



People's Democratic Republic of Algeria
Ministry of Higher Education and Scientific Research
University of Echahid Hamma Lakhdar - El Oued



Faculty of Technology
Department of Mechanical Engineering
Dissertation

ACADEMIC MASTER
Domain: **Science and Technology**
Division: **Mechanical Engineering**
Specialty: **Electromechanical**

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Entitled:

Model Predictive Control for 3-Level NPC Inverters

Dissertation Submitted in Partial Fulfillment of the Requirements for the Master

MEM

Degree in : Electromechanical

Publicly defended in: 24 /05 /2026

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Academic Year: 2025/2026

ACKNOWLEDGEMENTS

We would like to express our sincere gratitude to our supervisor for his valuable guidance, continuous support, and helpful advice throughout the preparation of this thesis. We would also like to thank the members of the examination committee for reviewing this work and for their constructive comments and suggestions that contributed to improving its quality. Our sincere thanks also go to the professors of the Faculty of Technology who guided and taught us throughout the past five years, contributing greatly to our academic development. Finally, we would like to express our appreciation to University of Echahid Hamma Lakhdar El Oued for providing the academic environment and resources that enabled us to successfully complete our studies and accomplish this work.

DEDICATION

I dedicate this humble work to the souls of my beloved father and grandfather, may Allah grant them His infinite mercy and eternal peace.

Your memories remain a source of strength, wisdom, and inspiration in every step of my life. Though you are no longer by my side, your values, sacrifices, and prayers continue to guide my path and motivate me to move forward with patience and determination.

To my beloved mother and grandmother, whose endless love, kindness, prayers, and support have always surrounded me with hope and strength. Your sacrifices and encouragement have been a constant source of comfort throughout my journey.

I would also like to express my sincere gratitude and deepest respect to my supervisor, Dr. Ali Bebboukha, for his valuable guidance, patience, and continuous support throughout this work.

To my family, friends, and everyone who supported me, directly or indirectly, in completing this study, I extend my heartfelt thanks and appreciation.

Finally, I dedicate this work to every seeker of knowledge who strives to use knowledge and education for the benefit of humanity.

Bekkouche Kheir Eddine

Bekkouche ahmed amine

DEDICATION

I dedicate this work with all my love and gratitude to my beloved parents.

To my father, thank you for your endless sacrifices, guidance, and unwavering support. Your strength, wisdom, and encouragement have always inspired me to move forward and believe in myself.

To my mother, thank you for your unconditional love, patience, prayers, and constant care. Your support has been the light that guided me through every challenge and difficulty.

I would also like to express my sincere appreciation and deepest respect to my supervisor, Dr. Ali Bebboukha, for his valuable guidance, patience, and continuous support throughout the completion of this work.

Finally, I dedicate this achievement to everyone who supported and encouraged me during this journey.

Bedda abdallah

Abstract

Model Predictive Control (MPC) has emerged as a powerful control strategy for multilevel power converters due to its fast dynamic response, straightforward inclusion of system constraints, and ability to handle multiple control objectives within a single optimization framework. This paper investigates the application of MPC to three-level Neutral-Point-Clamped (NPC) inverters, which are widely used in medium- and high-power applications because of their reduced voltage stress, improved output waveform quality, and lower harmonic distortion compared with conventional two-level inverters. The proposed control approach focuses on accurate current tracking, mitigation of switching frequency effects, and maintenance of neutral-point voltage balance, which remains one of the main challenges in three-level NPC topology. By selecting the optimal switching state at each sampling instant based on a predefined cost function, the controller ensures enhanced steady-state and transient performance while preserving the dc-link capacitor voltage balance. The study highlights the operating principle of MPC for 3-level NPC inverters, discusses the formulation of the predictive model and cost function, and evaluates the control performance in terms of tracking accuracy, harmonic quality, and dynamic behavior. The results demonstrate that MPC provides an effective and flexible solution for improving the performance of 3-level NPC inverters in advanced power electronic applications

Keywords:

Model Predictive Control (MPC)

Finite Control Set Model Predictive Control (FCS-MPC)

Voltage Source Inverter (VSI)

Grid-Connected Photovoltaic System

Photovoltaic (PV)

Three-Level Neutral Point Clamped (NPC) Inverter

Space Vector Pulse Width Modulation (SVPWM)

Pulse Width Modulation (PWM)

الملخص العام

برز التحكم التنبؤي بالنموذج (Model Predictive Control - MPC) كاستراتيجية تحكم فعالة لمحاولات القدرة متعددة المستويات، وذلك بفضل استجابته الديناميكية السريعة، وسهولة تضمين قيود النظام، وقدرته على التعامل مع أهداف تحكم متعددة ضمن إطار تحسين واحد. تبحث هذه الورقة في تطبيق التحكم التنبؤي بالنموذج على العواكس ثلاثية المستويات من نوع Neutral-Point-Clamped (NPC)، والتي تُستخدم على نطاق واسع في تطبيقات القدرة المتوسطة والعالية نظراً لقدرتها على تقليل الإجهاد الواقع على عناصر القدرة، وتحسين جودة شكل موجة الخرج، وخفض التشوه التوافقي مقارنةً بالعواكس التقليدية ثنائية المستويات.

يركز منهج التحكم المقترح على تحقيق تتبع دقيق للتيار، والحد من تأثيرات تردد التبديل، والحفاظ على توازن جهد النقطة المتعادلة (Neutral Point Voltage Balance)، والذي يُعد أحد أبرز التحديات في بنية العاكس ثلاثي المستويات من نوع NPC. ومن خلال اختبار حالة التبديل المثلى عند كل لحظة أخذ عينات اعتماداً على دالة كلفة (Cost Function) محددة مسبقاً، يضمن المتحكم تحسين الأداء في حالتي الاستقرار والانتقال، مع المحافظة على توازن جهد مكثفات وصلة التيار المستمر (DC-Link).

تسلط هذه الدراسة الضوء على مبدأ عمل التحكم التنبؤي بالنموذج في العواكس ثلاثية المستويات من نوع NPC، وتناقش صياغة النموذج التنبؤي ودالة الكلفة، كما تقيم أداء نظام التحكم من حيث دقة تتبع التيار، وجودة التوافقيات، والاستجابة الديناميكية.

وتُظهر النتائج أن التحكم التنبؤي بالنموذج (MPC) يوفر حلاً فعالاً ومرناً لتحسين أداء العواكس ثلاثية المستويات من نوع NPC في تطبيقات إلكترونيات القدرة المتقدمة.

الكلمات المفتاحية

- التحكم التنبؤي بالنموذج (MPC)
- العاكس ثلاثي المستويات (3-Level NPC Inverter)
- تتبع التيار
- موازنة جهد النقطة المتعادلة
- دالة الكلفة
- إلكترونيات القدرة
- جودة القدرة الكهربائية
- التشوه التوافقي الكلي (THD)
- التبديل الأمثل
- الاستجابة الديناميكية

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List of Symbols

Symbol	Meaning
S_a, S_b, S_c	Switching states of phases a, b and c
$S1...S6$	Power switches
v_{a0}, v_{b0}, v_{c0}	Phase voltages with respect to neutral point
V_{dc}	DC-link voltage
V_{dc1}	Upper capacitor voltage
V_{dc2}	Lower capacitor voltage
v_{c1}	Voltage across capacitor C1
v_{c2}	Voltage across capacitor C2
i_a, i_b, i_c	Three-phase currents
i_{dc}	DC source current
i_{c1}	Current through capacitor C1
i_{c2}	Current through capacitor C2
R	Load resistance
L	Load inductance
T_s	Sampling period
k	Sampling instant
g	Cost function
λ	Weighting factor
j_{op}	Optimal switching state
n_{nc}	Number of commutations
$H1a, H1b, H1c$	Upper capacitor switching functions
$H2a, H2b, H2c$	Lower capacitor switching functions
$H1x$	Upper capacitor connection indicator
$H2x$	Lower capacitor connection indicator
x	Phase index (a,b,c)
i_α	Alpha-axis current
i_β	Beta-axis current
i_α^*	Reference alpha-axis current
i_β^*	Reference beta-axis current
$i_{\alpha p}$	Predicted alpha-axis current
$i_{\beta p}$	Predicted beta-axis current
V	Space voltage vector
V_0	Zero voltage vector
V_1	Active voltage vector
$a=e^{(j2\pi/3)}$	Complex operator
i	Current vector
i_p	Predicted current vector
$\hat{e}$	Estimated back-EMF

Abbreviations

Abbreviation	Meaning
MPC	Model Predictive Control
FCS-MPC	Finite Control Set Model Predictive Control
NPC	Neutral Point Clamped
VSI	Voltage Source Inverter
PWM	Pulse Width Modulation
SVPWM	Space Vector Pulse Width Modulation
THD	Total Harmonic Distortion
AC	Alternating Current
DC	Direct Current
IGBT	Insulated Gate Bipolar Transistor

General Introduction

Model Predictive Control (MPC) has emerged as a powerful control strategy for multilevel power converters due to its fast dynamic response, straightforward inclusion of system constraints, and ability to handle multiple control objectives within a single optimization framework. This paper investigates the application of MPC to three-level Neutral-Point-Clamped (NPC) inverters, which are widely used in medium- and high-power applications because of their reduced voltage stress, improved output waveform quality, and lower harmonic distortion compared with conventional two-level inverters.

The proposed control approach focuses on accurate current tracking, mitigation of switching frequency effects, and maintenance of neutral-point voltage balance, which remains one of the main challenges in three-level NPC topology. By selecting the optimal switching state at each sampling instant based on a predefined cost function, the controller ensures enhanced steady-state and transient performance while preserving the dc-link capacitor voltage balance. The study highlights the operating principle of MPC for 3-level NPC inverters, discusses the formulation of the predictive model and cost function, and evaluates the control performance in terms of tracking accuracy, harmonic quality, and dynamic behavior.

The results demonstrate that MPC provides an effective and flexible solution for improving the performance of 3-level NPC inverters in advanced power electronic applications

Chapter I

control of photovoltaic systems integrated into the electrical grid

I.1 Introduction

Model Predictive Control (MPC) is considered one of the most advanced control strategies used in power electronics and electrical drives. This method is based on predicting the future behavior of the system using a mathematical model and selecting the optimal control action according to a defined cost function. Compared with conventional control methods, MPC offers faster dynamic response, better handling of system constraints, and improved control performance. In power converter applications, MPC has gained significant attention due to the development of high-speed processors that allow real-time implementation. This work focuses on the principles of predictive control and its application to three-phase Neutral-Point Clamped (NPC) inverters, including system modeling, switching states, and predictive current control strategies.

I.2 Overview and Motivation

The growing worldwide demand for electrical energy, mainly supplied by fossil fuels such as oil and coal, has exerted significant pressure on fossil fuel reserves and has greatly affected the global environment. The finite availability of fossil fuels, which still represent the dominant energy source, leads to considerable emissions of greenhouse gases, including nitrous oxide (N_2O), carbon dioxide (CO_2), and methane (CH_4), all of which are major contributors to climate change (IPCC, 2007).

In addition, the extensive use of fossil fuels in transportation and the continuous growth of industrial activities have resulted in serious air pollution, further aggravating environmental problems [1, 2]. In order to maintain economic development while preserving natural ecosystems for future generations, the adoption of alternative, sustainable, and clean energy sources has become essential. Reaching these objectives requires collective international efforts, as highlighted in global agreements such as the Kyoto Protocol [3].

To address these concerns, renewable energy sources (RES) have gained increasing attention as an alternative solution for electricity generation. During the last few decades, the integration of renewable energy into electrical grids has expanded considerably due to policies aimed at reducing climate change impacts and ensuring sustainable energy production (World Energy Outlook). By 2023, RES represented more than 33% of the global electricity generation capacity, as shown in Figure 1.1, reflecting their growing importance within the global energy sector [4]. Unlike fossil fuels, renewable energy resources such as wind, solar, biomass, and

hydropower generate electricity without producing greenhouse gas emissions, thereby helping to reduce climate change effects and air pollution.

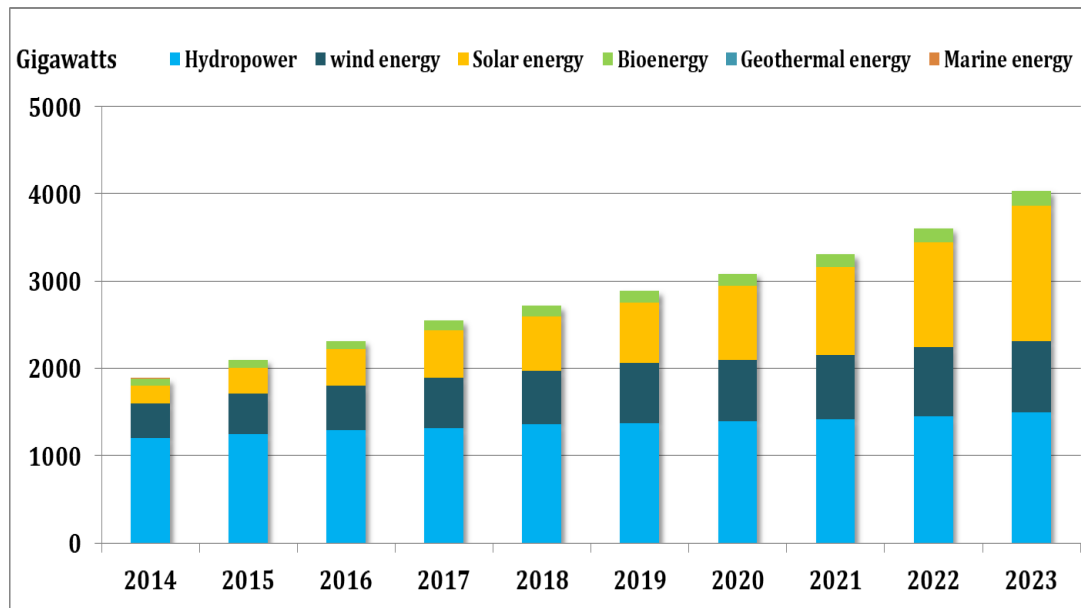


Figure I.1 Global power generating capacity [4].

Among renewable energy technologies, solar photovoltaic energy and wind power have shown remarkable growth, surpassing other types of renewable energy sources. As illustrated in Figure 1.2, photovoltaic (PV) systems and wind energy account for nearly 33% and 28% of newly installed renewable energy capacity, respectively. This development highlights the strong potential of these technologies to become major contributors to the decarbonization of the energy sector. In particular, the availability of solar energy resources differs considerably from one region to another, as presented in Figure 1.3.

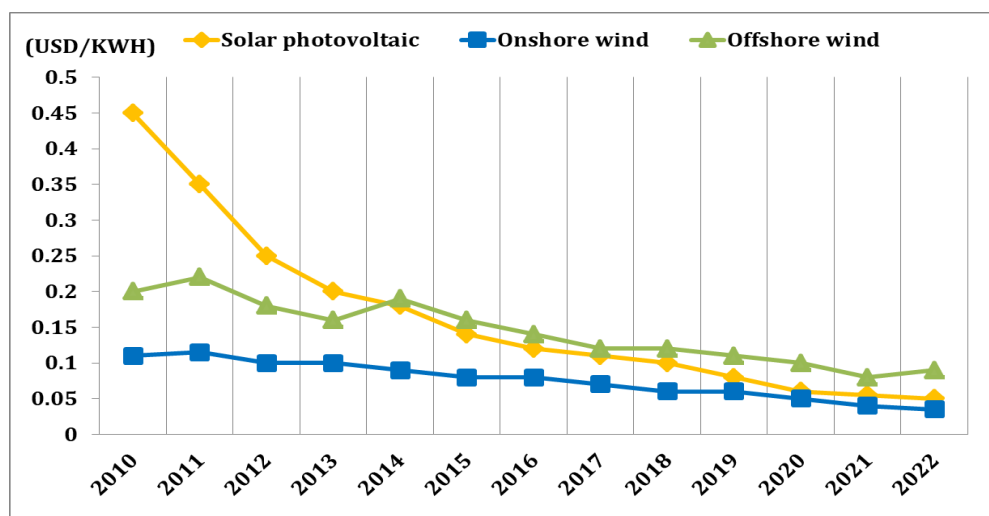


Figure I.2 Levelised cost of electricity from newly commissioned solar PV, onshore wind power and offshore wind power, 2010-2022 [5].

