMCFC). It features a user-friendly interface with pre-built libraries, allowing users to design systems by dragging and dropping blocks. Its integration with MATLAB provides powerful tools for data analysis and visualization, while supporting real-time simulation testing for validating control algorithms. SIMULINK's use of the fixed-step ode5 (Dormand-Prince) solver, known for its accuracy and stability, makes it particularly effective for simulating systems with fast-switching dynamics like MMC-FC. This solver ensures stable, precise simulations, capturing rapid transitions and maintaining predictable performance, which is crucial for evaluating power electronic systems.

### III .6 Conclusion

In this chapter, we explored the intricacies of the Modular Multilevel Matrix Converter with Flying Capacitors (MMMCFC), a cutting-edge topology in power electronics renowned for its efficient and high-quality AC to AC conversion. The MMCFC's suitability for medium- and high-voltage applications, coupled with its modular design, ensures scalability and operational flexibility. The integration of three flying capacitors per output phase was shown to enhance the converter's performance by improving voltage balancing and significantly reducing harmonic distortion.

The chapter provided a comprehensive overview of the modeling and control strategies critical to the effective operation of the MMCFC. Fundamental principles and operational characteristics of this advanced converter topology were discussed in detail, followed by a rigorous exploration of its mathematical modeling. Additionally, key control strategies, including modulation techniques for generating switching signals, voltage balancing control for flying capacitors, and feedback mechanisms to optimize performance under varying load conditions, were thoroughly examined. This detailed analysis underscores the MMCFC's potential to address the demands of modern energy conversion systems.

Finally, in the next chapter, we will discuss the results obtained from implementing the MMCFC, perform a comparative analysis of its performance against existing solutions, and propose a new approach to further improve the performance of the MMCFC. This will validate its effectiveness.

**Chapter IV:  
Advanced Techniques  
for an Enhanced  
Performance of  
MMMC-FC**

## **IV.1 INTRODUCTION:**

The Multilevel Converter have emerged as a promising technology for high-voltage, high-power applications due to their inherent modularity, scalability, and reduced harmonic distortion. This chapter focuses on the simulation of The Modular Multilevel Matrix Converter with three Flying Capacitors (MMMCFC) with a specific configuration. The MMC's performance is evaluated under various operating conditions, providing valuable insights into its behavior and potential applications.

The objective of this chapter is to analyze the behavior of the MMMCFC under various operating conditions, with a focus on the harmonic performance of key output parameters. The simulations are carried out using the powerful MATLAB SIMULINK environment, a widely recognized platform for modeling and simulating dynamic systems. In this context, the fixed-step ode5 (Dormand–Prince) solver is employed to accurately simulate the dynamic behavior of the converter system. SIMULINK, being a highly flexible and user-friendly tool, enables engineers to model complex systems like MMCs with precision and detail. The fixed-step ode5 solver, based on the Dormand–Prince method, is particularly well-suited for stiff systems—systems where certain components or variables change much more rapidly than others. Power electronic converters like MMMCFC often exhibit such stiff behavior due to the high-frequency switching operations of the semiconductor devices involved. The solver ensures accurate time-domain simulation, which is essential for capturing the transient and steady-state responses of the system.

## **IV.2 Simulation Results**

We have structured this work into two main parts. In the first part, we focus on analyzing the performance of the Modular Multilevel Matrix Converter with Flying Capacitors (MMMC-FC). This analysis is conducted through three distinct tests designed to evaluate its operational capabilities and performance under various conditions. In the second part, we implement and assess an advanced control strategy, aimed at optimizing the converter's performance, improving its stability, and ensuring efficient operation in a variety of scenarios. This comprehensive approach allows us

to address both the hardware's performance and the effectiveness of the proposed control methodology.

### **IV.2.1 The Performance of MMMCFC**

We have 3 simulation cases. In each case, we change the value of  $q$ : in the first case,  $q=0.5$ ; in the second case,  $q=0.3$ ; and in the third case,  $q=0.9$ .

#### **IV.2.1.1 First test (Case one: $q=0.5$ )**

In Fig **IV.1.a** appears to show the output voltage of a MMMCFC over a period of 5 seconds. The output voltage appears to be a non-sinusoidal waveform, which is common for MMMCFC. The voltage appears to have several levels, which is characteristic of a MMMCFC. The voltage waveform appears to be fluctuating slightly over time. This could be due to a number of factors, such as variations in the input voltage or the load current.

Fig **IV.1.b** the graph represents three-phase load currents over a time period of 5 seconds. The current ranging from -1 A to 1 A. The graph showcases three distinct current waveforms designated as phase a ( $I_a$ ), phase b ( $I_b$ ), and phase c ( $I_c$ ). These phases are equally spaced across the time axis, signifying a balanced three-phase system. Each phase current adheres to a sinusoidal wave pattern, a defining characteristic of AC systems.

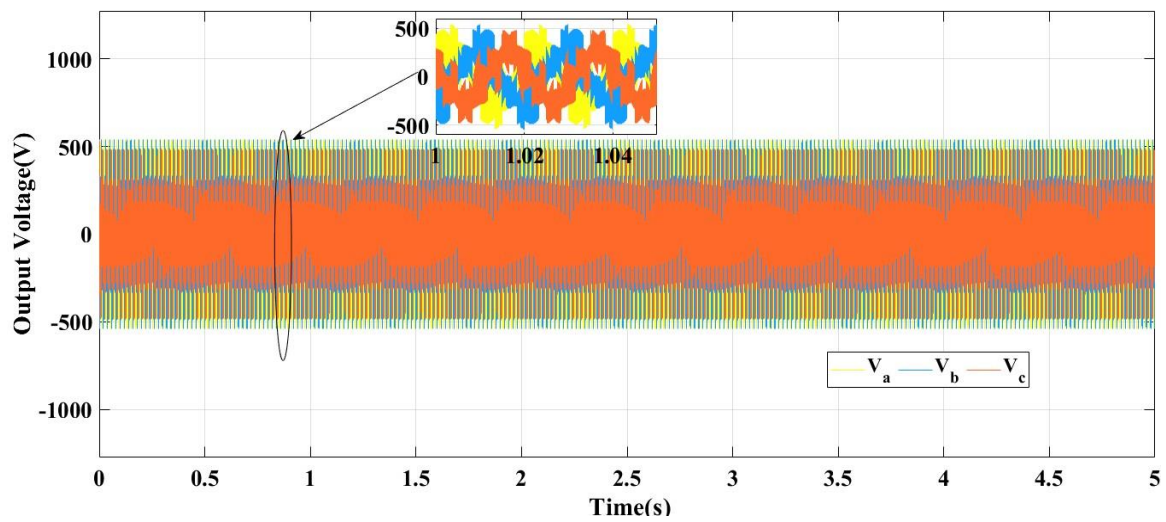
Fig **IV.1.c** provided show the output voltage characteristics of a modular multilevel matrix converter with a tree flying capacitor for three separate phases (A, B, and C). Each figure shows a comparison between the reference input voltage (black line) and the corresponding phase output voltage (colored line). The OV in each figure ( $V_a(\text{out})$ ,  $V_b(\text{out})$ ,  $V_c(\text{out})$ ) show non-sinusoidal waveform with several voltage levels. This characteristic is a defining characteristic of multilevel converters. It achieves a near-sinusoidal output voltage with reduced THD compared to traditional two-level converters.

The black line in each figure likely depicts the reference input voltage  $V_{a_{\text{int}}}$ ,  $V_{b_{\text{int}}}$ ,  $V_{c_{\text{int}}}$ . By comparing it to the output voltage, we can analyze the modulation strategy employed by the converter regulates the output voltage by manipulating the switching of its internal power electronic elements based on the reference input.

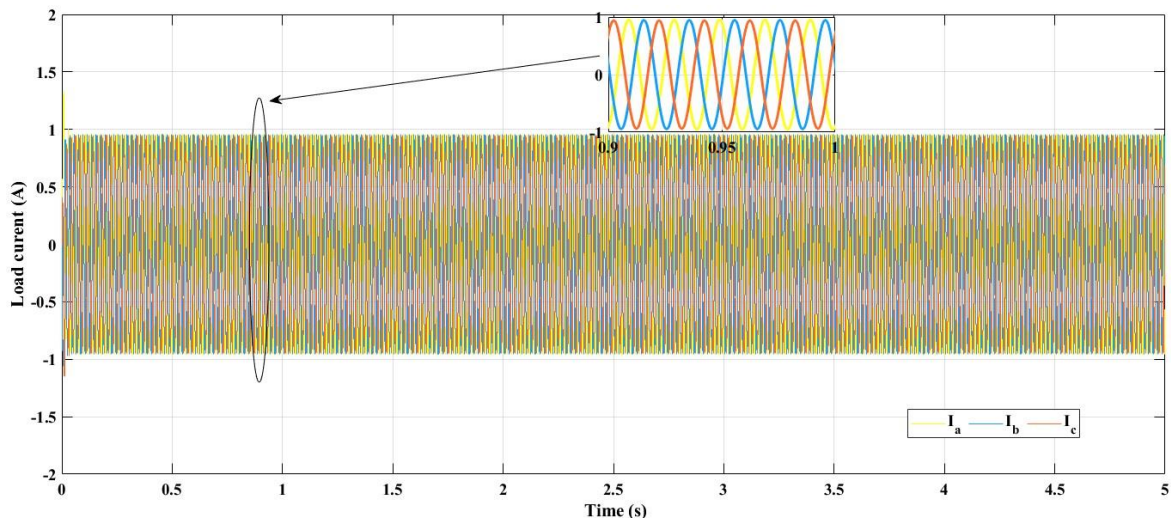
Fig IV.1.d shows the THD for the output voltage (phase a) with Fundamental value 274.8 and THD in this case 0.27 % is a relatively low value. This means the voltage waveform for phase A is close to a pure sine wave.

Fig IV.1.e depicts three current waveforms, designated "Load current" for each phase (L1, L2, L3) of a three-phase system. The waveforms closely resemble sinusoids, indicating a balanced linear load with minimal harmonic distortion.

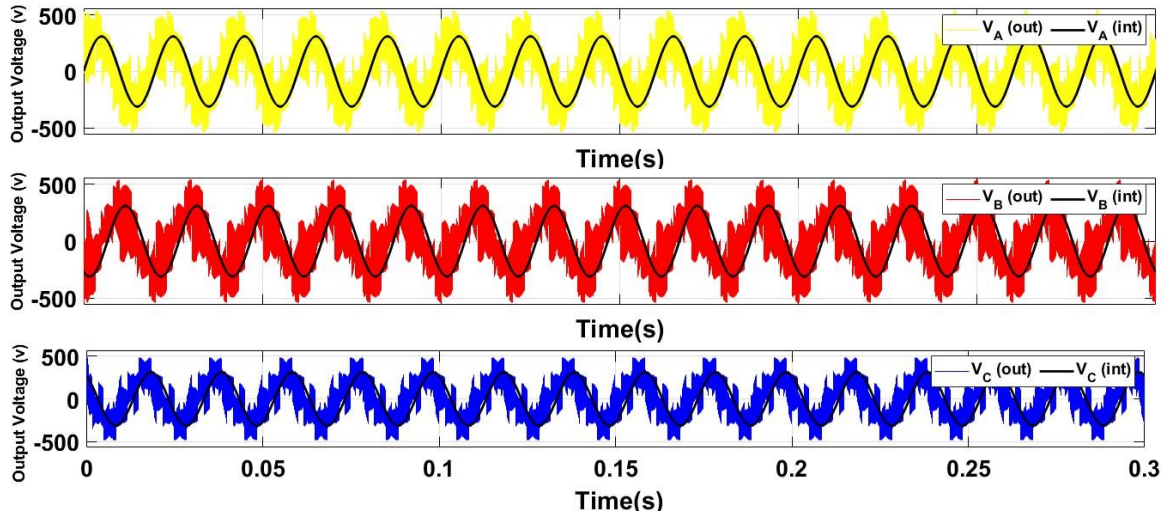
Fig IV.1.f shows the THD for the load current with Fundamental value 0.9688 and THD in this case 0.12 % is a relatively low value. This means the voltage waveform for phase A is close to a pure sine wave



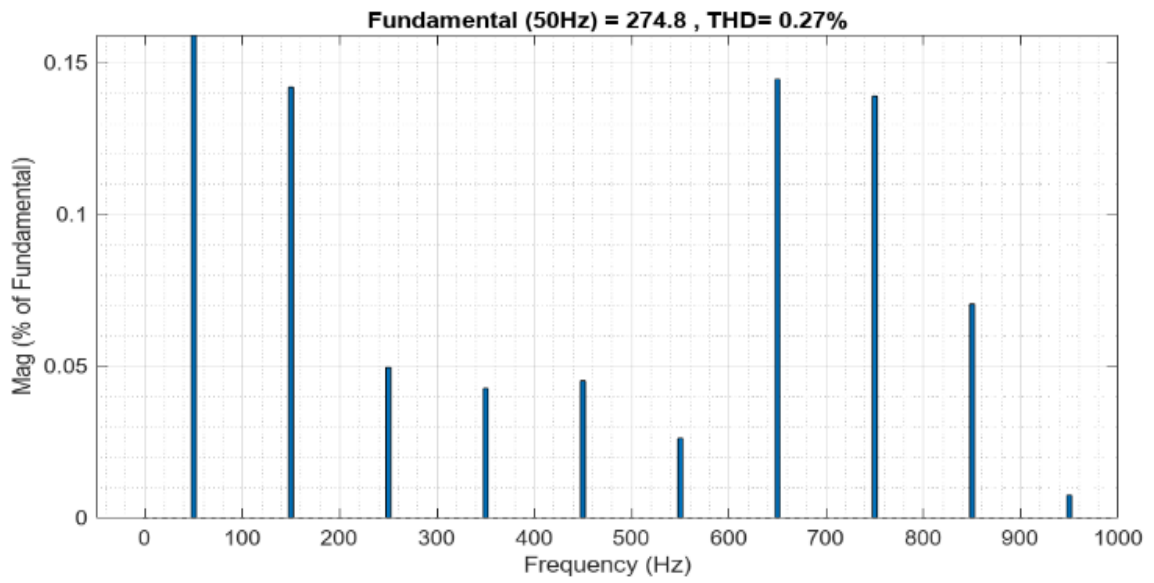
(a)



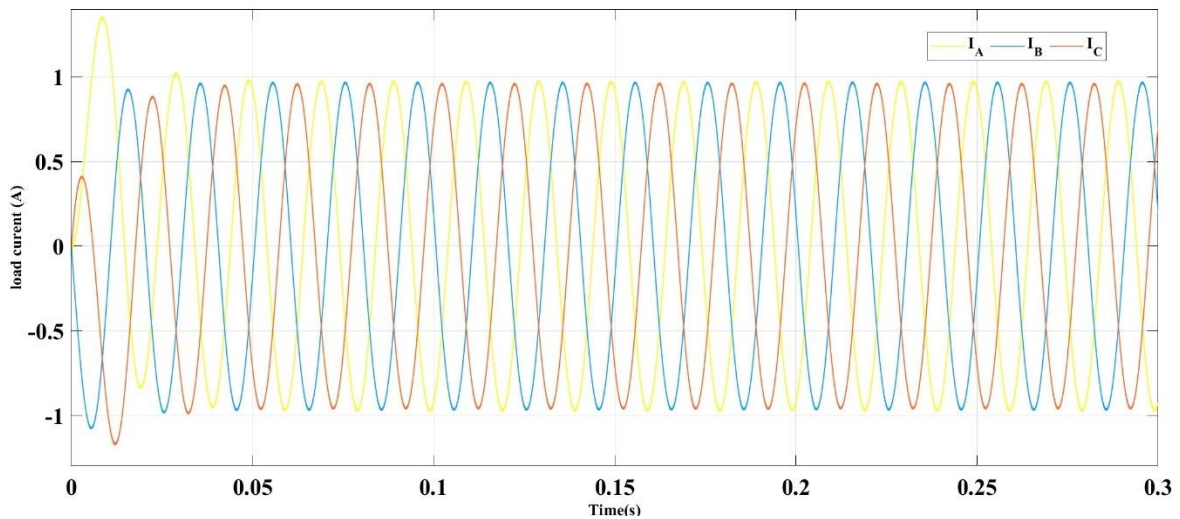
(b)



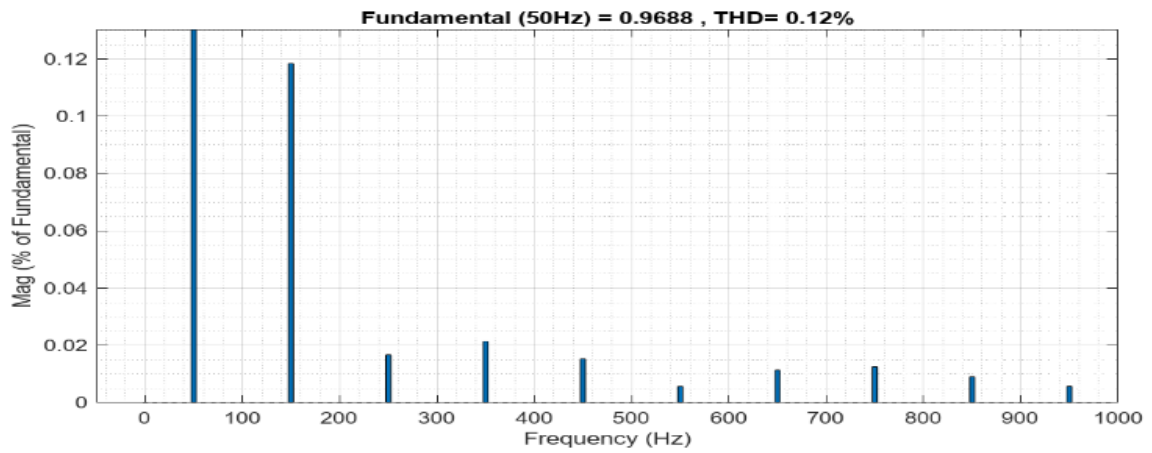
(c)