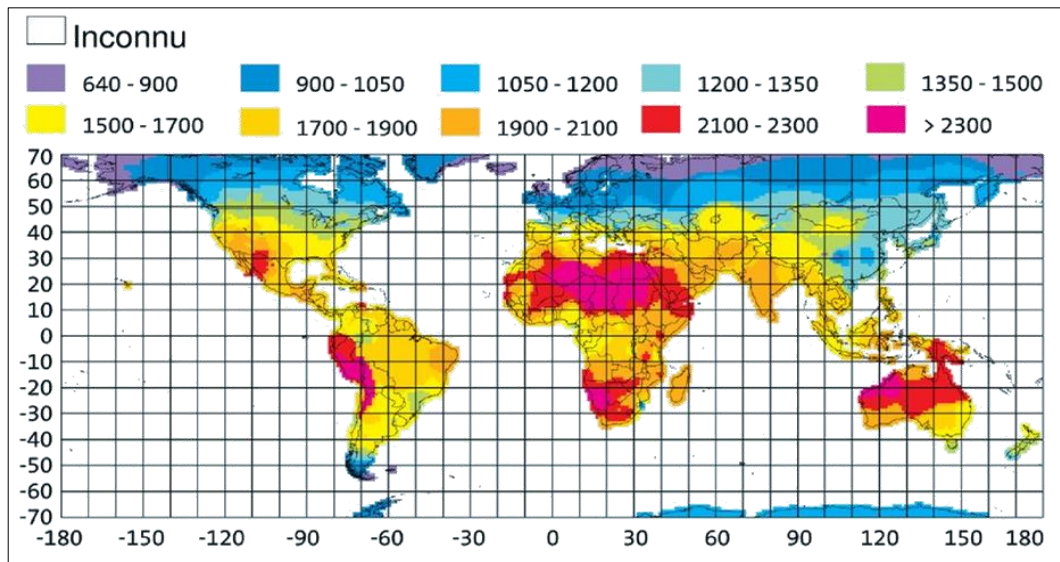


Figure I.3 Solar irradiation map of the world from photovoltaic guiden

The levelized cost of electricity (LCOE) for renewable energy technologies has decreased significantly in recent years. Among these technologies, onshore wind energy has experienced the largest reduction, with the global average LCOE falling by 50% between 2010 and 2022 to reach USD 0.033 per kilowatt-hour (kWh). Likewise, solar photovoltaic (PV) systems have achieved considerable cost reductions, with the global average LCOE reaching USD 0.049 per kWh in 2022. In comparison, offshore wind energy remains relatively more costly, with an LCOE of USD 0.081 per kWh (see Figure 1.2).

Despite these improvements in economic competitiveness, integrating renewable energy sources, particularly solar PV systems, into the electrical grid still presents important challenges because of their intermittent behavior. The direct current (DC) voltage generated by these systems is naturally variable and strongly affected by changing environmental conditions, making direct connection to the grid unsuitable. This issue has accelerated the development of power electronic converters (PECs) as an essential technological solution.

Power electronic converters act as interfaces between renewable energy systems and the electrical grid. These converters compensate for output voltage variations by continuously regulating the voltage, ensuring efficient power conversion, and maintaining balanced power flow. Through these functions, PECs improve grid compatibility and guarantee reliable integration of renewable energy into power systems.

I.3 Power Electronics Converters for Renewable Energy System

Power electronic converters (PECs) play a crucial role in enabling the integration of renewable energy sources (RES) into electrical grids and load systems. Their operation has a direct effect on the overall system performance, particularly in terms of stability, reliability, efficiency, power quality, and energy utilization.

To achieve energy conversion that is both efficient and economically viable, several advanced PEC systems are being developed in parallel with the growing deployment of renewable energy technologies [4]. Figure 1.4 illustrates a comprehensive framework for integrating renewable energy sources through the use of power electronic converters. The integration of RES into electrical systems requires PECs to adapt the output characteristics of renewable sources to the specifications of the power grid. As a result, considerable efforts have been directed toward improving the efficiency of PEC systems. These enhancements can generally be achieved through two main approaches: (a) designing new power converter topologies, or (b) applying advanced control strategies.

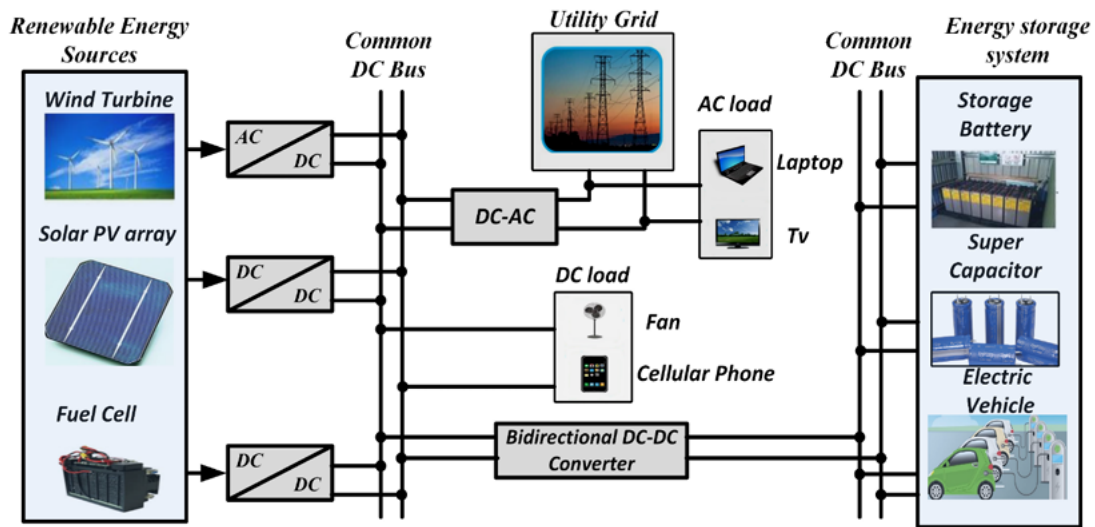


Figure I.4 Schematic exhibiting the relationship of a RES to the electricity grid.

The classification of converters used in renewable energy systems (RES) mainly includes two categories: galvanically isolated and non-isolated converters [6], [7]. Galvanically isolated converters, also referred to as transformer-based converters, use a transformer to provide electrical isolation between the input and output stages, as discussed in the topological studies presented in [8], [9], [10]. This isolation feature improves their operational capabilities and safety characteristics. However, the integration of transformers also introduces several

drawbacks, such as higher cost, increased size and weight, and lower efficiency. These disadvantages are generally not present in non-isolated, or transformer-less, converter configurations, as demonstrated in the experimental studies reported in [11, 12]. Consequently, when considering overall performance and practical constraints, non-isolated converters are often regarded as a more suitable solution for power conversion applications.

I.3.1 Review of Multilevel Inverters for PV Energy System Applications

Photovoltaic (PV) energy conversion systems play an important role in integrating renewable energy into the utility grid by providing a sustainable and efficient method for electricity generation. Figure 1.5 presents the structural configuration of such a system, starting with PV arrays that capture solar irradiance and convert it into direct current (DC) electrical energy, which is then stabilized through DC bus structures.

A multilevel power electronic converter acts as the key component of the system by converting the DC power into high-quality alternating current (AC) power with reduced Total Harmonic Distortion (THD). A filtering stage is included to satisfy grid standards by reducing high-frequency harmonics and noise. In some configurations, a transformer is also used to adapt the voltage level and provide electrical isolation between the PV system and the utility grid.

The control unit, which includes a Maximum Power Point Tracking (MPPT) controller, guarantees optimal extraction of energy from the PV arrays and accurate control of the power electronic converter. Finally, the generated AC power is delivered to the utility grid, illustrating the effective integration of advanced control techniques and power conversion technologies for efficient solar energy utilization and reliable grid compatibility.

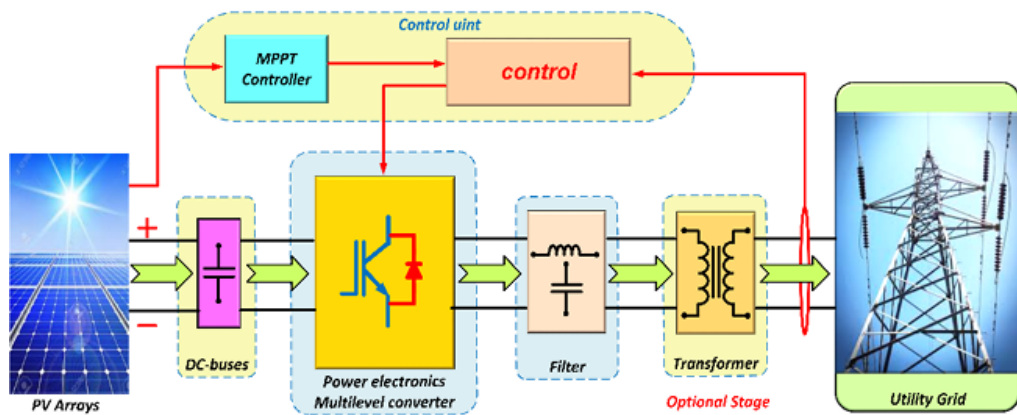


Figure I.5 A photovoltaic (PV) system with power electronics and the needed control.

I.3.2 Classification of power converters

Power electronic converters play a vital role in numerous industrial applications by enabling efficient power conversion and supporting energy-saving processes. These converters can be classified according to the type of electrical power conversion they perform and the direction of power flow. The four main categories of power converters are as follows:

- **AC-DC Rectifiers:** These devices convert single-phase or three-phase alternating current (AC) voltage into direct current (DC). They are commonly employed as front-end components in variable-speed motor drives and wind energy conversion systems.
- **DC-DC Converters:** This category of converters modifies a DC voltage from one magnitude and polarity to another, with certain applications requiring a change in polarity as well.
- **DC-AC Inverters:** These converters transform DC into AC with variable voltage and frequency, making them essential for variable-speed motor drives. Additionally, they facilitate the conversion of regulated or unregulated DC into fixed AC, a key requirement for grid integration of renewable energy sources.

AC-AC Cycloconverters: These converters adjust an AC voltage from one level, frequency, and phase configuration to another, with some applications necessitating a modification in the number of phases.

I.3.3 Classification of DC–DC converters

Numerous researchers have investigated different types of DC-DC converters for renewable energy applications and energy storage systems with the objective of improving efficiency while overcoming the drawbacks of conventional converter structures. DC-DC converters are generally classified into three main categories according to their operating modes, as illustrated in Figure 2 [13–15]: linear mode, hard-switching mode, and soft-switching mode.

The linear mode is known for its simple structure, low noise level, effective regulation capability, and fast dynamic response. However, its efficiency remains relatively low because of the power losses occurring under different operating conditions. On the other hand, hard-switching converters can be divided into isolated and non-isolated topologies depending on whether galvanic isolation is included. Typical non-isolated converter topologies include buck, boost, buck-boost, and Cuk converters, which are commonly referred to as chopper circuits. When converters are supplied from the utility grid, galvanic isolation through a transformer becomes necessary for safety requirements.

Power converters (PCs), together with advanced control methods, play an essential role in regulating voltage levels at various points within a microgrid that may contain different categories of loads, including resistive, inductive, nonlinear, constant power, and critical loads. Nevertheless, constant power loads (CPLs) introduce significant challenges to the voltage stability of power converter outputs and are often difficult to control using conventional control techniques [16, 17].

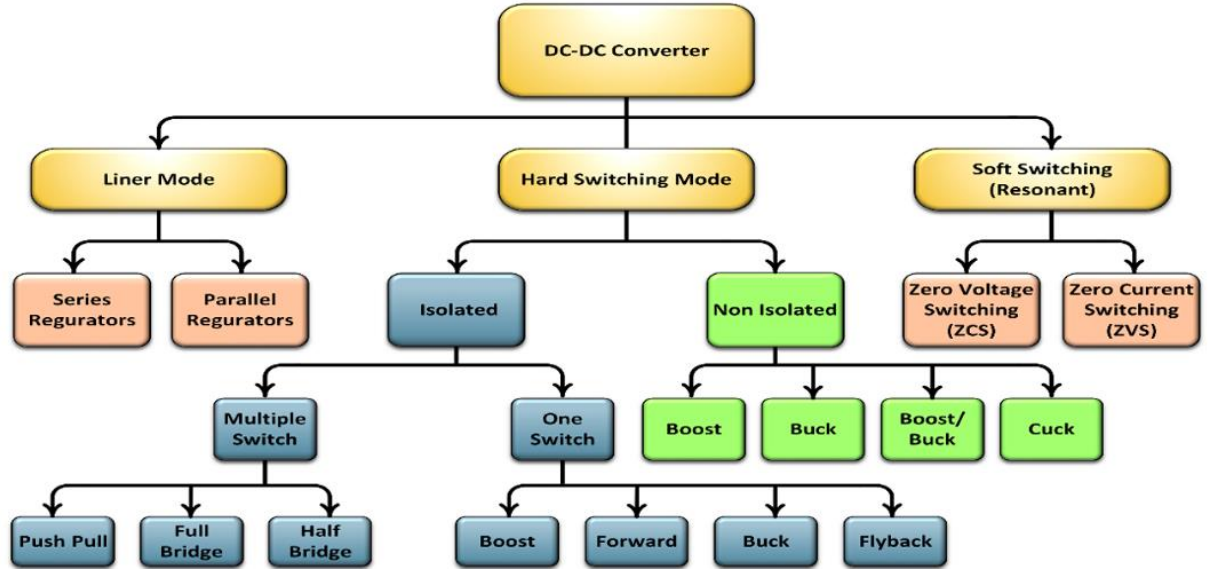


Figure I.6. Classification of DC–DC converters [18].

I.3.4 Classification of Voltage source inverter

Voltage Source Inverters (VSIs) are a well-established technology that utilizes a DC capacitor as the energy storage element in the DC-link. Over the last decade, VSIs have achieved greater technological progress and broader industrial adoption compared to Current Source Inverters (CSIs) and matrix inverters. These converters are widely employed in several power conversion applications, including electrical drive systems, renewable energy integration, and Flexible AC Transmission Systems (FACTS) [19]. The major developments in VSI technology are presented in Figure I.6.

The conventional three-phase two-level inverter is mainly intended for low-voltage and low-power applications. However, it faces several limitations, including high electrical stress and considerable harmonic distortion, especially in medium- and high-voltage applications [20]. To overcome these issues, low-voltage systems generally require parallel-connected semiconductor devices to support high current levels, while medium-voltage systems rely on series-connected devices to achieve higher voltage ratings with lower current capability. Nevertheless, neither parallel nor series configurations significantly improve power quality,

particularly regarding the reduction of voltage and current harmonics or the mitigation of dv/dt effects. In addition, series-connected devices often suffer from unequal power loss distribution and uneven voltage blocking capability, which reduces their effectiveness in high-power applications.

As a result, two-level converters are not considered the most suitable option for high-power applications, motivating researchers to develop more advanced converter topologies to address these limitations. Among the proposed alternatives, multilevel power converters have attracted considerable attention [18, 20].

Several multilevel inverter topologies have been proposed for high-power applications, including the Neutral Point Clamped (NPC) inverter, the Cascaded H-Bridge (CHB) inverter, and the Flying Capacitor (FC) inverter [21, 22].

A multilevel converter is designed to produce an output voltage waveform composed of several discrete voltage levels, which are generally obtained from capacitor voltages. In its basic configuration, a multilevel converter operates with three voltage levels and commonly includes a neutral connection between the capacitors. By introducing diode-clamping structures and different topological modifications, additional voltage levels can be generated, thereby improving the step resolution of the output waveform. Increasing the number of voltage levels enables the converter to operate efficiently in higher-voltage applications [23, 24].

However, the achievable number of voltage levels in multilevel converters is limited by the difficulty of maintaining balanced voltages across the capacitors. Among the different multilevel inverter topologies, the Three-Level Neutral Point Clamped (NPC) inverter has become one of the most commonly used and commercially successful solutions. This popularity is mainly due to its advantages, such as low voltage total harmonic distortion (THD), nearly sinusoidal output currents, reduced input and output filter size, high efficiency, low common-mode voltage, and, in certain applications, inherent fault-tolerant capability [22, 25].