(d)



(e)



(f)

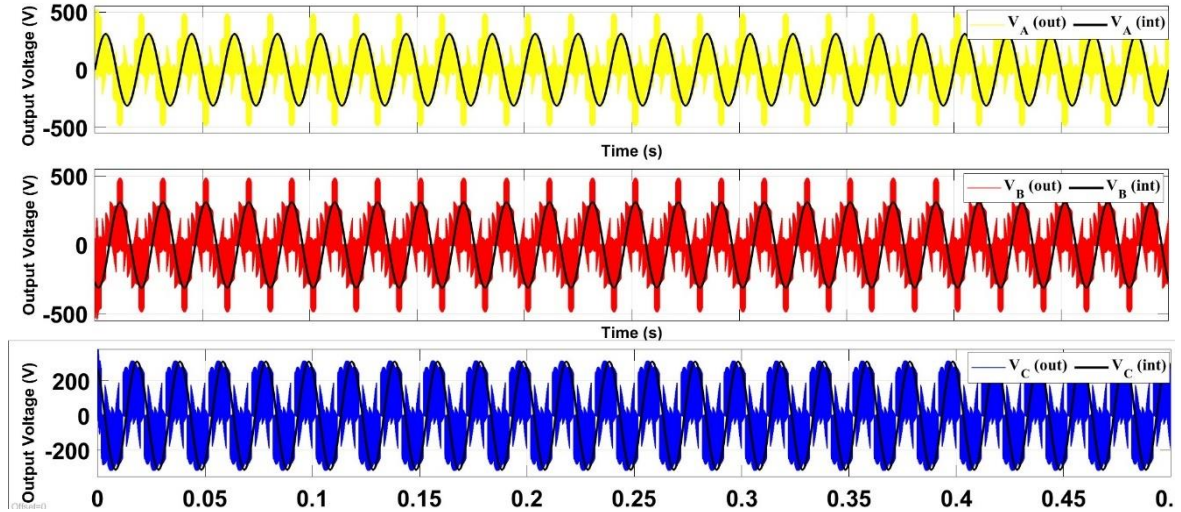
**Figure IV. 1: Results of the first case**

#### IV.2.1.2 Second test (Case tow: $q=0.3$ )

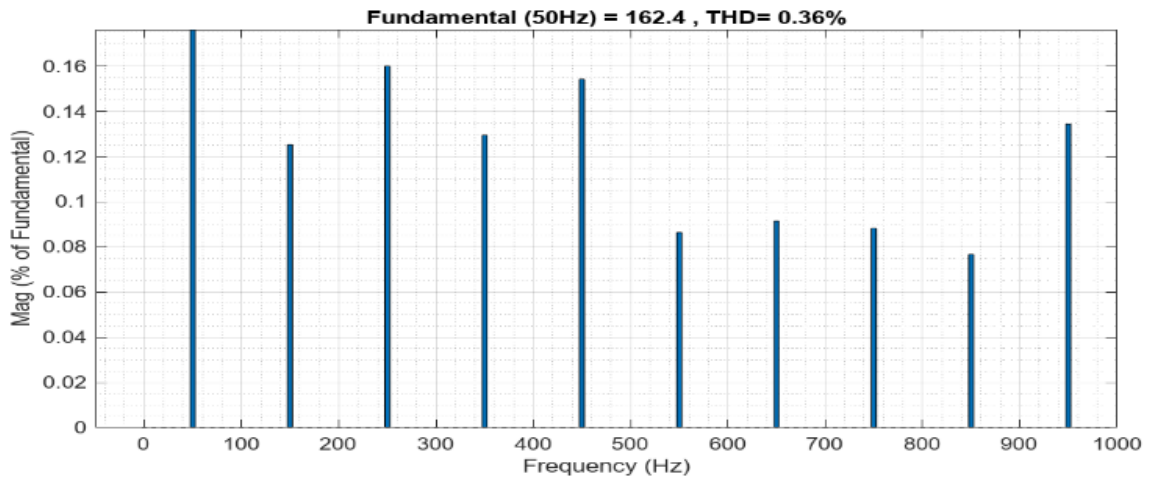
Fig IV.2.a depict the output voltage behavior of a MMMCFC across three phases (A, B, and C). Each graph compares the reference IV (black line) with the OV for each phase (colored line). The output voltage exhibits a non-sinusoidal waveform with multiple voltage levels, a characteristic feature of multilevel converters, aiming to achieve near-sinusoidal OV with reduced THD compared to traditional converters. By comparing the reference IV with the OV, the modulation strategy employed by the converter, which manipulates internal power electronic elements' switching based on the reference input to regulate the OV, can be analyzed. Fig IV.2.b depicts the THD for the output voltage (phase a) with value of THD in this case 0.36 % is a relatively low value. This means the voltage waveform for phase A is close to a pure sine wave.

Fig IV.2.c illustrates three current waveforms labeled "Load current (A)" for each phase (L1, L2, L3) within a three-phase system. These waveforms exhibit a close resemblance to sinusoidal patterns, suggesting a well-balanced linear load with minimal harmonic distortion.

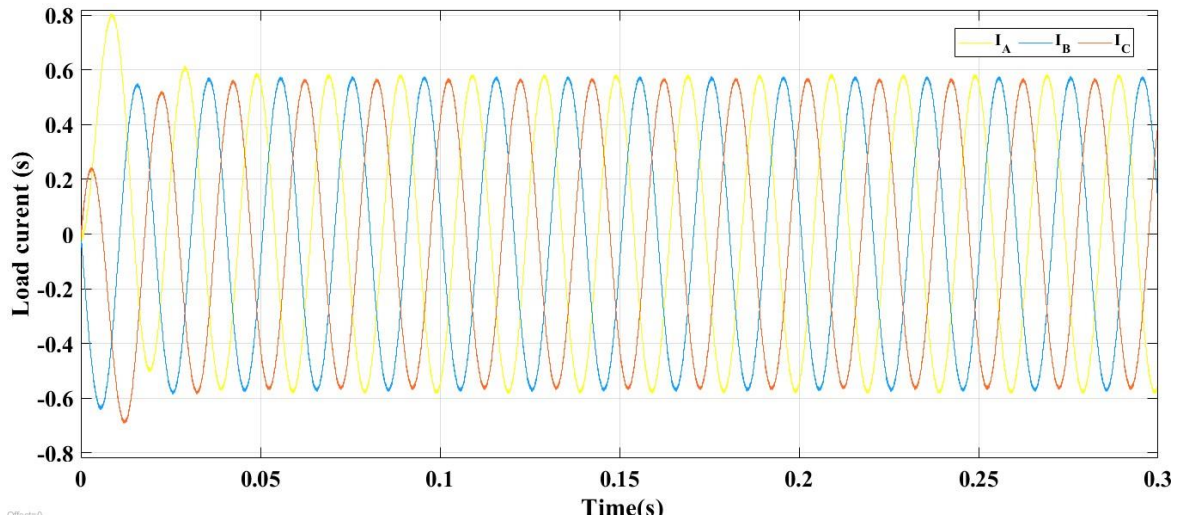
Fig IV.2.d presented The Fundamental value 0.5762 and THD value of 0.19% is a relatively low value, indicating minimal THD in the load current. This means the current waveform is close to a pure sine wave.