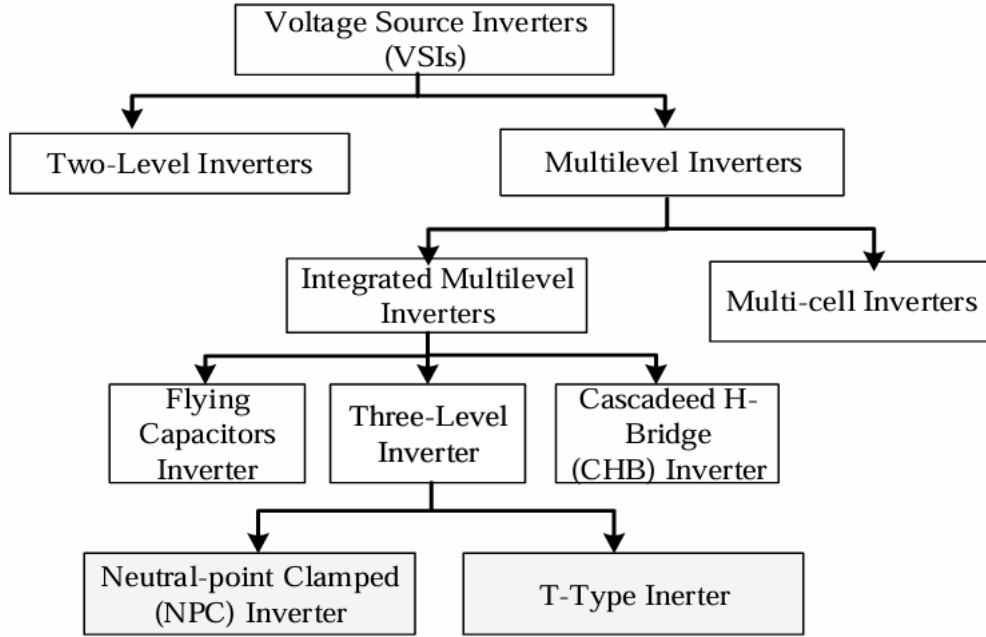


Figure I.7 Voltage source inverter types

I.4 Modeling of the DC/AC Converter (Inverter)

Voltage inverters are power electronic devices that convert DC bus voltage into alternating voltage. These converters are used in a wide range of applications. Their significant development is mainly due to two key factors: first, advances in semiconductor technology, which have led to devices that are fully controllable, robust, high-power, and fast-switching; and second, the widespread use of pulse width modulation (PWM) techniques.

I.4.1 Structure of the Two-Level Voltage Inverter

The two-level three-phase voltage inverter consists of three arms, each equipped with two switches. To ensure the continuity of alternating currents and to prevent a short circuit of the DC voltage source at the inverter's input, the switches S_a and $\bar{S}_a$, S_b and $\bar{S}_b$, S_c and $\bar{S}_c$ must be controlled complementarily. Each switch includes a recovery diode mounted in antiparallel with the semiconductor.

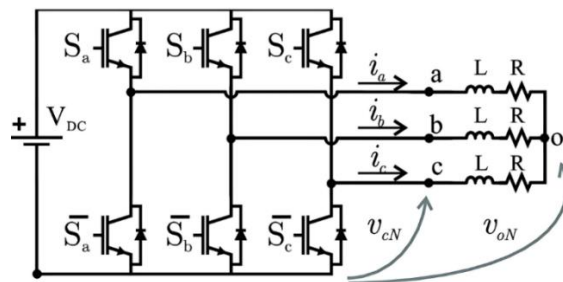


Figure I.8: Structure of the two-level three-phase voltage inverter.

To simplify the study and the complexity of the inverter structure, we will assume that:

- The switching of the switches is instantaneous.
- The voltage drop across the switches is negligible.
- The three-phase load is balanced, star-coupled, with an isolated neutral.

The DC source and the switching states of power switches S_1 through S_6 can be symbolized by the switching signals S_a, S_b and S_c , as specified in the following manner:

$$S_a = \begin{cases} 1 & \text{if } S_1 \text{ on and } S_2 \text{ off} \\ 0 & \text{if } S_1 \text{ off and } S_2 \text{ on} \end{cases} \quad \text{I.1}$$

$$S_b = \begin{cases} 1 & \text{if } S_3 \text{ on and } S_4 \text{ off} \\ 0 & \text{if } S_3 \text{ off and } S_4 \text{ on} \end{cases} \quad \text{I.2}$$

$$S_c = \begin{cases} 1 & \text{if } S_5 \text{ on and } S_6 \text{ off} \\ 0 & \text{if } S_5 \text{ off and } S_6 \text{ on} \end{cases} \quad \text{I.3}$$

The dynamic behavior of the load current for each phase can be described by utilizing the variable definitions shown in Figure II.27. This formulation for each phase is expressed as follows.

$$U_{an} = L \frac{di_a}{dt} + Ri_a + e_a + U_{nN} \quad \text{I.4}$$

$$U_{bn} = L \frac{di_b}{dt} + Ri_b + e_b + U_{nN} \quad \text{I.5}$$

$$U_{cn} = L \frac{di_c}{dt} + Ri_c + e_c + U_{nN} \quad \text{I.6}$$

The load inductance (L), load resistance (R), and the electromotive force (EMF) of the grid, denoted as e , are represented in this context.

I.4.2 Voltage Source Inverter-Based Techniques for Digital Control

Connecting the grid to a distributed generation system is a critical process, and any failure in its proper implementation may lead to issues such as grid instability and operational disturbances. To overcome these challenges, the design of an appropriate control system is essential. This section presents the most effective control strategies according to their specific applications. The literature reports various single-loop and multi-loop control schemes for power droop control, as well as for voltage and current regulation. In these configurations, the inner loop is typically responsible for current control, while the outer loop handles voltage

regulation [6–8]. The classification of classical and advanced control techniques is clearly presented in Figure I.9

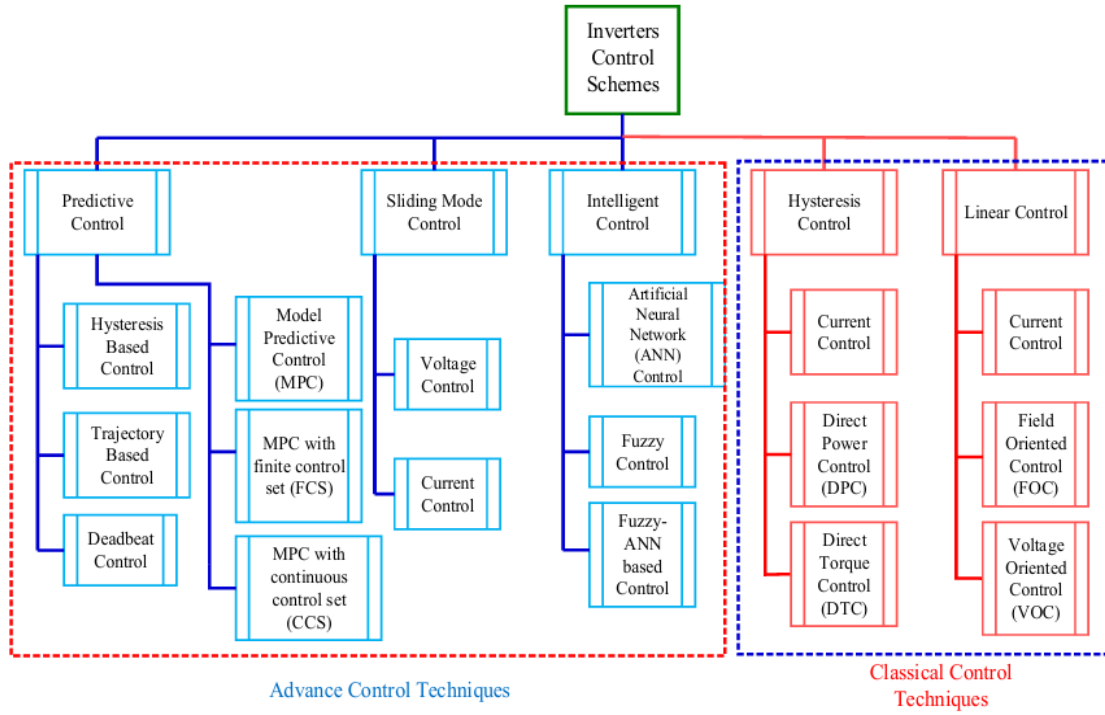


Figure I.9: Classification of control techniques for VSIs.

I.4.2.1 Classical Control Techniques

The traditional controllers are those designed to adjust the proportional response and apply the necessary corrections to the system. This category includes proportional (P), proportional-integral (PI), proportional-integral-derivative (PID), and proportional-derivative (PD) controllers. These controllers are considered the basic building blocks in industrial applications for regulating linear systems and are regarded as a cornerstone of control theory. A large amount of research has been devoted to these controllers in the literature [9–19]. Their main advantages are their ability to automatically adapt to system requirements, along with their simple structure. In addition, they are widely used in industrial applications, which makes them easily available. However, compared to modern advanced control techniques, they show lower performance in terms of tracking accuracy, dynamic response, and error stability.

The diagram illustrating a digital PI controller used to regulate a three-phase VSI with an LC filter in stand-alone mode is presented in Figure II.29. In Figure II.29, i_{af} , i_{bf} , and i_{cf} represent the filter current across phase a, b, and c respectively. Likewise, v_a , v_b , and v_c characterize the voltage across phase a, b, and c respectively. Likewise, i_d and i_q represent the current across the d and q axes respectively. Moreover, S_a , S_b , and S_c represent the switching

commands across phase a, b, and c respectively. Correspondingly, V_{ref}^d and V_{ref}^q symbolize the reference voltages along the d and q axes respectively.

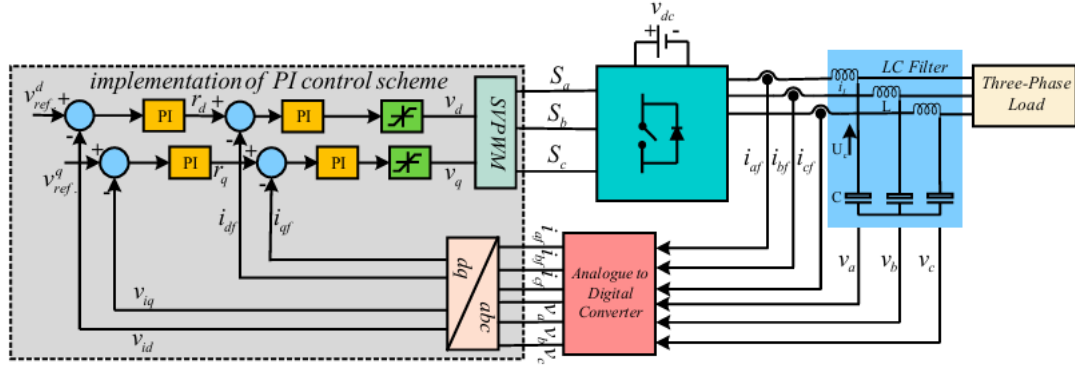


Figure I.10: Diagrammatic Representation of a PI Control Algorithm for a VSI.

I.4.2.2 Hysteresis Control Technique

Hysteresis control is regarded as a nonlinear approach [20-27]. Hysteresis controllers are employed to monitor the deviation between the desired and measured currents. As a result, gating signals are generated based on this error correction. The bandwidth of the hysteresis is fine-tuned to eliminate the error in reference tracking. This straightforward approach has been in use since the widespread application of analog control systems. Notably, this method eliminates the need for a modulator, meaning the switching frequency of the inverter is influenced by the operating conditions of the hysteresis bandwidth and the parameters of the filter [28].

The primary limitation of the hysteresis controller lies in its unpredictable switching frequency. Nonetheless, ongoing research efforts are focused on enhancing this controller, with numerous studies and proposed techniques emerging in the literature. Significant progress in this area includes the development of direct torque control (DTC) [21, 22, 29, 30] and the method of Direct Power Control (DPC) [31-34]. In Direct Power Control (DPC), both active and reactive powers are regulated directly, whereas in Direct Torque Control (DTC), the focus is on controlling the system's torque and flux. The error signals in DTC are generated by hysteresis controllers, and the corresponding drive signals are determined using a look-up table, based on the magnitude of these error signals. When implemented on a digital platform, hysteresis controllers necessitate a high-frequency operation to maintain the variables within the specified hysteresis band limits, as illustrated in Figure I.11.

Additionally, the switching losses associated with this type of controller are significantly elevated, making hysteresis controllers unsuitable for high-power applications.

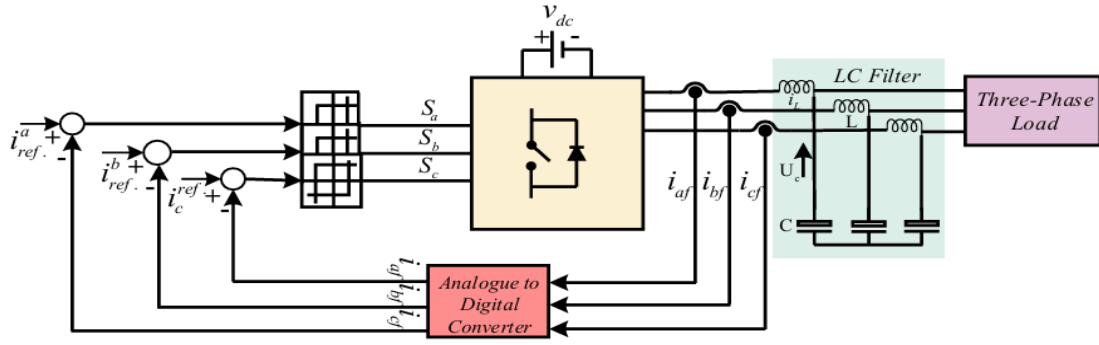


Figure I.11: A Hysteresis-Based Control Method for VSI.

I.4.2.3 Repetitive Control

The fundamental concepts of repetitive control (RC) are the plug-in scheme (PIS) and the internal model (IM) principle. RC is based on an internal model that represents a periodic signal, derived using trigonometric Fourier series expansion. By embedding this reference model into the closed-loop system, accurate tracking of periodic reference signals can be achieved. In addition, RC provides strong robustness against disturbances, allowing effective disturbance rejection. It is mainly applied to periodic signals, and its performance is evaluated based on the closed-loop response and the frequency characteristics of the internal model, especially in the presence of frequency variations or system uncertainties. These factors are key indicators of performance degradation when variations or uncertainties exist in the reference signal.

Under periodic disturbance conditions, RC aims to minimize tracking errors when following either periodic or constant reference inputs. It achieves this by predicting the error based on previous periods and correcting it in the next cycle through feedback from the control system. However, its capability to handle physical noise is limited. To overcome this limitation, a low-pass filter (LPF) can be introduced, and Kalman filtering techniques are also widely used to reduce noise effects [35–38]. The general structure of a repetitive controller is shown in Figure I.12.

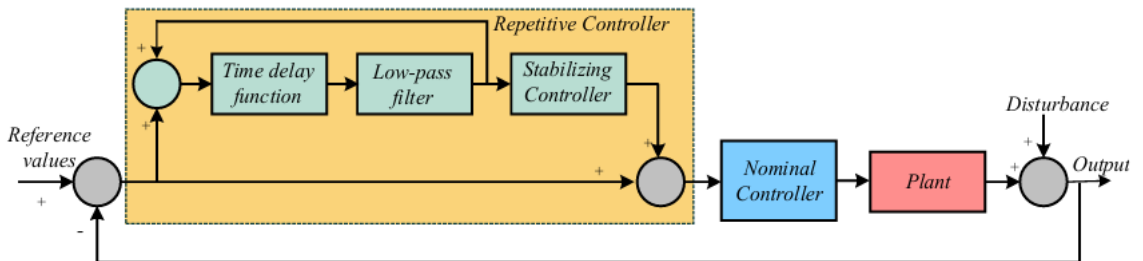


Figure I.12: Schematic Representation of the Repetitive Control Algorithm.

I.4.2.4 Fuzzy Control

This control method belongs to the family of intelligent control systems. In this approach, the conventional PI controller is replaced by a fuzzy logic controller, as illustrated in Figure I.13, where the fuzzified output voltage, the corresponding block diagram, and controller design considerations are presented. The inputs to the fuzzy controller include the load current tracking error and its derivative. The design of this controller strongly depends on the designer's expertise, knowledge, skills, and experience, particularly regarding the definition of the involved functions.

Due to the inherent nonlinear nature of power converters, the system can maintain stability even in the presence of parameter variations, despite the absence of an exact mathematical model of the converter. Fuzzy logic controllers, which are classified as nonlinear controllers, are often considered effective solutions within intelligent control strategies [39–42]. The fuzzification process requires strong assumptions and significant expertise. It depends on the system inputs, while decisions are made based on a predefined rule set established during the modeling and design phase.

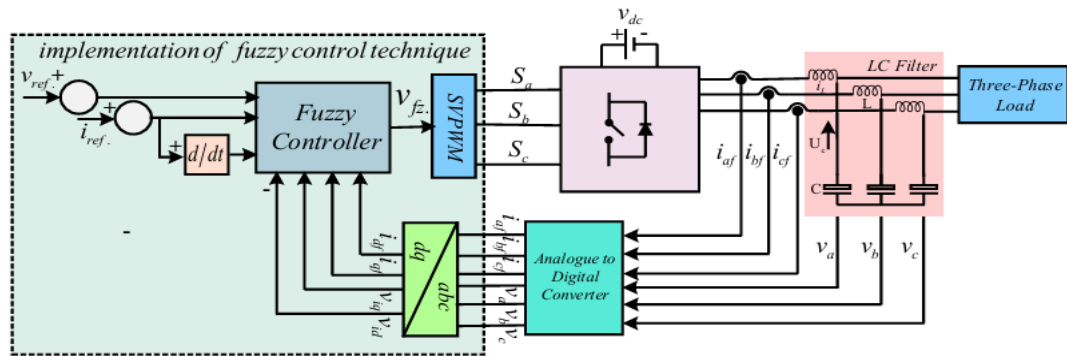


Figure I.13: A Topological Framework for Fuzzy Control Algorithms in VSI.

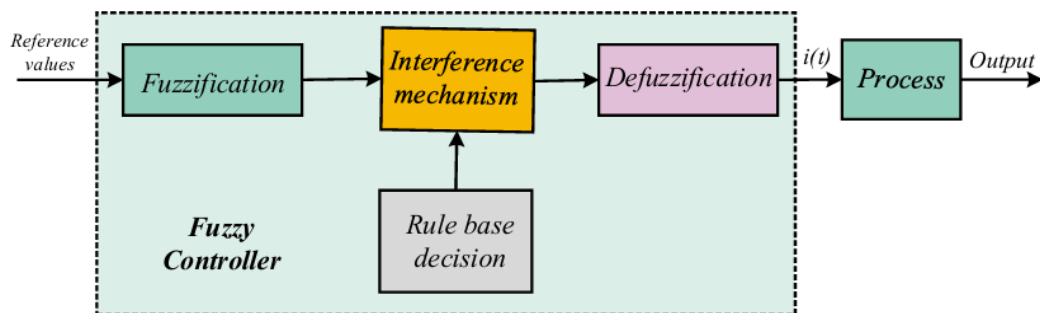


Figure I.14: Schematic Representation of the Fuzzy Control Algorithm.

I.4.2.5 Artificial Neural Network Control

Controllers based on Artificial Neural Networks (ANN) are designed to emulate human cognitive processes. These systems consist of a large number of artificial neurons that operate in a manner similar to the biological human brain. Reference tracking error signals are supplied to the ANN through an appropriate gain or scaling factor (S), enabling the generation of switching signals for power converters. This approach ensures stable switching operation in power electronic converters. ANNs can be implemented in both online and offline modes when used for system control. Their robustness to faults is significant due to their ability to approximate nonlinear function mappings. The structure of this system is shown in Figure I.15.

The combination of Fuzzy Logic and Artificial Neural Networks (ANN) can be used to achieve improved control performance in power converters [39–41]. ANNs do not require an explicit mathematical model of the converter to operate. However, it remains essential for the designer or operator to have a deep understanding of the converter's operating behavior when developing an ANN-based control system.

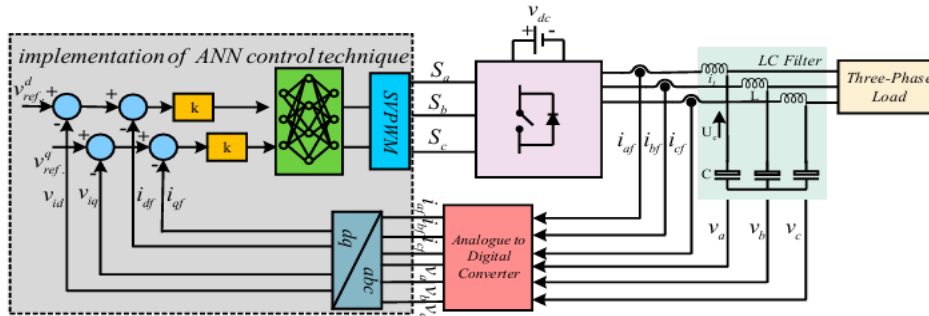


Figure I.15: Diagram of Artificial Neural Network-based Control for VSIs.

I.4.3 Predictive Controllers

Predictive controllers have become a promising solution for the control of electronic inverters. In this approach, the system model is thoroughly analyzed, and the future behavior of the control variables is predicted according to a predefined set of criteria. This method is relatively simple to implement and is highly effective for controlling multivariable systems. Moreover, it can handle systems that include constraints or nonlinearities.

This control strategy is widely preferred because of its fast static and dynamic response, as well as its strong capability in reducing steady-state errors. However, its computational complexity is higher compared to conventional control methods. Predictive control techniques are generally classified into different categories, such as Deadbeat Control and Model

Predictive Control (MPC), as discussed in the literature [43–46]. A comparative study of predictive control methods, including their main advantages and disadvantages, is presented in Table 2.

Predictive Control	Deadbeat Control
	• - Modulator required
	• - Fixed switching frequency
	• - Low computations
	• - Limitations not undertaken
	Trajectory Based Control
	• - Modulator not required
	• - Variable frequency
	• - No cascaded structure
	Hysteresis Based Predictive Control
	• - Modulator not required
	• - Variable frequency
	• - Uncomplicated structure
	Model Predictive Control
	• - Modulator required in case of continuous control set (CCS) and not required in case of finite control set (FCS).
	• - Likewise, fixed switching frequency (CCS) and variable switching frequency exists in (FCS).
	• - Online optimization and simple designing is included in case of FCS.
	• - Constraints are considered in both cases.

Table I.1. Description of predictive controllers on the basis of their pros. & cons.

I.4.3.1 Deadbeat Control

The deadbeat control method is considered one of the most reliable, efficient, and attractive control approaches because of its capability to achieve low total harmonic distortion (THD), excellent frequency response, and fast transient performance. In this strategy, the system differential equations are formulated and discretized in order to control the dynamic behavior of the system. The control signal is predicted for the next sampling interval to ensure that the

reference value is reached. The controller's wide bandwidth and strong dynamic characteristics enable effective current regulation.

A major feature of deadbeat control is its error compensation capability. However, its main drawback is its high sensitivity to network parameters and the need for an accurate mathematical model of the filter [6, 47–57]. The structure of this system is illustrated in Figure I.16, where a disturbance observer, a state estimator, and a digital deadbeat controller are used to regulate the voltage and current of a Voltage Source Inverter (VSI). the coefficient $\hat{d}$ represents the output of the disturbance observer, which includes both current and voltage disturbances. In addition, $\hat{v}_d$ and $\hat{v}_q$ denote the controlled voltages along the d-axis and q-axis, respectively.

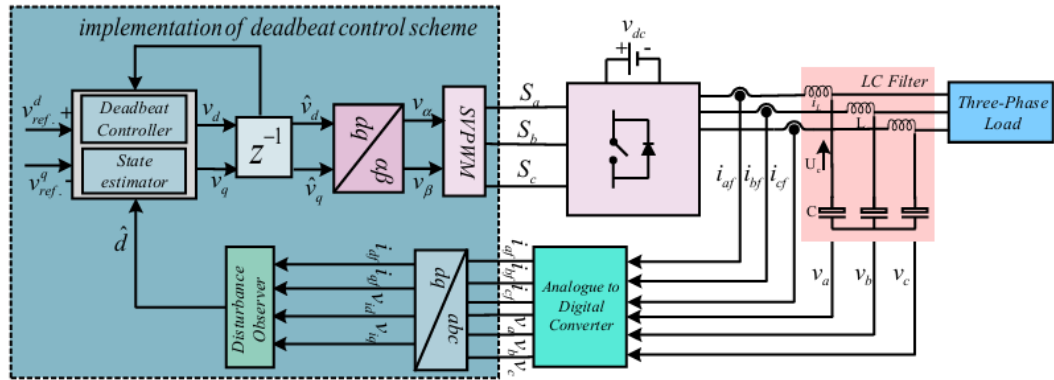


Figure I.16: Deadbeat control topology for VSIs

I.4.3.2 Model Predictive Control (MPC)

In Model Predictive Control (MPC), the behavior of the system is predicted using a mathematical model, as implied by its name. This control technique relies on a cost function that is defined to guide the optimization process and determine the most suitable control actions. The controller adjusts the switching states according to the cost function in order to obtain the optimal solution. Furthermore, the prediction error can be minimized to improve the accuracy of current tracking.

Model Predictive Control (MPC) is also capable of handling system constraints, nonlinearities, and systems with multiple inputs and outputs. It uses the present control actions to predict the required actions for the next operating state. Similar to deadbeat control, MPC is sensitive to parameter variations within the system [58, 59]. The implementation structure of MPC for the VSI is shown in Figure I.17, while the associated control diagram is illustrated in Figure I.18.

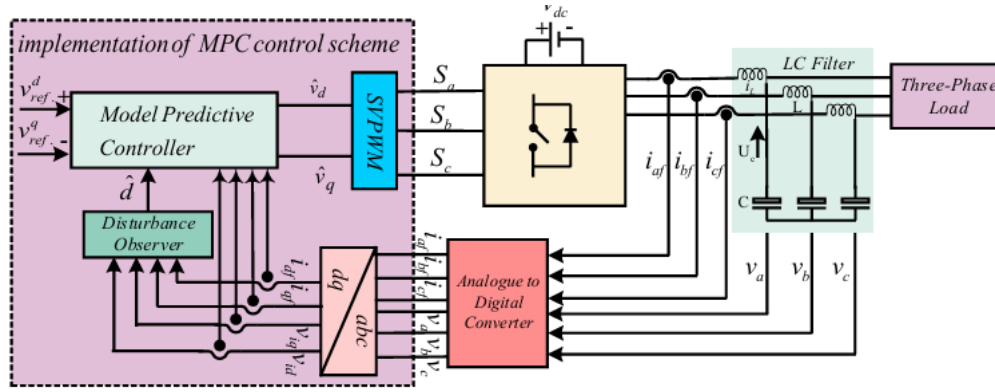


Figure I.17: Topological Approach to Model Predictive Control for VSIs.

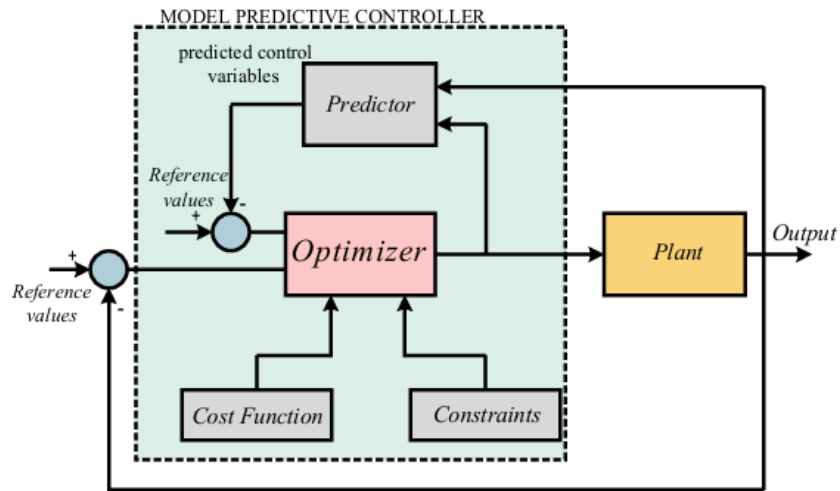


Figure I.18: Diagrammatic Representation of the Model Predictive Control Algorithm.

I.5 Computer-Based Control System

In digital control systems, the stages of modeling, design, implementation, and analysis are performed within the discrete-time or z-transform domain. These systems mainly deal with the processing and analysis of digital signals, which requires the sampling and quantization of time in state-space representations. Since digital computers operate with finite precision, special attention must be given to possible coefficient errors, such as those introduced by A/D and D/A conversions, in order to prevent undesirable or unstable effects. In addition, the output of a digital controller is obtained from a weighted combination of present and previous input and output samples, which requires storing the necessary data for proper implementation.

Digital controllers are generally implemented using computers, making them a cost-effective solution for plant control applications. They are also easier to configure and modify through software, and programs can be optimized according to the available memory resources without additional hardware costs. Furthermore, digital controllers can adapt to changing program

constraints more easily than analog controllers. Compared with analog control systems, digital controllers are less affected by environmental variations. Their main advantages include flexibility, scalability, ease of implementation for comparative logic, intelligent systems, and multiple-input multiple-output (MIMO) systems, as well as high accuracy and strong immunity to interference. However, they also present certain limitations, such as slower processing speed, reduced dynamic range, and interfaces that may be less user-friendly.

The implementation of digital controllers relies on several technologies, which can generally be classified into three main categories, as described below:

1. Implementation Utilizing Microcontrollers (MC) [10]
2. Implementation Based on Digital Signal Processing (DSP) [47]
3. Implementation Using Field Programmable Gate Arrays (FPGA) [60]

In credible scientific studies, Digital Signal Processing (DSP) is commonly employed. Typically, fixed-point and floating-point operations are utilized in the implementation of digital control techniques via DSP. Conventional microprocessors, which are slower, are generally used for applications with low-speed requirements. On the other hand, Field-Programmable Gate Arrays (FPGAs) are deemed suitable for high-speed controllers due to their capacity for bug resolution and reconfiguration in complex systems.

Figure I.19 presents the overall structure of a closed-loop digital control system, interconnected with the grid. This system comprises an inner current loop and an outer voltage loop, with the inclusion of a voltage source inverter and an output filter. An AC bus is linked to the point of common coupling (PCC). Additionally, a phase angle (PH) is utilized for the coordinate transformation from abc to dq. The phase-locked loop (PLL) is also depicted in this system. The symbols $S_1, S_2, S_3, S'_1, S'_2$ and S'_3 identify the switches that are responsible for generating the positive and negative sequences in the output of the inverter.

The v_{dref} and v_{qref} represent the reference voltages in the dq frame. The Space Vector Pulse Width Modulation (SVPWM) method is employed to produce control signals that operate voltage source inverters.

The voltage across the capacitors u_c and the current through the inductors i_L are measured and subsequently converted into a synchronized dq reference frame. The input voltage in the dq frame is determined based on the reference voltage v_{ref} from the three-phase reference frame. The computed values are then transformed from the rotating dq frame back to the abc reference frame. Finally, a suitable PWM technique is selected according to the derived results.

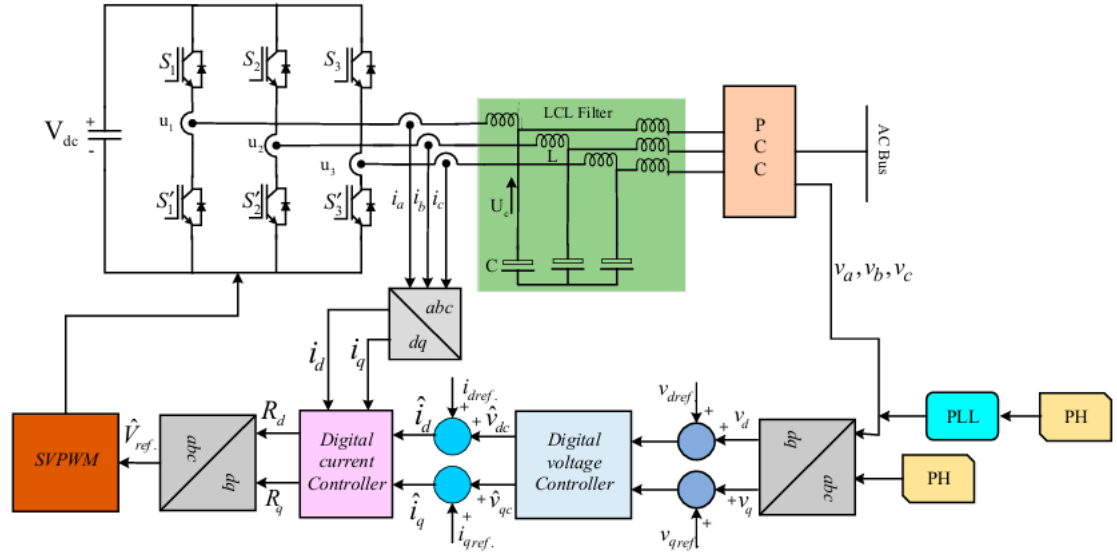


Figure I.19: Schematic diagram of a controlled three-phase grid connected VSI with a digital controller.