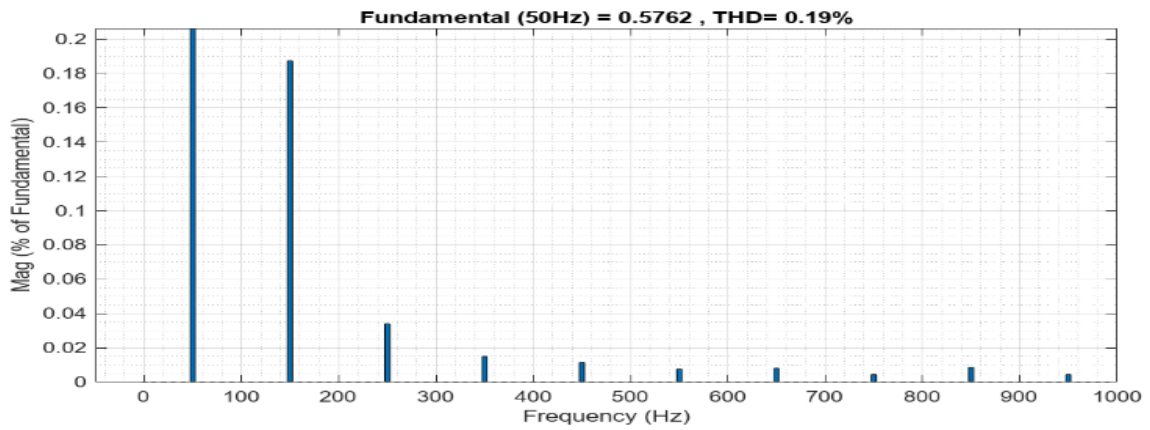
(a)



(b)



(c)



(d)

**Figure IV. 2: Results of the second case.**

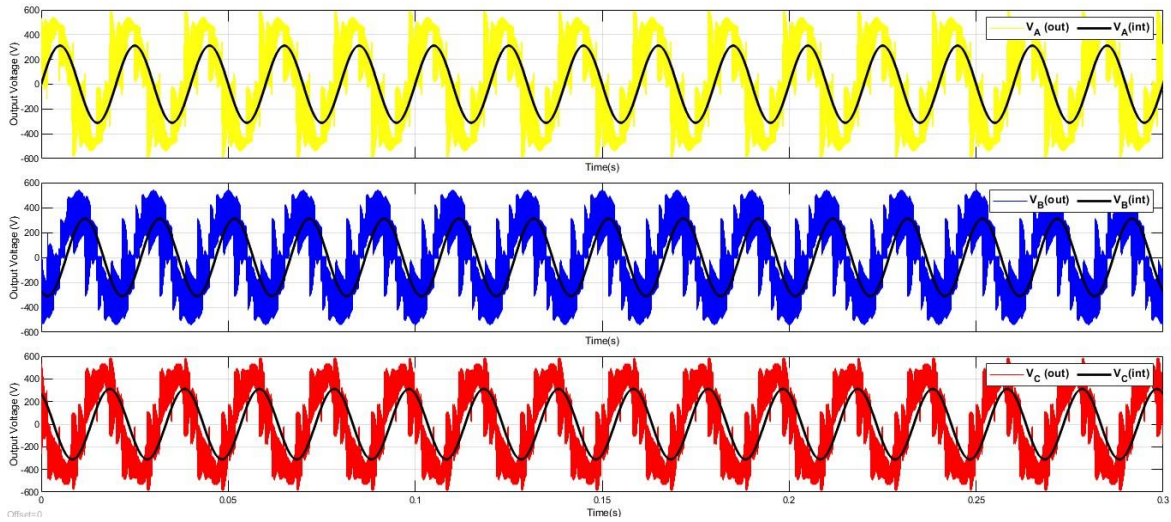
#### IV.2.1.3 Third test (Case three: $q=0.9$ )

Fig IV.3.a show that the allure of the OV is perturbed compared to the IV .The top graph shows the OV  $V_{A_{out}}$  and the internal voltage  $V_{int}$  plotted over time. The OV appears to be oscillating more frequently than the IV and the same comment for the middle graph and the bottom graph. In all three graphs, the OV waveform is more complex than the internal voltage waveform. This suggests that the output voltage is being perturbed by some external factor.

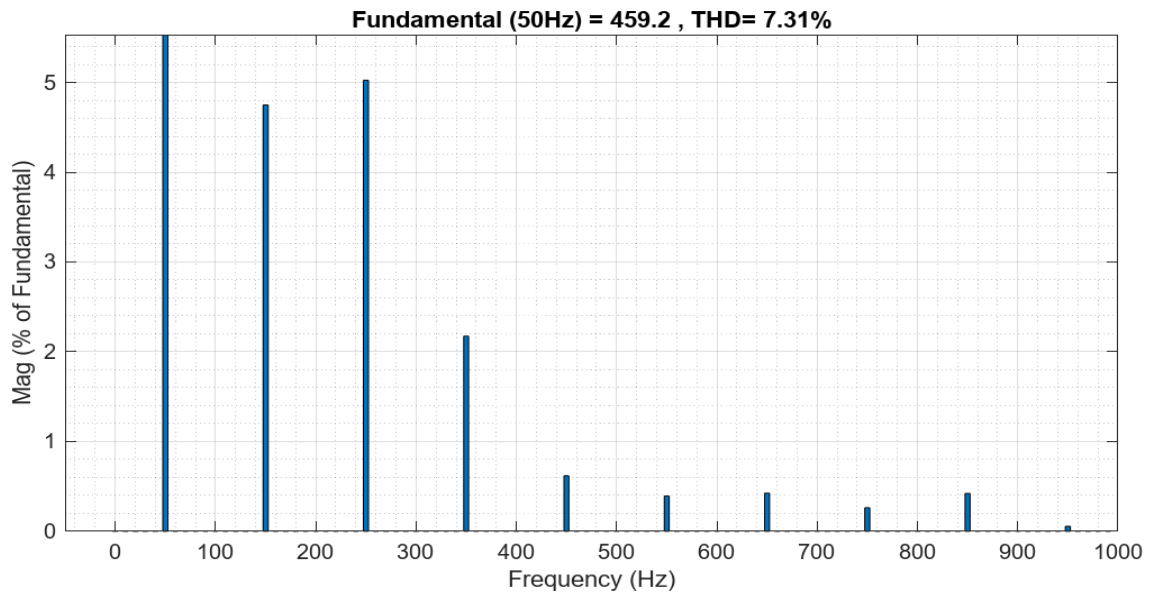
Fig IV.3.b depict the THD for the OV (phase a) with Fundamental value 459.2 and THD in this case 7.31 %.

Fig IV.3.c depicts three current waveforms, designated "Load current" for each phase (L1, L2, L3) of a three-phase system. The waveforms closely resemble sinusoids, indicating a balanced linear load with harmonic distortion.

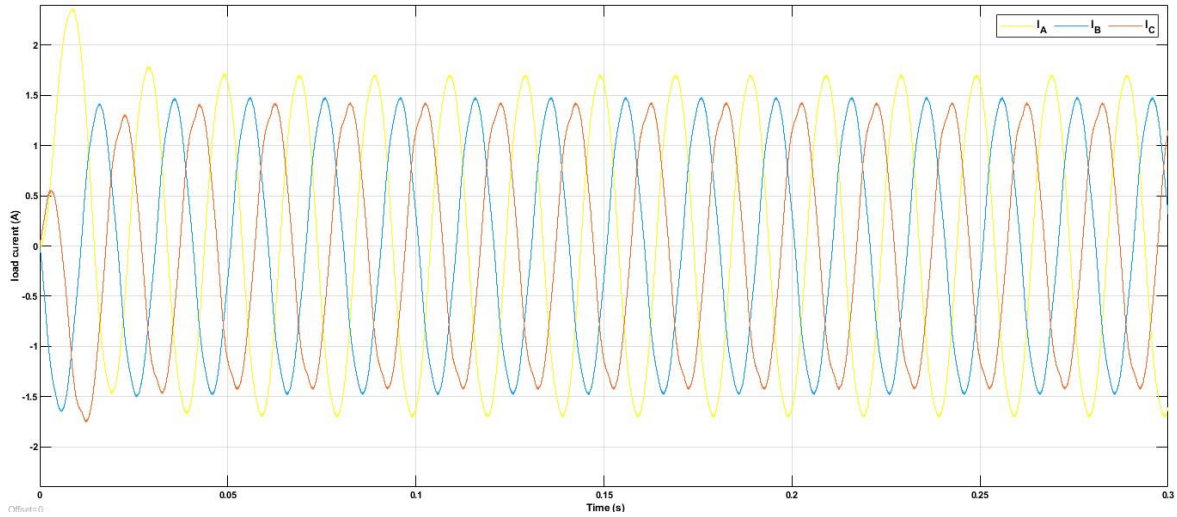
Fig IV.3.d This fig presented The Fundamental value 1.719 and THD value of 2.60% is a relatively low value, indicating THD in the load current.



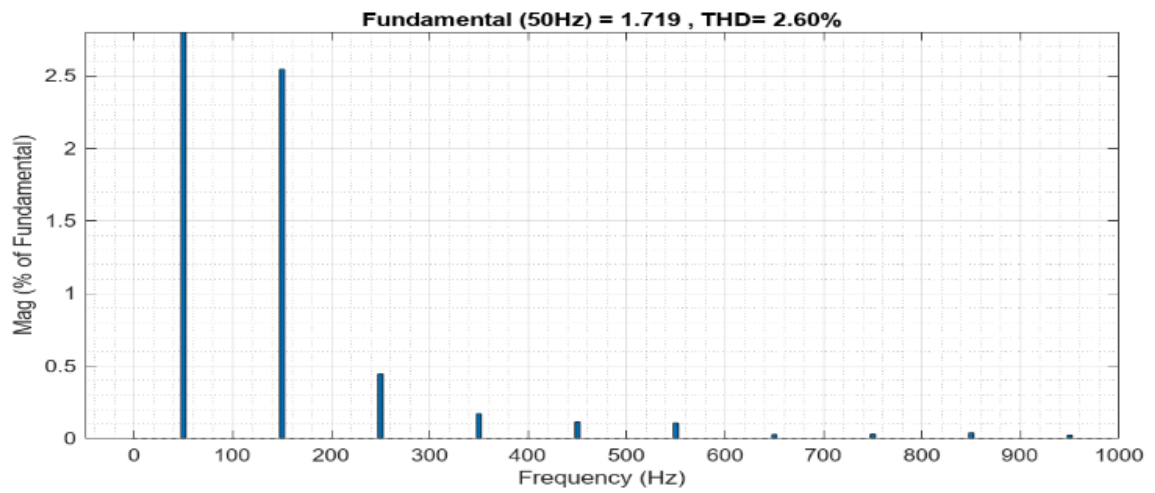
(a)



(b)



(c)



(d)

**Figure IV. 3: The results of the third case.**

After analyzing the **Table IV.1**, we conclude that Case one ( $q=0.5$ ) exhibits the best performance among the other cases, with the lowest harmonic distortion of phase A at 0.27%, a peak fundamental of 274.8, a peak input current of 0.9688, and a harmonic distortion of load current of 0.19%.