I.6 Output Filters for Inverters

Harmonic reduction is one of the main concerns for researchers in the design of power electronic and electrical systems. To overcome this issue, output filters are commonly employed. These filters take advantage of the controlled switching operation of semiconductor devices to reduce harmonic components. Different filter topologies have been proposed in the literature, combining inductors (L) and capacitors (C), such as L, LC, and LCL filters, which are connected to the output of inverters.

I.6.1 L-Filter

Inverters operating at high switching frequencies generally employ a first-order L-filter, which is considered one of the most suitable filtering solutions. However, the presence of the inductance reduces the overall dynamic performance of the system.

I.6.2 LC-Filter

An LC filter is considered a second-order filter and provides improved damping characteristics compared to an L-filter. This filter topology offers a relatively simple design procedure by balancing the values of inductance and capacitance. The cut-off frequency mainly depends on the inductance value, whereas the voltage quality can be improved by increasing the capacitance. When the system is connected to the utility grid, the resonant frequency is influenced by the grid impedance. LC filters are generally preferred in standalone applications.

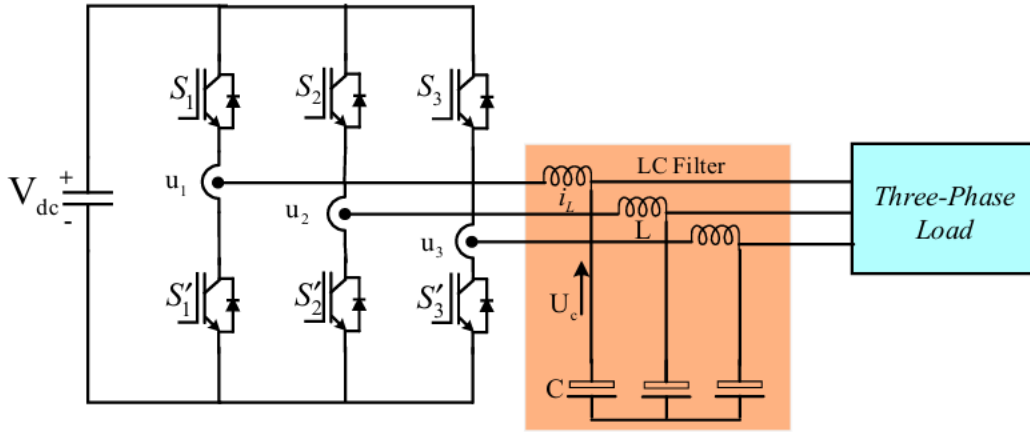


Figure I.20: Two-level three Phase VSI with an Output LC Filter.

Figures I.20 illustrate two-stage, three-phase, four-leg voltage source inverters equipped with integrated LC filters.

I.6.3 LCL-Filter

An LCL filter is a third-order filter widely used in grid-connected inverters. It is especially effective at lower frequencies when combined with the previously mentioned filter types. This filter configuration provides better decoupling between the filter and the grid impedance. Proper design is essential because it must take into account the specific parameters of the inverter; otherwise, even small inductance values may cause resonance and system instability. On the other hand, lower inductance values can improve current ripple attenuation.

A three-phase voltage source inverter (VSI) equipped with an LCL filter is shown in Figure I.21 where V_{th} and Z_{th} represent the Thevenin voltage and Thevenin impedance, respectively. However, the use of more complex filter structures significantly increases the complexity of the control system, which may affect the inverter's dynamic performance. Therefore, these filter topologies are generally more suitable for high-power applications operating at low switching frequencies.

Figures I.22 and I.23 present the one-leg block diagrams of single-phase and three-phase grid-connected systems, respectively. In these figures, PWM represents the pulse width modulation characteristic of the system, while u_g , u_i , u_c , L_g , L_i , i_i , and i_g denote the grid-side voltage, inverter-side voltage, capacitor voltage, grid-side inductance, inverter-side inductance, inverter-side current, and grid-side current, respectively.

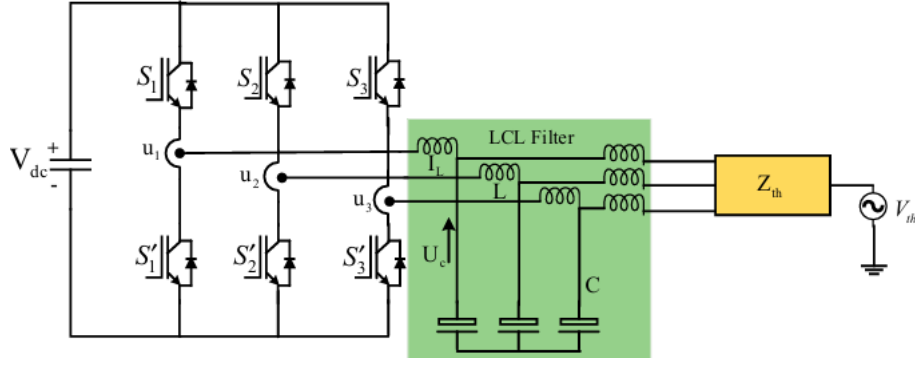


Figure I.21: A Three-Phase VSI Operating in Grid-Connected Configuration.

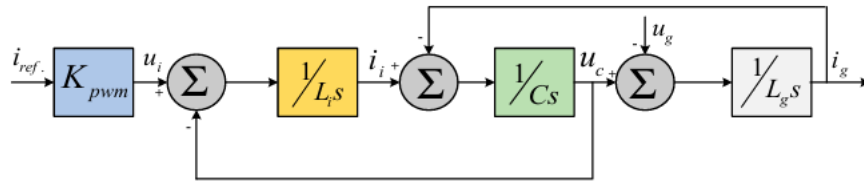


Figure I.22: Single-Phase Grid-Connected System with One-Leg Block Representation.

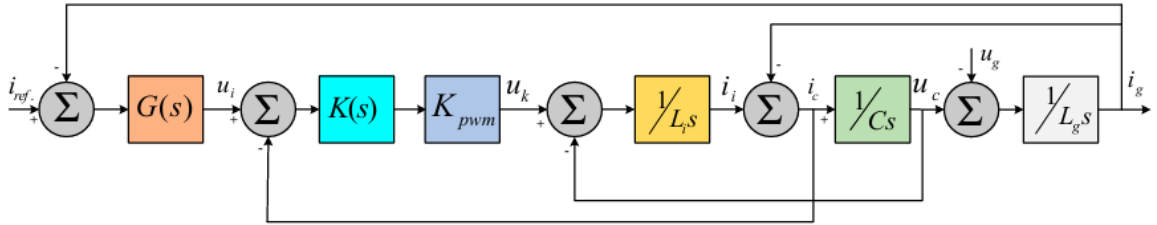


Figure I.23: One-leg block diagram of a dual-loop current control strategy for VSI.

I.7 Conclusion

This chapter has presented a comprehensive study of the modeling and control of grid-connected PV systems, with emphasis on optimizing energy conversion and ensuring efficient grid integration. PV systems convert solar energy into electrical power, but their performance is strongly influenced by environmental conditions such as solar irradiance and temperature, making accurate modeling essential for performance optimization.

To regulate voltage levels, DC-DC converters play an important role in stabilizing power transfer. Buck, boost, and buck-boost converters are commonly employed to adapt the PV

output voltage for further processing, ensuring efficient energy management in applications such as renewable energy systems, automotive technologies, and telecommunications.

Maximum Power Point Tracking (MPPT) techniques are essential for maximizing the energy extracted from PV systems under changing environmental conditions. The Perturb and Observe (P&O) method is widely used because of its simplicity, while more advanced approaches such as Incremental Conductance (IncCond) and fuzzy logic-based MPPT methods provide improved tracking accuracy and adaptability.

For grid integration, Voltage Source Inverters (VSIs) convert DC power into AC power while ensuring compatibility with grid voltage and frequency requirements. To improve inverter performance, several control techniques are applied, including Proportional-Integral (PI) control, Model Predictive Control (MPC), and artificial intelligence-based strategies. In addition, pulse width modulation (PWM) methods, such as Sinusoidal PWM (SPWM) and Space Vector PWM (SVPWM), are used to reduce harmonic distortion and improve power quality.

Finally, grid synchronization techniques, such as the Phase-Locked Loop (PLL), ensure smooth integration of PV-generated power into the electrical grid by synchronizing the inverter output with the grid voltage and frequency. Proper synchronization contributes significantly to system stability and operational reliability.

Chapter II

Model predictive control

II.1 Introduction

Three-level neutral-point clamped (NPC) inverters are widely employed in industry for high-power, medium-voltage energy conversion and drive systems [1, 2]. In this power range, issues such as switching losses and output current quality are of significant importance [3–5]. Another key challenge in this topology is the balancing of the neutral point, which has been extensively studied in recent years [6–8]. Among the commonly used control techniques for this converter are nonlinear methods, such as hysteresis control, and linear approaches, such as PI controllers combined with pulse width modulation (PWM) [9–12].

The general predictive control framework introduced in Chapter 3 is applied here to the NPC inverter. The system behavior is predicted for each possible switching state of the inverter, and the switching state that minimizes a defined cost function is chosen to be applied during the next sampling period, following the same approach described in Chapters 3 and 4. Compared to the two-level inverter discussed in the previous chapter, the NPC inverter has a larger number of switching states. This expanded set of possible control actions provides greater flexibility and enables different formulations of the cost function. Based on the control requirements specific to this topology and its applications, several variations of the algorithm are analyzed and compared with classical linear control using PWM, including aspects such as load current reference tracking, DC-link capacitor voltage balancing, and switching frequency reduction [13].

II.2 Predictive Control Methods for Power Converters and Drives

Predictive control includes a broad range of control strategies that have only recently been applied to power converters. A classification of these different predictive control approaches is presented in Figure 3.1, as introduced in [1].

The key feature of predictive control is the use of a system model to forecast the future behavior of the variables being controlled. Based on these predictions, the controller determines the optimal control action according to a predefined optimization objective.

In hysteresis-based predictive control, the objective is to maintain the controlled variable within a specified hysteresis band [2]. In trajectory-based control, the variables are forced to follow a predefined reference path [3]. For deadbeat control, the goal is to select the control action that drives the error to zero in the next sampling instant [4, 5].

Model Predictive Control (MPC) employs a more flexible approach, where the objective is defined through a cost function that must be minimized [6].

A major distinction between these control methods is that deadbeat control and MPC with a continuous control set require a modulator to generate the desired voltage, resulting in a fixed switching frequency. In contrast, the other methods directly produce switching signals for the converter without needing a modulator, which leads to a variable switching frequency.

One of the advantages of predictive control is its simplicity and intuitive nature. Depending on the method used, implementation can also be straightforward, as seen in deadbeat control and finite control set MPC (particularly for a two-level converter with a prediction horizon of $N = 1$). However, implementations based on continuous control sets in MPC can be more complex. Similarly, modified versions of deadbeat control designed to improve robustness may also become complicated and harder to interpret.

Predictive control techniques can eliminate the need for cascaded control structures commonly used in linear control systems, enabling very fast transient responses. An example is speed control using trajectory-based predictive control.

Additionally, system nonlinearities can be directly incorporated into the model, removing the necessity for linearization around a specific operating point and improving performance across a wider operating range.

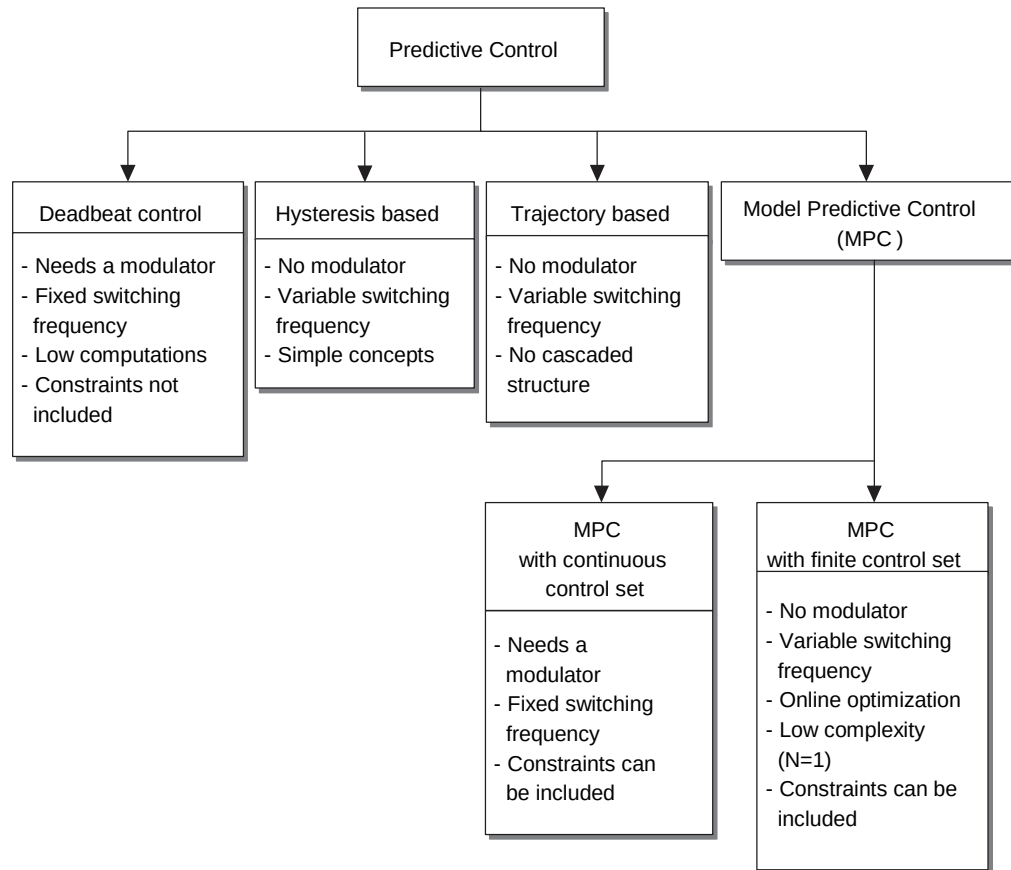


Figure II.1: Classification of predictive control methods used in power electronics

It is also possible to incorporate constraints on certain variables during controller design. These benefits are straightforward to implement in control strategies like MPC, but much harder to achieve with approaches such as deadbeat control.

This book focuses on applying MPC to power converters and drives, using a finite control set and a finite prediction horizon. Further details are provided in the following chapters.

II.3 Basic Principles of Model Predictive Control

Among advanced control methods, meaning those beyond conventional PID control, MPC is one that has been effectively applied in industrial environments [7–9]. Although the foundations of MPC date back to the 1960s as part of optimal control theory, industrial adoption began in the late 1970s [10]. Since that time, MPC has been widely used in the chemical process industry, where system dynamics are slow enough to allow all necessary computations. Initial applications of MPC concepts in power electronics appeared in the 1980s, mainly in high-power systems operating at low switching frequencies [2]. At that stage, higher switching frequencies were not feasible due to the significant computational burden of the control algorithm. However, Model Predictive Control 33

with the evolution of fast and high-performance microprocessors, interest in applying MPC in power electronics has grown considerably over the past decade.

MPC represents a broad class of controllers, not a single specific control strategy [7]. The common features of this type of controller include the use of a system model to forecast the future behavior of variables over a predefined time horizon, and the determination of optimal control actions through the minimization of a cost function. This framework offers several important advantages:

- The concepts are straightforward and easy to interpret.
- It can be utilized for a wide range of systems.
- Multivariable systems can be addressed without difficulty.
- Dead times can be effectively handled.
- Nonlinearities can be readily incorporated into the model.
- Constraints can be managed in a simple way.
- The resulting controller is easy to implement.
- This approach allows for easy inclusion of modifications and extensions depending on specific applications.

However, certain drawbacks should also be considered, such as the higher computational effort compared to traditional controllers. The accuracy of the model directly impacts the controller performance, and if system parameters vary over time, adaptation or estimation techniques must be taken into account.

The fundamental ideas behind MPC are:

- Using a model to predict the future behavior of variables over a given time horizon.
- Defining a cost function that reflects the desired system performance.
- Obtaining the optimal control action by minimizing the cost function.

The prediction model is a discrete-time model, which can be written in state-space form as follows:

$$\mathbf{x}(k+1) = A\mathbf{x}(k) + B\mathbf{u}(k) \quad (1.1)$$

$$\mathbf{y}(k) = C\mathbf{x}(k) + D\mathbf{u}(k) \quad (1.2)$$

A cost function that represents the desired behavior of the system needs to be defined. This function considers the references, future states, and future actuations:

$$J = f(\mathbf{x}(k), \mathbf{u}(k), \dots, \mathbf{u}(k + N)) \quad (1.3)$$

MPC can be formulated as an optimization problem that involves minimizing the cost function J over a predefined prediction horizon N , subject to the system model and its constraints. The solution yields a sequence of N optimal control actions. The controller then applies only the first element of this sequence.

$$\mathbf{u}(k) = [1 \ 0 \ \dots \ 0] \arg \min_u J \quad (1.4)$$

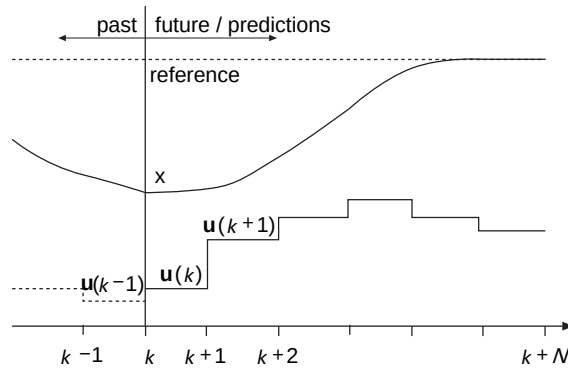


Figure II.2 Working principle of MPC

In this approach, the optimization problem is solved again at every sampling instant, using updated measured data and generating a new sequence of optimal control actions each time. This approach is known as a receding horizon strategy.

The operating principle of MPC is illustrated. The future states of the system are predicted up to a predefined horizon $k + N$ using the system model and the available measurements up to time k . The optimal control sequence is then obtained by minimizing the cost function, and only the first control action is applied. This procedure is repeated at each sampling instant using the updated measured data.

II.4 Model Predictive Control for Power Electronics and Drives

Although MPC theory was established in the 1970s, its use in power electronics and drives is relatively recent, mainly due to the very fast sampling times required in these systems. The

availability of high-speed microcontrollers in the past decade has stimulated research into new control approaches, such as MPC, for power electronics and drive applications.

As previously stated, MPC encompasses a broad range of controllers, and multiple implementations have been introduced. One notable alternative is generalized predictive control (GPC), which enables an analytical solution to the optimization problem when the system is linear and constraints are absent, resulting in an explicit control law that can be readily implemented [11, 12]. This method has been applied in various power converter [13–15] and drive applications [16–18].

To enable practical implementation of MPC in real systems, given the limited computation time imposed by fast sampling rates, a strategy known as explicit MPC has been proposed. In this approach, most of the optimization is performed offline using the system model, constraints, and control objectives. The result is a look-up table that provides the optimal solution as a function of the system state. Explicit MPC has been used in controlling power converters such as DC–DC converters and three-phase inverters [19, 20], as well as in the control of permanent magnet synchronous motors [21].

Most GPC and explicit MPC approaches approximate the power converter model as a linear system by introducing a modulator. This simplification makes the optimization process easier and enables the derivation of an explicit control law, thus avoiding the need for online optimization. However, this approximation neglects the discrete nature of power converters.

By taking into account the discrete characteristics of power converters, the optimization problem can be simplified in a way that makes online implementation feasible. Considering the limited number of switching states and the high-speed microprocessors available today, it becomes possible to compute the optimal control action by evaluating each switching state in real time. This approach provides greater flexibility and simplicity in the control scheme, as will be discussed in the following chapters of this book. Since the switching states of power converters define a finite set of possible control actions, this method is often referred to as finite control set MPC.

II.4.1 Controller Design

In the design stage of finite control set MPC for controlling a power converter, the following steps can be identified:

- Modeling the power converter by determining all possible switching states and their relationship with input or output voltages or currents.

- Defining a cost function that reflects the desired system behavior.
- Deriving discrete-time models that make it possible to predict the future behavior of the variables to be controlled.

When modeling a converter, the fundamental component is the power switch, which may be an IGBT, a thyristor, a gate turn-off thyristor (GTO), or other devices. The simplest representation of these switches assumes an ideal device with only two states: on and off. Consequently, the total number of switching states of a power converter corresponds to all possible combinations of the two states of each switch. However, certain combinations are not feasible, such as those that result in a short circuit of the DC link.

As a general rule, the number of possible switching states N is:

$$N = x^y \quad (1.5)$$

where x is the number of possible states of each leg of the converter, and y is the number of phases (or legs) of the converter. In this way a three-phase, two-level converter has $N = 2^3 = 8$ possible switching states, a three-phase, three-level converter has $N = 3^3 = 27$ switching states, and a five-phase, two-level converter has $N = 2^5 = 32$ switching states. In some multilevel topologies the number of switching states of the converter can be very high, as in a three-phase, nine-level cascaded H-bridge inverter, where the number of switching states is more than 16 million. Another aspect of the model of the converter is the relation between the switching states and the voltage levels, in the case of single-phase converters, or voltage vectors, in the case of three-phase or multi-phase converters. For current source converters, the possible switching states are related to current vectors instead of voltage vectors. It can be found that, in several cases, two or more switching states generate the same voltage vector.

For example, in a three-phase, two-level converter, the eight switching states produce seven distinct voltage vectors, where two switching states correspond to the zero voltage vector. In a three-phase, three-level converter, there is significant redundancy, as 27 switching states generate 19 different voltage vectors. Figure 1.3 illustrates the relationship between switching states.

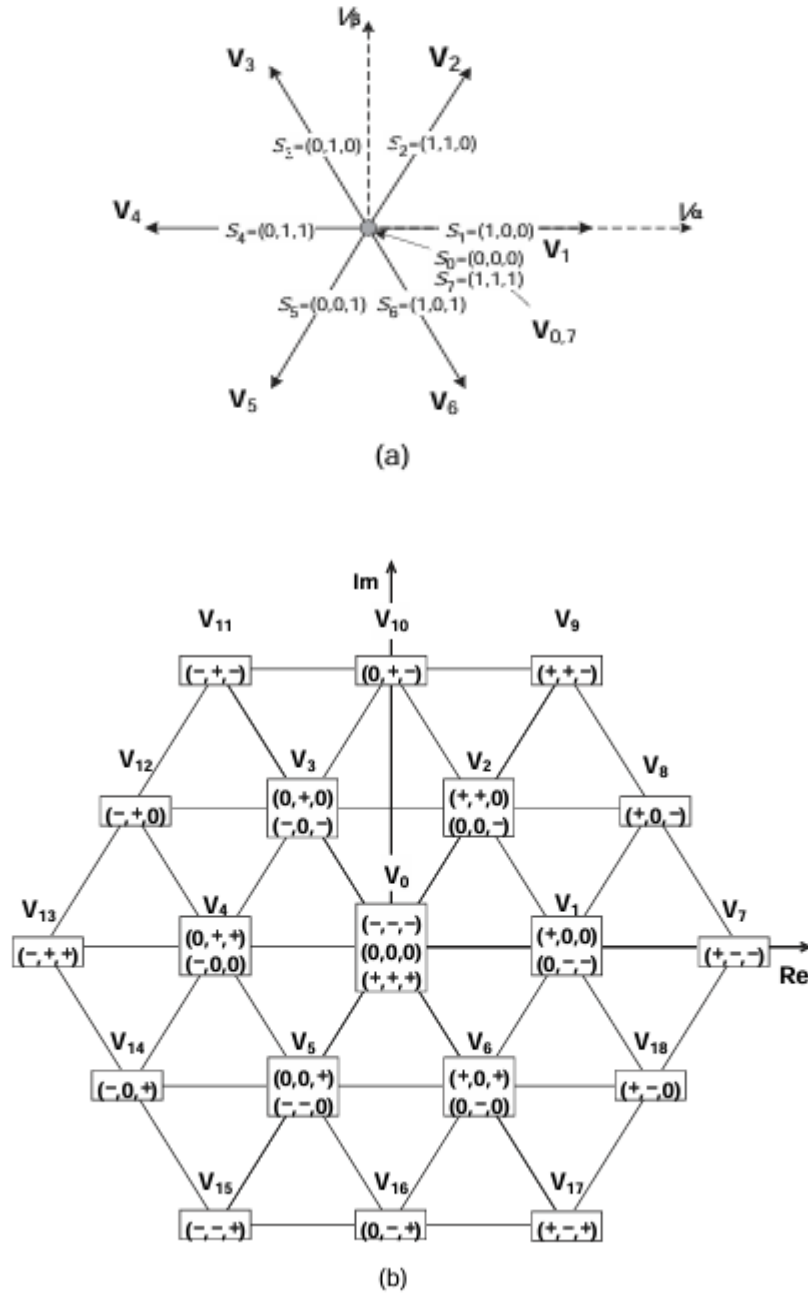


Figure II.3 Voltage vectors generated by different converters. (a) Three-phase, two-level inverter.

(b) Three-phase, three-level inverter

states and voltage vectors for two different converter topologies. In some other topologies, the procedure for determining the possible switching states may differ.

Each application imposes different control requirements on the system, such as current control, torque control, power control, or operation with low switching frequency. These requirements can be formulated as a cost function to be minimized. The simplest form of cost

function is typically based on the error between a reference value and a predicted variable, such as load current error, power error, or torque error, among others, as will be discussed in the following chapters of this book. However, one of the main advantages of predictive control methods is the ability to handle different types of variables and to include constraints directly in the cost function. To account for the different units and magnitudes of the controlled variables, each term in the cost function is multiplied by a weighting factor that adjusts the relative importance of each term.

When constructing the prediction model, the controlled variables must be taken into account in order to obtain discrete-time models suitable for prediction. It is also necessary to specify which variables are measured and which are not, since in some cases required variables for the predictive model are not directly measured and must therefore be estimated.

To obtain a discrete-time model, discretization methods are required. For first-order systems, a simple and commonly used approach is to approximate the derivatives using the Euler forward method, that is, using

$$\frac{dx}{dt} = \frac{x(k+1) - x(k)}{T_s} \quad (1.6)$$

where T_s is the sampling time. However, for higher-order systems, the discrete-time model obtained using the Euler method is not sufficiently accurate, since the approximation error becomes significant. In such cases, an exact discretization approach must be used.

II.4.2 Implementation

When implemented, the controller must perform the following tasks:

- Predict the behavior of the controlled variables for all possible switching states.
- Evaluate the cost function for each predicted case.
- Select the switching state that minimizes the cost function.

The implementation of predictive models and control strategies may present different challenges depending on the hardware platform used. When using a fixed-point processor, special care must be taken in programming to ensure adequate accuracy in the fixed-point representation of variables. In contrast, when using a floating-point processor, the same programming structure used in simulations can often be applied directly in experimental setups.

Depending on the complexity of the system being controlled, the required number of calculations can become considerable and may limit the minimum achievable sampling time. In the simplest case, such as predictive current control, the computational burden is relatively low. However, in more complex schemes such as torque and flux control, the computation time becomes the key factor that determines the allowable sampling period.

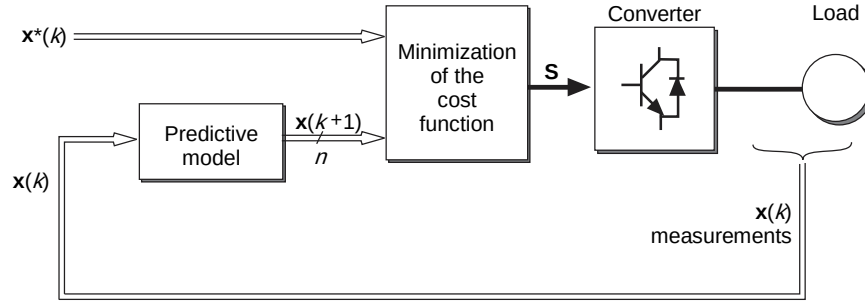


Figure II.4 General MPC scheme for power converters

To select the switching state that minimizes the cost function, all possible states are evaluated, and the optimal one is stored for application in the next step. The computational effort is directly linked to the number of possible switching states. In the case of a three-phase, two-level inverter, evaluating the eight possible switching states is not problematic. However, for multilevel and multiphase systems, alternative optimization methods must be used to reduce the computational burden.

II.4.3 General Control Scheme

A general MPC control scheme for power converters and drives is shown in Figure 3.4. The power converter may have any topology and number of phases, while the generic load illustrated can represent an electrical machine, the grid, or any other active or passive load. In this structure, the measured variables $x(k)$ are used in the model to predict the future values $x(k+1)$ of the controlled variables for each of the n possible control actions, such as switching states, voltages, or currents. These predictions are then evaluated through a cost function that incorporates the reference values $x^*(k)$ and system constraints, and the optimal switching state S is selected and applied to the converter.

II.5 System Model

The power circuit of the NPC inverter is illustrated in Figure 2.1. Each phase of the inverter consists of four switches and two diodes, where the two middle switches together with the diodes enable the output terminal to be connected to the neutral point of the DC link. This

structure makes it possible to generate three voltage levels at the output terminal of phase x with respect to the neutral point 0, according to the switching combinations listed in Table 2.1.

The switching state variable S_x represents the switching condition of phase x , where $x = \{a, b, c\}$. It can take three possible values denoted by $+$, 0 , and $-$, corresponding to the switching combinations that produce $V_{dc}/2$, 0 , and $-V_{dc}/2$, respectively, at the inverter output phase.