**Table IV. 1: Comparison MMCFC Simulation Results**

n	parameters	Line to line OV		Phase A IC	
		THD %	Peak fundamental (v)	THD %	Peak fundamental (A)
Case one	$q=0.5$	0.27	274.8	0.12	0.9688
Case tow	$q=0.3$	0.36	162.4	0.19	0.5762
Case three	$q=0.9$	7.31	459.2	2.60	1.719

Table **IV.2** presents a comparison between the THD values of our MMCFC and another converter. The data clearly demonstrates the significant improvement achieved by our MMCFC in reducing THD compared to the referenced converter. Specifically, the THD reduction ratio of the MMCFC, when compared to reference [49], is 73%.

**Table IV. 2 : A comparison between the THD values of our MMCFC and another converter**

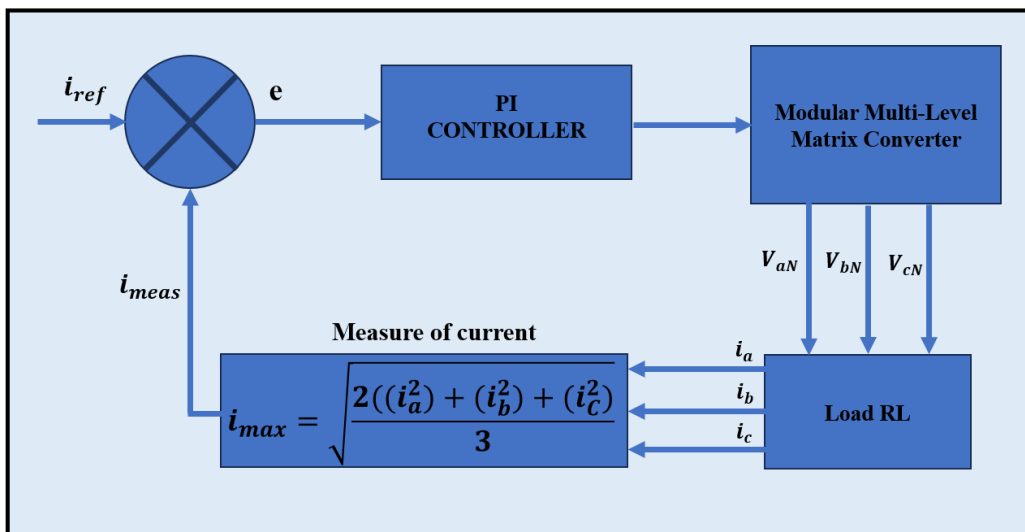
Reference	THD of output voltage (%)
Ref [47]	7.78
Ref [48]	23
Ref [49]	1.02
Proposed (MMC-FC) with $q=0,5$	0.27

## IV.2.2 High-Performance Control of MMMC-FC Using ASOSMC

After completing the first part of our study, where we analyzed various scenarios, we selected the best-performing case for further optimization. In the second part, we implemented an advanced control strategy, specifically the Second-Order Sliding Mode Control (SOSMC). This sophisticated control method was integrated into the system to enhance performance, improve robustness, and ensure greater stability. We retained the Venturini modulation strategy as the foundation and introduced a closed-loop control mechanism to precisely adjust the current. Additionally, we incorporated both PI control and SOSMC to compare their results in terms of performance, stability, and efficiency. This comprehensive approach allowed us to evaluate and benchmark the effectiveness of the proposed advanced control strategy for the Modular Multilevel Matrix Converter with Floating Capacitors (MMMC-FC).

### IV.2.2.1 PI Control of a MMMCFC

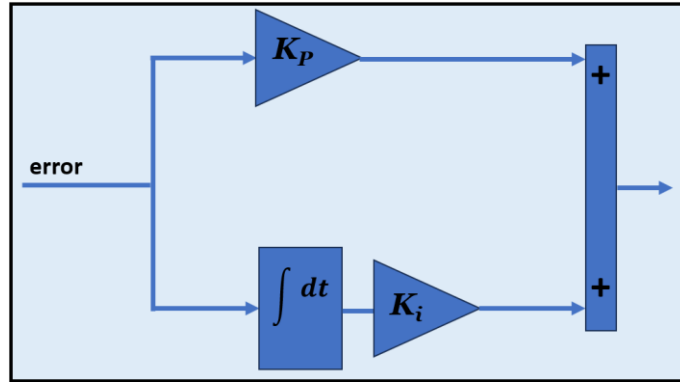
The accompanying figure IV. 5 shows Load current readings made with a PI controller.



**Figure IV. 4 : PI Control for Modular Multilevel matrix converter.**

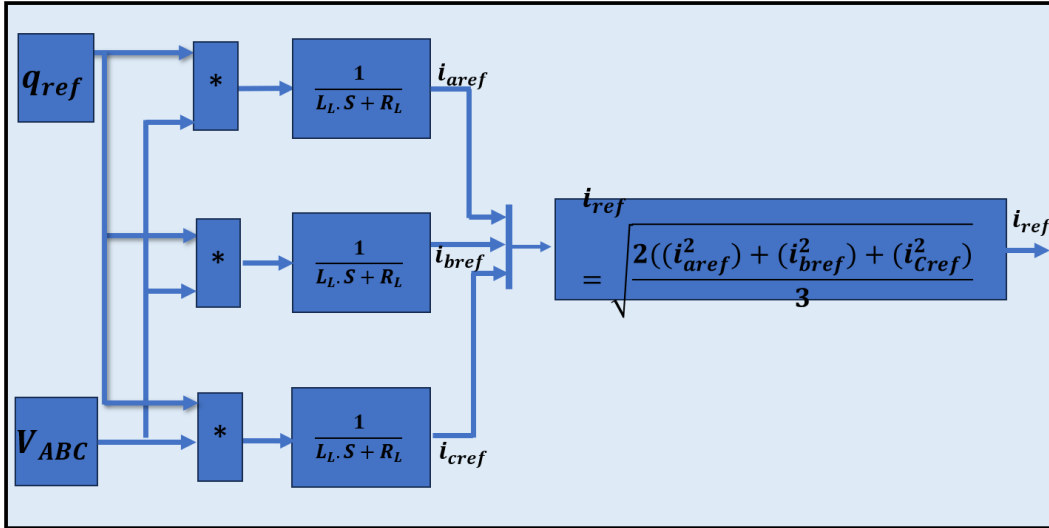
Trial and error were used to calculate the PI controller's  $k_p$  and  $k_i$  settings.

Figure IV. 5 shows the schematic diagram of the PI controller.