Considering the three phases of the inverter, a total of 27 switching states are obtained, which result in 19 distinct voltage vectors, as depicted in Figure II.2. It should be noted that some switching states are

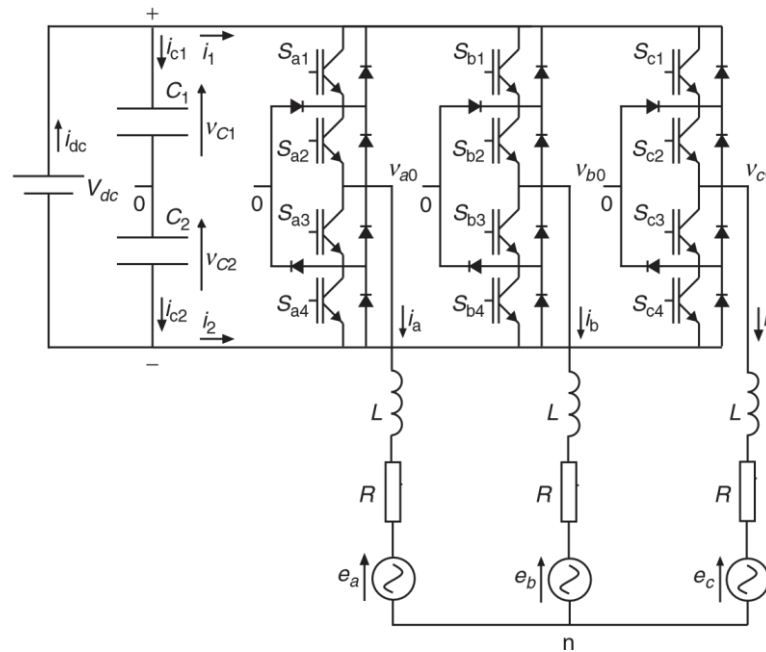


Figure II.5 Circuit of a three-phase NPC inverter connected to a resistive–inductive–active load

Table II.1 Switching states for one phase of the inverter

Table 5.1 Switching states for one phase of the inverter

S_x	S_{x1}	S_{x2}	S_{x3}	S_{x4}	v_{x0}
$+$	1	1	0	0	$V_{dc}/2$
0	0	1	1	0	0
$-$	0	0	1	1	$-V_{dc}/2$

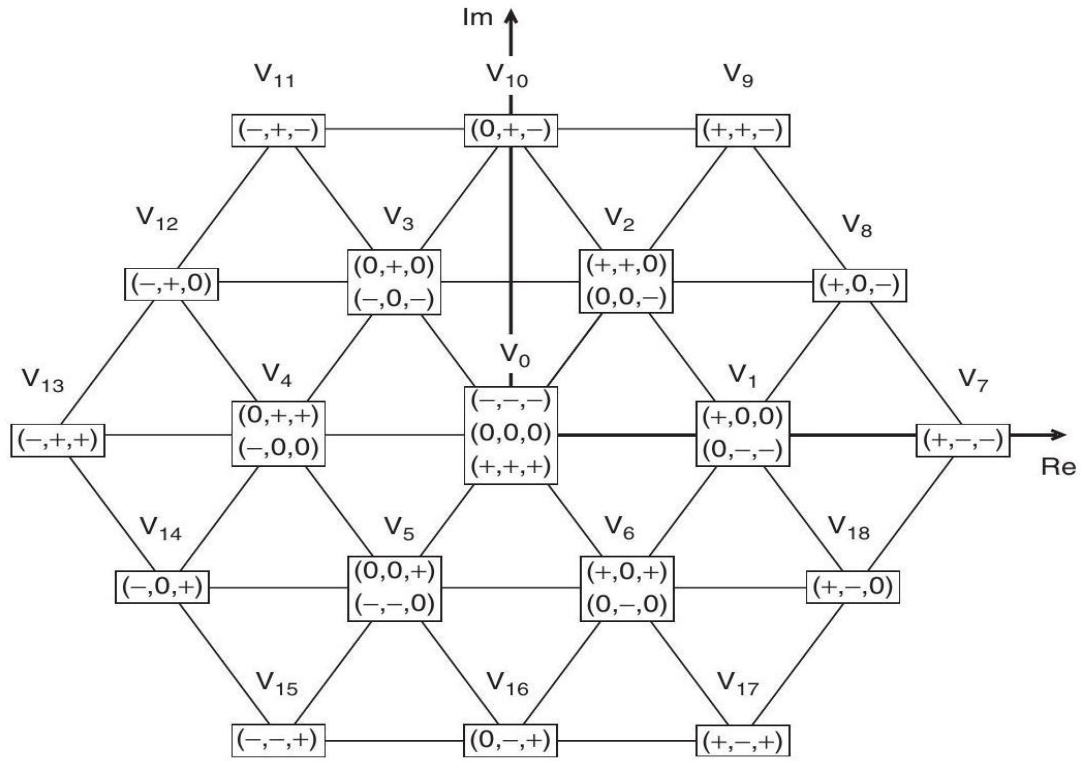


Figure II.7 Possible voltage vectors and switching states generated by a three-level inverter

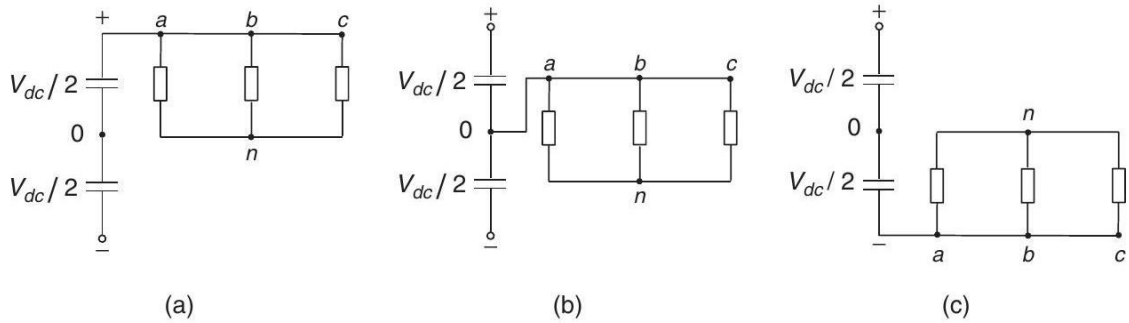


Figure II.8 Different switching states that generate the zero vector V_0 . (a) $(+,+,+)$. (b) $(0,0,0)$. (c) $(-,-,-)$

redundant, generating the same voltage vector. For example, vector V_0 can be generated by three different switching states: $(+,+,+)$, $(0,0,0)$, and $(-,-,-)$, which generate the load configurations shown in Figure II.3. Considering the space vector definition for the output voltage

$$\mathbf{v} = \frac{2}{3}(v_{a0} + \mathbf{a}v_{b0} + \mathbf{a}^2v_{c0}) \quad (2.1)$$

these three switching states generate the following voltage vectors:

$$\mathbf{V}_0 = \frac{2}{3} \left(\frac{V_{dc}}{2} + \mathbf{a} \frac{V_{dc}}{2} + \mathbf{a}^2 \frac{V_{dc}}{2} \right) = 0 \quad (2.2)$$

$$\mathbf{V}_0 = \frac{2}{3} (0 + \mathbf{a}0 + \mathbf{a}^2 0) = 0 \quad (2.3)$$

$$\mathbf{V}_0 = \frac{2}{3} \left(-\frac{V_{dc}}{2} - \mathbf{a} \frac{V_{dc}}{2} - \mathbf{a}^2 \frac{V_{dc}}{2} \right) = 0 \quad (2.4)$$

Voltage vectors $\mathbf{V}_1$ to $\mathbf{V}_6$ can be generated by two different switching states, that is, they present redundant switching states. The switching states that generate $\mathbf{V}_1$ are shown in Figure 2.4. Switching state (+,0,0) results in

$$\mathbf{V}_1 = \frac{2}{3} \left(\frac{V_{dc}}{2} + \mathbf{a}0 + \mathbf{a}^2 0 \right) = \frac{V_{dc}}{3} \quad (2.5)$$

and switching state (0,-,-) generates the same vector

$$\mathbf{V}_1 = \frac{2}{3} \left(0 - \mathbf{a} \frac{V_{dc}}{2} - \mathbf{a}^2 \frac{V_{dc}}{2} \right) = \frac{V_{dc}}{3} \quad (2.6)$$

It can also be observed in Figure 5.4 that although both switching states generate the same voltage vector, they have a different effect on the charge or discharge of the DC link capacitors.

Outer vectors present no redundancies. Figure II.5 shows switching state (+,0,-) that generates vector $\mathbf{V}_8$, calculated as

$$\mathbf{V}_8 = \frac{2}{3} \left(\frac{V_{dc}}{2} + \mathbf{a}0 - \mathbf{a}^2 \frac{V_{dc}}{2} \right) = \frac{V_{dc}}{3} (1 - \mathbf{a}^2) = \frac{V_{dc}}{\sqrt{3}} e^{j\pi/6} \quad (2.7)$$

The rest of the voltage vectors are calculated following the same procedure.

The dynamics of the DC link capacitor voltages are described by the capacitor differential equations

$$\frac{dv_{c1}}{dt} = \frac{1}{C} i_{c1} \quad (2.8)$$

$$\frac{dv_{c2}}{dt} = \frac{1}{C} i_{c2} \quad (2.9)$$

where C is the capacitor value.

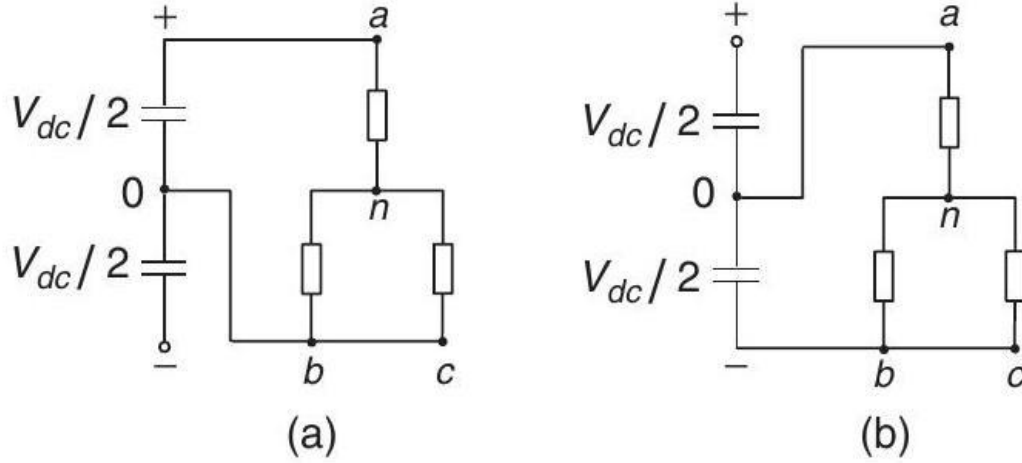


Figure II.9 Different switching states that generate vector $\mathbf{V}_1$. (a) $(+,0,0)$. (b) $(0,-,-)$

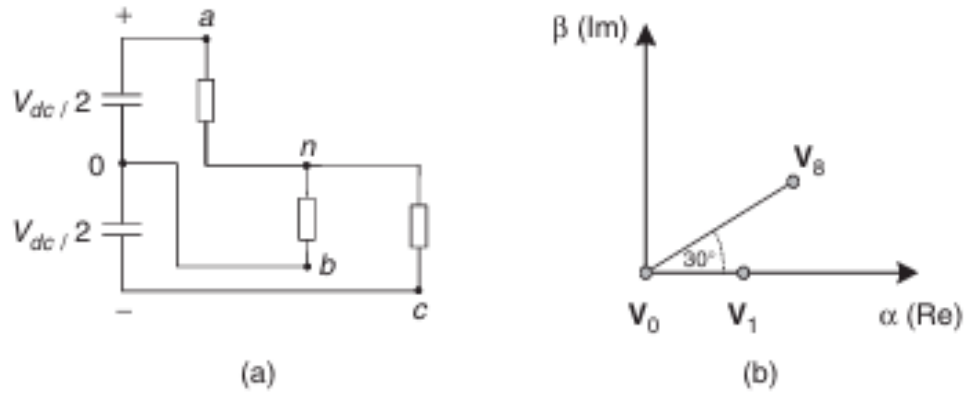


Figure II.10 Generation of voltage vector vector $\mathbf{V}_8$. (a) Switching configuration $(+,0,-)$.
(b) Vector $\mathbf{V}_8$ in the complex plane

The same approximation of the derivative considered in the previous chapter can be used for the capacitor voltages for a sampling time T_s ,

$$\frac{dv_{cx}}{dt} \approx \frac{v_{cx}(k+1) - v_{cx}(k)}{T_s} \quad (2.10)$$

giving the following discrete-time equations:

$$v_{c1}^p(k+1) = v_{c1}(k) + \frac{1}{C} i_{c1}(k) T_s \quad (2.11)$$

$$v_{c2}^p(k+1) = v_{c2}(k) + \frac{1}{C} i_{c2}(k) T_s \quad (2.12)$$

where currents $i_{c1}(k)$ and $i_{c2}(k)$ depend on the switching state of the inverter and the value of the output currents, and can be calculated using the following expressions:

$$i_{c1}(k) = i_{dc}(k) - H_{1a}i_a(k) - H_{1b}i_b(k) - H_{1c}i_c(k) \quad (2.13)$$

$$i_{c2}(k) = i_{dc}(k) + H_{2a}i_a(k) + H_{2b}i_b(k) + H_{2c}i_c(k) \quad (2.14)$$

where i_{dc} is the current supplied by the voltage source V_{dc} . Variables H_{1x} and H_{2x} depend on the switching states and are defined as

$$H_{1x} = \begin{cases} 1 & \text{if } S_x = "+" \\ 0 & \text{otherwise} \end{cases} \quad (2.15)$$

$$H_{2x} = \begin{cases} 1 & \text{if } S_x = "-" \\ 0 & \text{otherwise} \end{cases} \quad (2.16)$$

with $x = a, b, c$.

Hence, (2.11) (2.14) allow us to predict the effect of selecting a given switching state on the variation of the capacitor voltages.

The same three-phase resistive inductive active load considered in the previous chapter is used with the NPC inverter. The discrete-time model for the load current vector is expressed as

$$\mathbf{i}^p(k+1) = \left(1 - \frac{RT_s}{L}\right) \mathbf{i}(k) + \frac{T_s}{L} (\mathbf{v}(k) - \hat{\mathbf{e}}(k)) \quad (2.17)$$

where $\mathbf{v}(k)$ is the voltage vector under evaluation, which belongs to the set of 19 voltage vectors shown in Figure 2.2.

The same equations and assumptions for the estimation of the load back-emf are considered in this chapter

$$\hat{\mathbf{e}}(k-1) = \mathbf{v}(k-1) - \frac{L}{T_s} \mathbf{i}(k) - \left(R - \frac{L}{T_s}\right) \mathbf{i}(k-1) \quad (2.18)$$

II.6 Linear Current Control Method with Pulse Width Modulation

Before introducing the predictive control method, a brief review of conventional current control applied to a three-phase NPC inverter is presented in order to enable proper comparison. The chosen approach is based on linear controllers combined with a modulation technique known as level shifted phase disposition pulse width modulation (LS-PD-PWM). This option

was selected among various PWM strategies because it is commonly used for this type of inverter and offers an improved harmonic performance [1].

The classical PWM-based control scheme is illustrated. The load current is measured and compared with its reference value. A PI controller then produces the reference load voltages, which are fed into a modulator. At this stage, each reference voltage is compared with two triangular carrier signals, upper and lower, arranged with the same phase disposition. Based on the outcome of these comparisons, the switching state to be applied to the inverter is determined. For further details, see [2, 9–11].

II.7 Predictive Current Control Method

The predictive control scheme for the NPC inverter is illustrated in Figure 5.7. The future values of the load currents and capacitor voltages are predicted for all 27 switching states of the inverter using (5.17), (5.11), and (5.12). For this purpose, the present values of the load currents and capacitor voltages must be measured. After obtaining these predictions, a cost function g is evaluated for each switching state. The switching state that yields the minimum value of the cost function is then selected and applied during the next sampling interval.

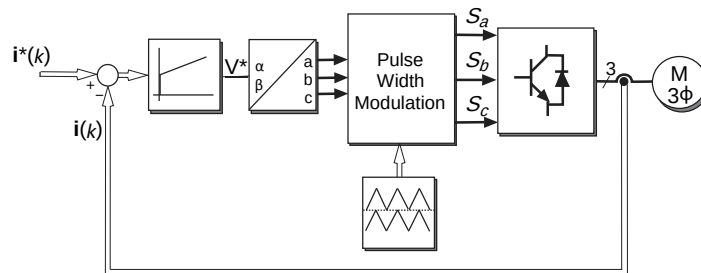


Figure II.11 Classical current control method for the NPC inverter

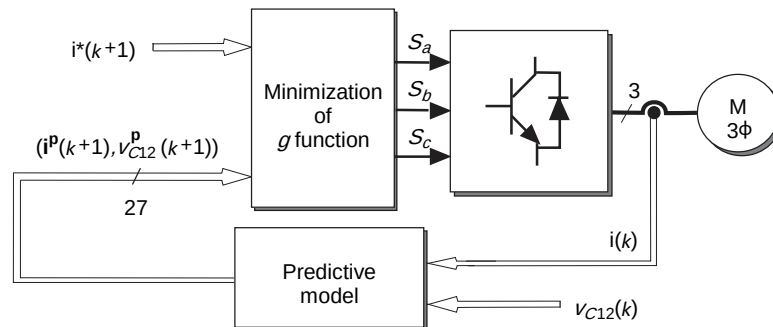


Figure II.12 Predictive current control method for the NPC inverter

The control requirements for the NPC inverter are:

- Load current reference tracking

- DC link capacitor voltages balance
- Reduction of the switching frequency.