**Figure IV. 5 : Structure of PI Controller**

The transfer function is not defined in this system. The calculation of the reference current is displayed in figure IV.7 [57]



**Figure IV. 6 : Load reference current.**

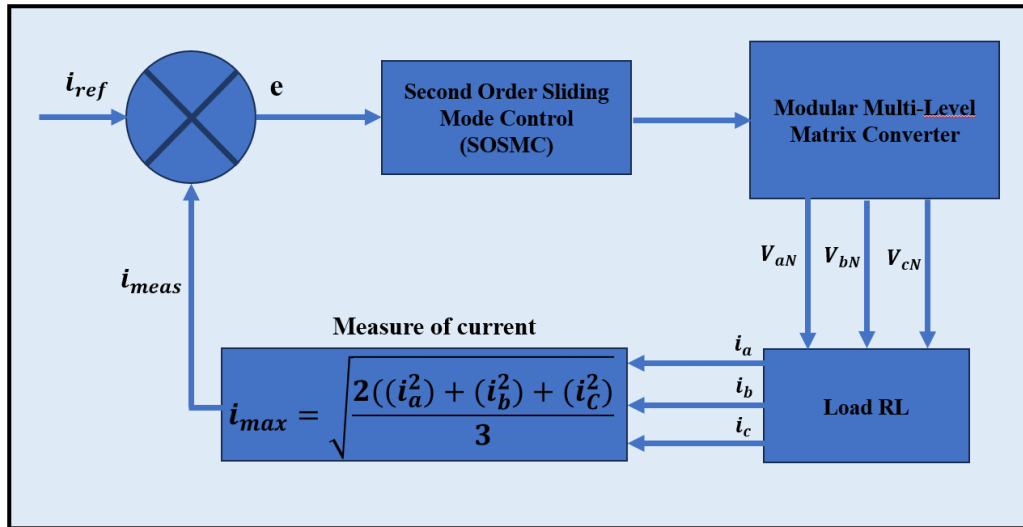
The measured Load current and the reference Load current are given by the equation (IV.16) and (IV.17) [57]

$$i_{ref} = \sqrt{\frac{2((i_{aref}^2) + (i_{bref}^2) + (i_{cref}^2))}{3}} \quad (IV.16)$$

$$i_{max} = \sqrt{\frac{2((i_a^2) + (i_b^2) + (i_c^2))}{3}} \quad (IV.17)$$

### IV.2.2.2 Advanced Second-Order Sliding Mode Control (ASOSMC) of Modular Multilevel Matrix Converter

The advanced second-order sliding mode control (ASOSMC) approach was created in accordance with the control requirements and operational characteristics of the matrix converter. Figure IV.9 displays the structure of the system.



**Figure IV. 7 : ASOSMC Control for MMMCFC**

The objective of this instruction is to control the output voltage of the Modular Multilevel Matrix Converter with Floating Capacitors (MMMC-FC). The MMMC-FC is a high-performance power converter that directly converts the three-phase input voltage to a three-phase output voltage. The key advantage of adopting an MMMC-FC is its ability to synthesize a wide range of output voltages with reduced harmonics and increased efficiency. In terms of structural complexity, this solution offers an undeniable benefit. The control principle of the MMMC-FC involves regulating the excitation coil current, which in turn regulates the flow of excitation, including permanent magnets and coiled excitation. The stator vacuum electromotive forces are then regulated, followed by controlling the three-phase source current. The structure and control of the conversion system are depicted in Fig IV. 6, showing the modular multilevel matrix converter's ability to efficiently convert AC power to AC power without the need for a DC link.

### IV.2.2.3 Current Control Using SOSMC

Sliding surfaces can be used to explain the current inaccuracy [59]

Put differently, the following expression can be used to convey it:

$$S_i = i_{ref}^* - i \quad (\text{IV.18})$$

There are two components to the Second-order sliding mode control law. While the second part,  $u_2$ , is defined by its time derivative [60]. the first part,  $u_1$ , is a continuous function that depends on the sliding variable. In order to achieve  $S = \dot{S} = 0$  in finite time, the primary goal of this proposed control approach is to push the sliding variable ( $S$ ) to converge to zero.

The proposed ASOSMC controller can be mathematically represented as follows [61-64] :

$$u = -u_1 - u_2 \quad (\text{IV.19})$$

Where:

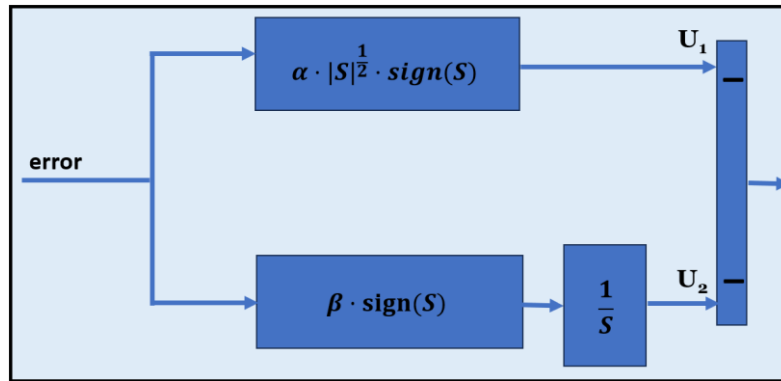
$$u_1 = \alpha \cdot \left| S S^{\frac{1}{2}} \cdot \text{sign}(S) \right. \quad (\text{IV.20})$$

$$u_2 = \beta \cdot \text{sign}(S) \quad (\text{IV.21})$$

The speed control is achieved using the ASOSMC to regulate the speed and can be expressed as follows:

$$u_i = -\alpha \cdot |S_i|^{\frac{1}{2}} \cdot \text{sign}(S_i) - \beta \cdot \text{sign}(S_i) \quad (\text{IV.22})$$

The Figure IV. 9 shows the schematic diagram of the ASOSMC controller.



**Figure IV.8 : Structure of ASOSMC Controller**

### IV.2.3 Results discussion

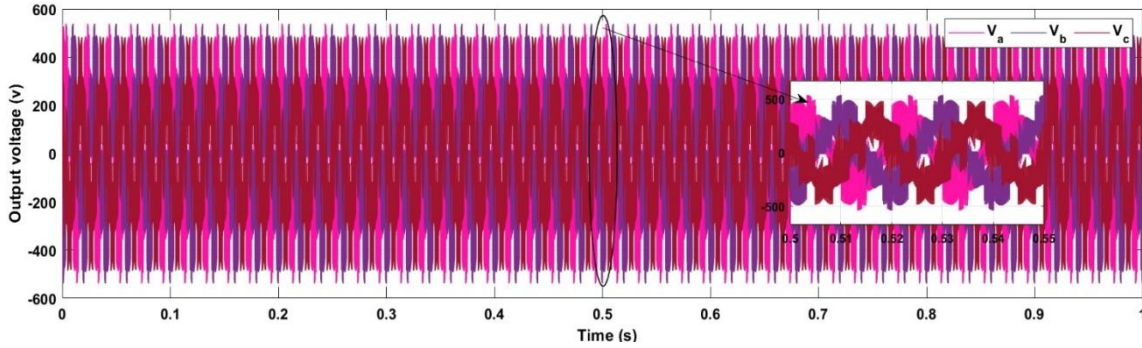
The output voltage of a 3MC with three FC over a one-second interval appears to be displayed in Fig. **IV.9.a**. It looks that the output voltage has a non-sinusoidal waveform, which is typical of 3MC. It looks that there are multiple voltage levels, which is indicative of a 3MC. It looks like there are small variations in the voltage waveform over time. There are several possible causes for this, including changes in the input voltage or the load current.

Fig. **IV.9.b**. shows three-phase load currents over a one-second time span. The current ranges from -60 A to 60 A. The graph displays three different current waveforms, identified as  $I_a$ ,  $I_b$ , and  $I_c$ . The phases are evenly spaced along the time axis, indicating a three-phase system that is balanced. Each phase current follows a sinusoidal wave pattern, which is a feature of AC systems.

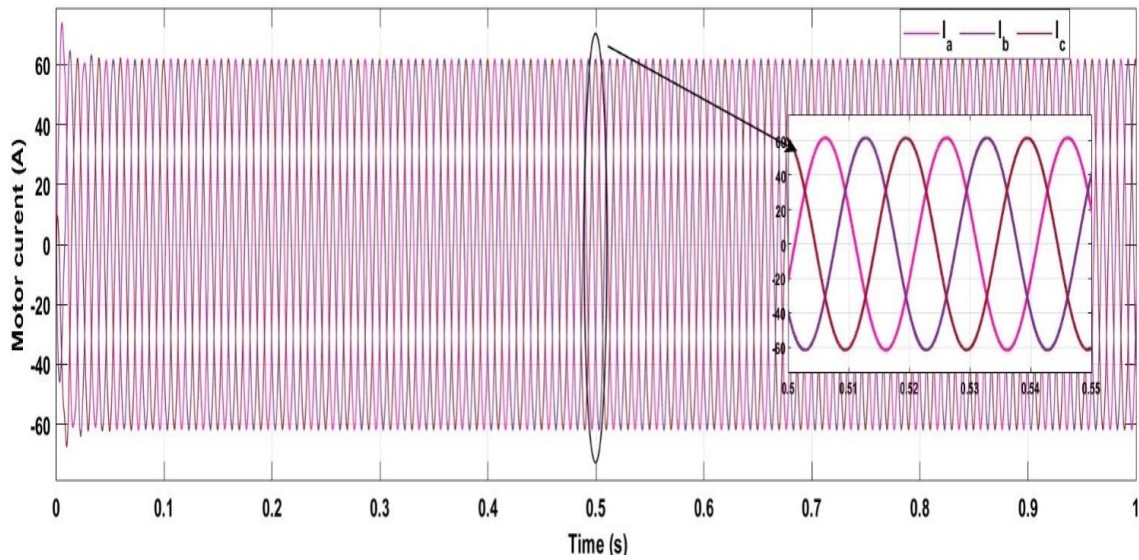
The graph in Fig. **IV.9.c** illustrates the performance of a control system. The lines represent the reference signal, proportional-integral controller output, and Advanced advanced second-order sliding mode control (ASOSMC) output. The initial transient and subsequent convergence suggest effective error reduction. The ASOSMC controller exhibits faster response time and less overshoot compared to the PI controller.

With a Fundamental value of 274.8, Fig. **IV.9.d**. displays the THD for the output voltage (phase a). In this instance, THD is 0.27 percent, which is a comparatively low amount. This indicates that phase A's voltage waveform resembles a pure sine wave.

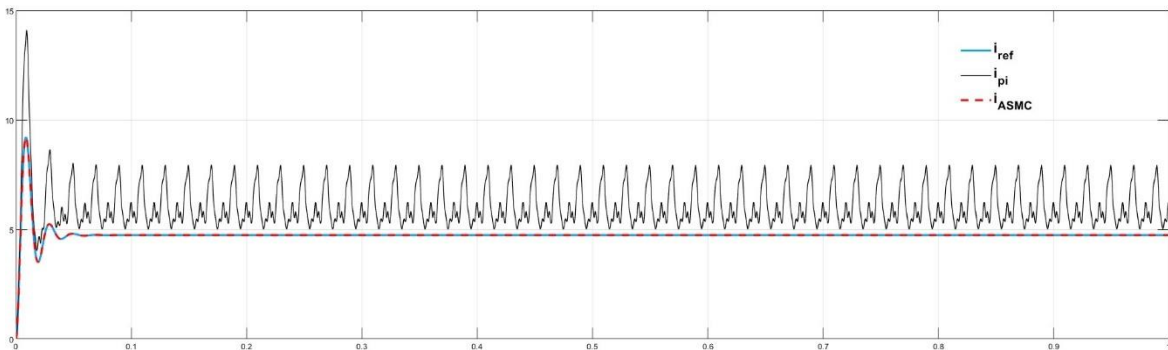
The THD for the load current with Fundamental value 0.9688 is displayed in Fig. IV.9.e. In this instance, the THD of 0.12% is a comparatively low number. This indicates that phase A's voltage waveform is nearly a pure sine wave.



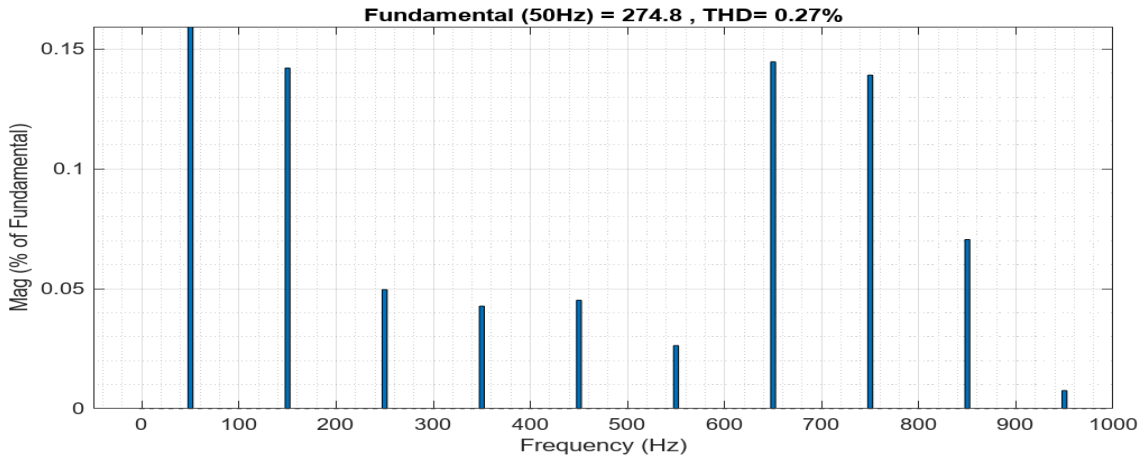
(a)



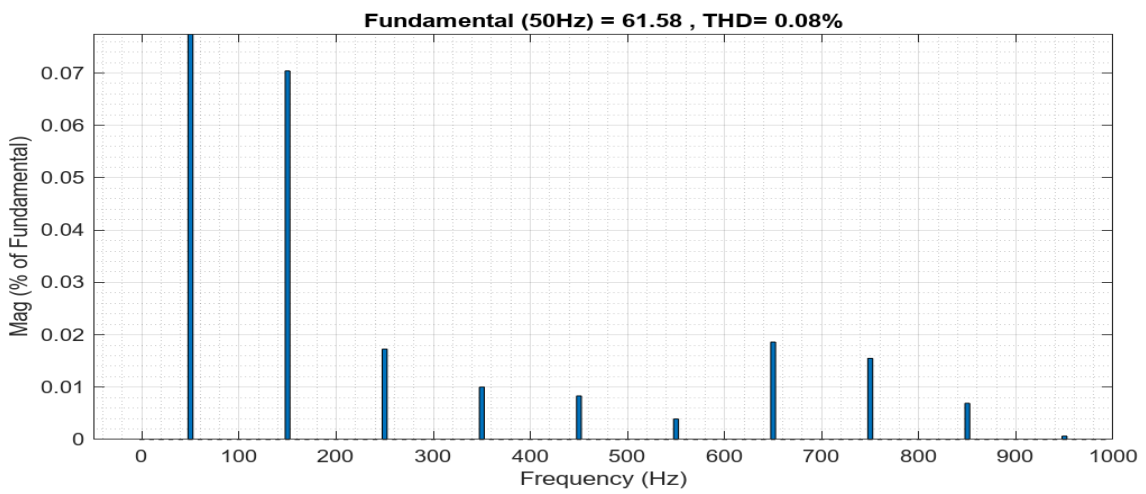
(b)



(c)



(d)



(e)

**Figure IV. 9: Simulation Results of load RL.**

Finally, based on the obtained results and the comprehensive comparison conducted, it can be concluded that the Modular Multilevel Matrix Converter with Flying Capacitors (MMMCFC) demonstrates superior performance, particularly when integrated with the Second Order Sliding Mode Control (SOSMC) technique. This combination not only ensures enhanced operational efficiency but also exhibits improved stability and robustness under various conditions. These findings validate the potential of the MMMCFC as an optimal choice for systems requiring precise and reliable control, further emphasizing its suitability for advanced applications.

## **IV.6 Conclusion**

The Modular Multilevel Matrix Converter with Flying Capacitors (MMMCFC) has demonstrated its potential as a promising technology for high-voltage, high-power applications. Through simulations conducted in MATLAB SIMULINK, this chapter has analyzed the performance of the MMMCFC under various operating conditions, with a specific focus on harmonic distortion and output parameter behavior. The use of the fixed-step ode5 (Dormand–Prince) solver has enabled precise modeling of the dynamic behavior of this stiff system, capturing both transient and steady-state responses effectively.

The findings confirm that the MMMCFC offers significant advantages in terms of modularity, scalability, and harmonic performance. When combined with the Second Order Sliding Mode Control (SOSMC) technique, it achieves enhanced operational efficiency, stability, and robustness. These results highlight the MMMCFC's suitability for advanced applications requiring reliable and efficient power conversion, establishing it as a benchmark for modern power electronic systems.

# **General Conclusion**

## General Conclusion

This thesis investigated advanced control and optimization strategies for modular multilevel matrix converters (MMMCs), a cutting-edge technology in power electronics. By addressing key challenges such as harmonic distortion, control complexity, and system reliability, this research has contributed to the development of efficient, scalable, and reliable solutions for modern power systems. Below is a detailed conclusion summarizing the key findings, contributions, and implications of this work.

### Summary of the Research

1. **Research Context and Motivation:** The increasing demand for efficient energy conversion technologies in renewable energy systems, industrial applications, and transportation has highlighted the importance of modular multilevel matrix converters. MMMCs combine the compactness of matrix converters and the scalability of multilevel converters, making them ideal for high-voltage, high-performance applications. However, the challenges posed by harmonic distortion, control complexity, and thermal management have limited their practical adoption. This thesis addressed these challenges by proposing advanced control strategies.
2. **Objectives Achieved:**
  - Development of proposed control algorithms to enhance harmonic performance and system stability.
  - Reduction in total harmonic distortion (THD) and improvement of output power quality.
  - Enhanced voltage balancing and reduced switching losses for improved efficiency.
  - Validation of the proposed methods through simulation and performance analysis.

## General Conclusion

3. **Methodology:** The research methodology combined a comprehensive literature review, mathematical modeling, advanced control design, and simulation-based validation. This systematic approach ensured the reliability and accuracy of the findings while providing insights into their practical applications.

### Key Contributions

1. **Advanced Control Strategies:** The thesis proposed control algorithms tailored for MMCs, addressing the limitations of traditional methods. These strategies successfully reduced harmonic distortions and enhanced voltage stability across submodules, demonstrating their effectiveness in improving system performance.
2. **Improved Efficiency and Reliability:** By optimizing switching patterns and reducing thermal stresses, the proposed methods enhanced the overall efficiency of MMCs.
3. **Comprehensive Simulation and Validation:** Using MATLAB/Simulink, the thesis provided detailed simulations to evaluate the performance of the proposed strategies. These simulations demonstrated significant improvements in efficiency, harmonic reduction, and power quality compared to existing methods.
4. **Scalability and Practical Applications:** The modular nature of the proposed solutions ensures scalability, making them suitable for a wide range of applications, including renewable energy systems, industrial motor drives, and high-power grid integration.

### Findings and Implications

1. **Harmonic Reduction:** One of the most critical challenges in MMCs is the presence of harmonic distortions caused by high-frequency switching. The advanced control algorithms developed in this thesis achieved substantial reductions in THD, with low frequency 5 kHz improving the sinusoidal nature of output waveforms and enhancing power quality.

## General Conclusion

2. **Efficiency Improvements:** By minimizing switching losses and optimizing thermal management, the proposed solutions improved the efficiency of MMCs. This is particularly important in high-power applications, where efficiency gains translate into significant energy savings and reduced operational costs.
3. **Voltage Balancing:** Maintaining voltage stability across submodules is crucial for the reliable operation of MMCs. The research demonstrated the effectiveness of the proposed voltage balancing mechanisms in ensuring stable and efficient performance under dynamic conditions.
4. **System Scalability:** The modular design of MMCs, combined with the proposed control strategies, provides scalability, enabling the integration of these converters into a wide range of applications. This adaptability ensures that MMCs can meet the demands of future energy systems.
5. **Renewable Energy Integration:** The enhanced performance of MMCs makes them ideal for integrating renewable energy sources into existing power grids. By improving efficiency and power quality, the proposed solutions support the seamless integration of wind and solar energy, contributing to global sustainability goals.

## Challenges and Limitations

While the thesis made significant contributions, some limitations remain:

1. **Experimental Validation:** Due to resource constraints, the proposed solutions were validated through simulations. While the results are promising, experimental validation would further confirm their effectiveness in real-world scenarios.
2. **Control Complexity:** The advanced control algorithms, while effective, require high computational power and sophisticated hardware for implementation. Future research could explore methods to simplify these algorithms without compromising performance.

## General Conclusion

3. **Thermal Management:** Although the proposed methods addressed thermal stresses, further research is needed to develop more efficient cooling solutions for high-power applications.

### Future Directions

1. **Experimental Implementation:** Extending this research to experimental setups would provide practical insights into the real-world performance of the proposed strategies. Collaborating with industry partners could facilitate access to advanced laboratory facilities.
2. **Real-Time Control Systems:** Developing real-time control systems with hardware-in-the-loop (HIL) simulations could enhance the practical applicability of the proposed algorithms, ensuring their compatibility with existing power systems.
3. **Integration with Emerging Technologies:** Exploring the integration of MMCs with advanced technologies such as energy storage systems, electric vehicles, and smart grids could expand their application scope.
4. **Optimization for Cost and Complexity:** Future research could focus on reducing the cost and complexity of MMCs, making them more accessible for widespread adoption.
5. **Exploration of Alternative Applications:** Investigating the potential of MMCs in other areas, such as aerospace, marine systems, and medical equipment, could unlock new opportunities for their deployment.

The research presented in this thesis has contributed significantly to the advancement of modular multilevel matrix converters by addressing key challenges in harmonic distortion, efficiency, and reliability. The proposed control strategies and their validation through simulation provide a solid foundation for future developments in this field. The findings underscore the potential of MMCs as a transformative technology in power electronics, particularly in renewable energy integration and high-performance industrial applications. By

## General Conclusion

enhancing the efficiency, reliability, and scalability of these converters, this thesis supports global efforts to build sustainable and efficient energy systems. through continued research and development, MMMCs can play a pivotal role in shaping the future of energy conversion technologies, paving the way for a cleaner, greener, and more sustainable future.

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## ملخص

يركز مشروع البحث هذا على نمذجة والتحكم في محولات المصفوفة ومحولات المصفوفة متعددة المستويات المعيارية، مع التركيز بشكل خاص، وخاصة للتحكم في المحركات. تبدأ الدراسة بمراجعة شاملة لاستراتيجيات التحكم في محولات RL خاص على تطبيقها في التحكم في حمل افتراضي. بعد ذلك، نستكشف استراتيجية التحكم المتجهي DC مع ناقل جهد وسيط PWM المصفوفة، بما في ذلك استراتيجيات فينتوريني و مزايا كبيرة في التحكم في تدفق SVM، والتي تضمن تديلاً مناسباً للتيار في محولات المصفوفة. يوفر (SVM) المسماة تعديل ناقل الفضاء التيار من خلال توفير أنظمة تبديل أكثر كفاءة

يتناول الجزء الثاني من هذا المشروع التحكم في محولات المصفوفة المباشرة متعددة المستويات المعيارية. الهدف الرئيسي هنا هو تقليل التشوه التوافقي وتحسين سلوك تبديل التيارات. تسمح محولات المصفوفة متعددة المستويات المعيارية بتحقيق أداء أفضل عن طريق تقسيم شكل الموجة الجهدية إلى عدة خطوات أصغر، مما يحسن جودة إشارة الخرج. يؤدي ذلك إلى كفاءة أفضل وتقليل التداخل الكهرومغناطيسي

من خلال الجمع بين هذين الجانبين - استراتيجيات التحكم في محولات المصفوفة ومحولات المصفوفة متعددة المستويات المعيارية - يهدف هذا البحث إلى تحسين الأداء العام للنظام، سواء في تحويل الطاقة أو تطبيقات التحكم في المحركات. الهدف النهائي هو تحسين الكفاءة وتقليل التشوهات التوافقية وتحسين عملية تبديل التيار في الأنظمة المعقدة

**كلمات مفتاحية:** محول مصفوفة متعدد المستويات وحدوي، استراتيجية تحويل المتجه الفضائي، استراتيجية فينتوريني، حمل، آلة مترامنة

## Résumé

Ce projet de recherche se concentre sur la modélisation et le contrôle des convertisseurs matriciels et des convertisseurs matriciels à multi niveaux modulaire, avec une attention particulière sur leur application à la commande de charge RL, notamment pour le contrôle de moteurs. L'étude commence par une revue exhaustive des stratégies de commande des convertisseurs matriciels, notamment les stratégies de Venturini et de PWM avec un bus de tension intermédiaire DC virtuel. Ensuite, nous explorons la stratégie de commande vectorielle appelée Modulation Vectorielle d'Espace (SVM), qui assure une commutation appropriée du courant dans les convertisseurs matriciels. Le SVM offre des avantages significatifs dans le contrôle du flux de courant en fournissant des schémas de commutation plus efficaces.

La deuxième partie de ce projet aborde le contrôle des convertisseurs matriciels directs à multi niveaux modulaire. L'objectif principal ici est de réduire la distorsion harmonique et d'améliorer le comportement de commutation des courants. Les convertisseurs matriciels à multi niveaux modulaire permettent d'obtenir de meilleures performances en décomposant la forme d'onde de tension en plusieurs étapes plus petites, ce qui améliore la qualité du signal de sortie. Cela conduit à une meilleure efficacité et à une réduction des interférences électromagnétiques.

En combinant ces deux aspects — stratégies de commande des convertisseurs matriciels et des convertisseurs matriciels à multi niveaux modulaire — cette recherche vise à améliorer les performances globales du système, à la fois dans la conversion d'énergie et les applications de commande de moteurs. L'objectif ultime est d'améliorer l'efficacité, de réduire les distorsions harmoniques et d'optimiser le processus de commutation du courant dans des systèmes complexes.

**Mots clés :** Convertisseur matriciel multi-niveaux Modulaire, stratégie SVM, stratégie Venturini, charge RL, machine synchrone

## Abstract

This research project focuses on the modeling and control of matrix converter and modular multi-level matrix converter, with an emphasis on their application in load RL, whether for motor control. The study begins with a comprehensive literature review on various control strategies for matrix converters, including the Venturini and PWM strategies with a virtual intermediate voltage dc-link. Following this, we delve into the vector control strategy known as Space Vector Modulation (SVM), which ensures the proper current switching in matrix converters. SVM offers significant advantages in controlling the current flow by providing more efficient switching patterns.

The second part of this project addresses the control of direct Modular multi-level matrix converters. The main goal here is to reduce harmonic distortion and enhance the switching behavior of the currents. Modular Multi-level matrix converters offer a pathway to achieving higher performance by breaking down the voltage waveform into smaller steps, which improves the quality of the output signal. This results in better efficiency and reduced electromagnetic interference.

By combining these two aspects—matrix converter and Modular multi-level matrix converter control strategies—this research aims to improve overall system performance in both energy conversion and motor drive applications. The ultimate objective is to enhance efficiency, reduce harmonic distortion, and optimize the current switching process in complex converter systems.

**Keywords:** Modular multilevel matrix converter, SVM strategy, Venturini strategy, RL load, synchronous machine