These requirements can be formulated in the form of a cost function to be minimized. The cost function for the NPC inverter has the following composition:

$$g = |i_{\alpha}^* - i_{\alpha}^p| + |i_{\beta}^* - i_{\beta}^p| + \lambda_{dc}|v_{c1}^p - v_{c2}^p| + \lambda_n n_c \quad (2.19)$$

The first two terms correspond to the load current errors in orthogonal coordinates, where i_{α}^p and i_{β}^p represent the real and imaginary components of the predicted current vector $\mathbf{i}^p$, and i_{α}^* and i_{β}^* are the real and imaginary components of the reference current vector $\mathbf{i}^*$, as defined in the previous chapter.

The third term of the cost function quantifies the difference between the predicted values of the DC link capacitor voltages. These voltages are obtained using (2.11) and (2.12). By minimizing this term, the capacitor voltages are driven toward balance.

The last term represents the number of commutations required to transition from the current switching state to the candidate switching state. States requiring fewer commutations are preferred, meaning this term has a direct influence on the switching frequency of the converter.

The weighting factors λ_{dc} and λ_n determine the trade off between reference tracking, voltage balancing, and switching frequency reduction within the cost function g . A higher value of a given λ gives more importance to the corresponding objective.

The basic predictive current control strategy, using cost function (2.19) with $\lambda_{dc} = \lambda_n = 0$, does not require parameter tuning and only depends on knowledge of the load. However, to fully exploit the capabilities of this control method, proper adjustment of λ_{dc} and λ_n is necessary. No formal design procedure has been established for this tuning. Still, some general guidelines for selecting weighting factors are provided in Chapter 11. Initially, the designer should consider the different units and magnitudes of the variables included in the cost function g , which helps estimate suitable orders of magnitude for equal weighting of all terms.

If the goal is to maintain DC link voltage balance solely by selecting among redundant switching states that generate the same voltage vector, a small value of λ_{dc} should be chosen. The minimum value allowed by the implementation platform is usually sufficient. A similar

approach applies to λ_n . With a small value, the controller tends to select switching states that require fewer commutations within the same voltage vector. As λ_n increases, the controller may favor switching states that reduce commutations even if they are not optimal in terms of reference tracking.

To evaluate the impact of the control strategy on switching frequency and tracking performance, it is necessary to define performance metrics. First, the average switching frequency per semiconductor f_s is defined as the mean switching frequency of the 12 controlled power semiconductors in the converter. Accordingly,

$$f_s = \sum_{i=1}^4 \frac{f_{sai} + f_{sbi} + f_{sci}}{12} \quad (2.20)$$

where f_{sk} is the average switching frequency, over a given time interval, of the power semiconductor i in phase k , with $i \in \{1,2,3,4\}$ and $k \in \{a,b,c\}$. A decrease in the inverter switching frequency leads to a reduction in f_s . As can be noted, f_s is defined as an average of the switching frequencies. The 12 power semiconductors do not necessarily operate at the same switching frequency. Furthermore, switching transitions generally occur at different current levels, so f_s is not directly proportional to the converter power losses. Nevertheless, it provides a useful indication of the inverter switching frequency and the losses associated with commutations.

The mean absolute reference tracking error $\bar{e}$ is defined as the average value of the absolute difference between the reference current and the measured load current over a time interval consisting of m samples:

$$\bar{e} = \frac{1}{m} \sum_{k=0}^m |i^*(k) - i(k)| \quad (2.21)$$

As a difference between currents it will be measured in amperes and will also be expressed as a percentage of the amplitude of the reference current.

II.8 Implementation

The control strategy was implemented using rapid prototyping system together with MATLAB and Simulink running on a host PC. The sampling period adopted for the predictive

strategy was $T_s = 100\mu s$, corresponding to a sampling frequency of 10 kHz. The predictive algorithm implemented on the platform is described by the flowchart shown in Figure (2.8).

The control loop starts by sampling the required signals. Then, the algorithm estimates the active component of the load using (2.18) and initializes the variable g_{op} , which stores the lowest value of the cost function obtained so far. After that, the method enters a loop where, for each possible switching state, the cost function (2.19) is evaluated considering.

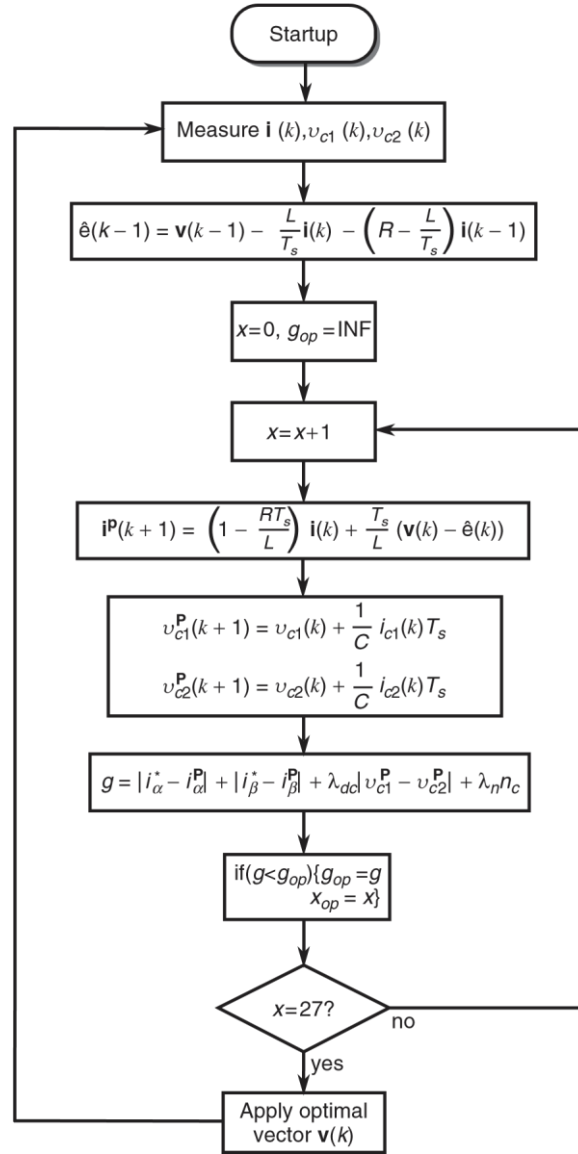


Figure II.13 Flow diagram of the implemented control algorithm

current and voltage predictions obtained from (2.17), (2.11), and (2.12), respectively. If, for a given switching state, the evaluated cost function g is lower than g_{op} , this new value is stored as g_{op} , and the corresponding switching state index is saved as j_{op} . The loop continues until all

27 switching states have been evaluated. The switching state that yields the minimum value of g , identified by j_{op} , is then applied to the converter during the next sampling interval, after which the control algorithm repeats the same process.

II.9 Reduction of the Switching Frequency

The performance of the predictive control strategy is analyzed next and compared to the classical current control. The predictive algorithm was implemented using the following cost function:

$$g = |i_{\alpha}^* - i_{\alpha}^p| + |i_{\beta}^* - i_{\beta}^p| + \lambda_n n_c \quad (2.22)$$

which corresponds to cost function (2.19) with $\lambda_{dc} = 0$. This cost function can be applied to systems where the DC link capacitor voltage balance is ensured by the rectifier.

II.10 Conclusion

In this chapter, the simulation performance of the proposed Model Predictive Control (MPC) strategy for the three-level Neutral-Point-Clamped (NPC) inverter has been successfully analyzed and evaluated using MATLAB/Simulink. The obtained results confirmed the effectiveness of the predictive controller in generating appropriate switching signals, maintaining stable inverter operation, and ensuring accurate control of the output electrical variables.

The analysis of the switching pulse waveforms demonstrated the capability of the MPC algorithm to provide precise switching state selection with stable commutation behavior. In addition, the three-phase output current waveforms i_a , i_b , and i_c exhibited balanced sinusoidal profiles with low harmonic distortion and accurate reference tracking performance. The voltage waveforms also confirmed the proper multilevel operation of the NPC inverter and the ability of the controller to manage the switching states efficiently.

Overall, the simulation results verified that the proposed MPC strategy offers fast dynamic response, improved power quality, reduced harmonic content, and reliable operation for three-level NPC inverter systems. These results demonstrate that Model Predictive Control represents an effective and flexible solution for advanced multilevel power electronic applications.

Chapter III

Simulation results and analysis

III.1. Introduction:

This chapter presents the simulation results and performance analysis of the proposed Model Predictive Control (MPC) strategy applied to the three-level Neutral-Point-Clamped (NPC) inverter. The complete system was developed and implemented in the MATLAB/Simulink environment in order to evaluate the effectiveness of the predictive controller under different operating conditions. The simulation model includes the DC-link capacitors, the three-phase NPC inverter, switching devices, load model, measurement blocks, and the predictive control algorithm responsible for selecting the optimal switching state at each sampling instant.

The obtained simulation results are analyzed through different voltage, current, and switching waveforms in order to investigate the dynamic and steady-state behavior of the inverter system. Particular attention is given to the switching pulse generation, three-phase output currents i_a , i_b , and i_c output voltage levels, harmonic quality, and the overall stability of the converter. The presented results demonstrate the capability of the MPC strategy to achieve accurate current tracking, balanced three-phase operation, reduced harmonic distortion, fast transient response, and effective switching state management. Therefore, this chapter provides a detailed evaluation of the proposed control approach and highlights its effectiveness in improving the performance of advanced multilevel power converters.

III.2 Simulation of the MPC-Controlled 3-Level NPC Inverter System

In order to evaluate the performance of the proposed Model Predictive Control (MPC) strategy, a complete simulation model of the three-level Neutral-Point-Clamped (NPC) inverter system was developed using the MATLAB/Simulink environment. The implemented model includes the DC-link capacitors, the three-phase NPC inverter, switching devices, measurement blocks, RL load, and the predictive control algorithm responsible for generating the optimal switching states. The simulation model was designed to analyze the dynamic behavior of the inverter, investigate the switching performance, and evaluate the effectiveness of the MPC strategy in terms of current tracking accuracy, harmonic reduction, voltage level generation, and overall system stability under steady-state operating conditions.

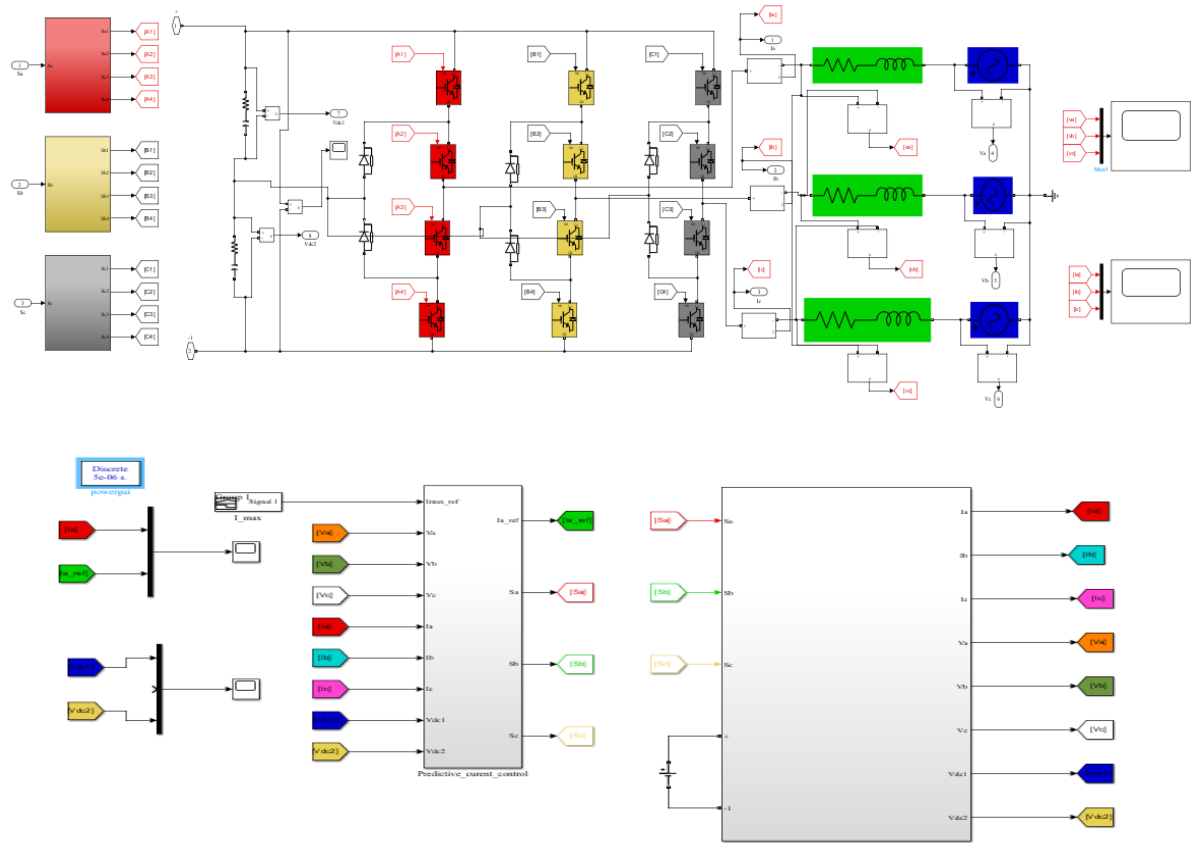


Figure III.1. Complete MATLAB/Simulink Model of the MPC-Controlled 3-Level NPC Inverter System

III.3 Constant Reference Current Simulation results

III.3.1 Analysis of Three-Phase Output Current Waveforms under MPC Control

The following waveform illustrates the three-phase output currents generated by the proposed MPC-controlled 3-level NPC inverter. The output currents, denoted by i_a , i_b , and i_c are balanced sinusoidal waveforms shifted by 120° with respect to each other, which confirms the proper operation of the three-phase inverter system. The obtained results demonstrate the excellent tracking capability of the predictive controller, as the generated currents accurately follow their reference values with smooth dynamic behavior and minimal steady-state error. Furthermore, the low distortion observed in the current waveforms indicates the effectiveness of the MPC strategy in reducing harmonic components and improving the overall power quality of the inverter output under steady-state operating conditions.

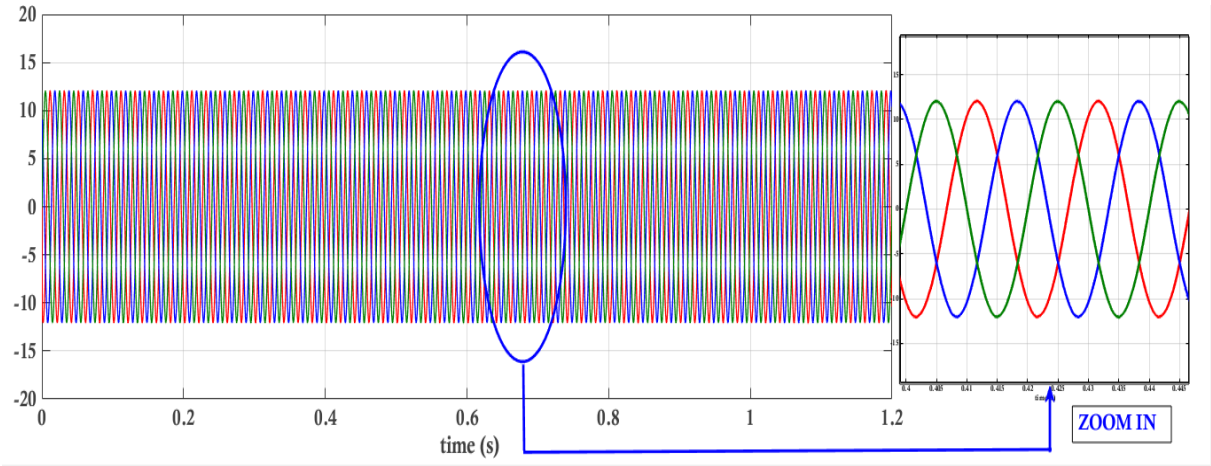


Figure III.2. Three-Phase Output Current Waveforms under MPC Control

III.3.2 Analysis of Switching Pulses of Switches A1 and A3 under MPC Control

The following waveform illustrates the switching pulse signals generated for switches A1 and A3 of the three-level Neutral-Point-Clamped (NPC) inverter under the proposed Model Predictive Control (MPC) strategy. The predictive controller continuously determines the optimal switching states according to the predefined cost function in order to ensure accurate converter operation and fast dynamic response. The obtained pulses exhibit regular and stable switching behavior, confirming the effectiveness of the MPC algorithm in controlling the upper switching devices with high precision and reduced switching disturbances.

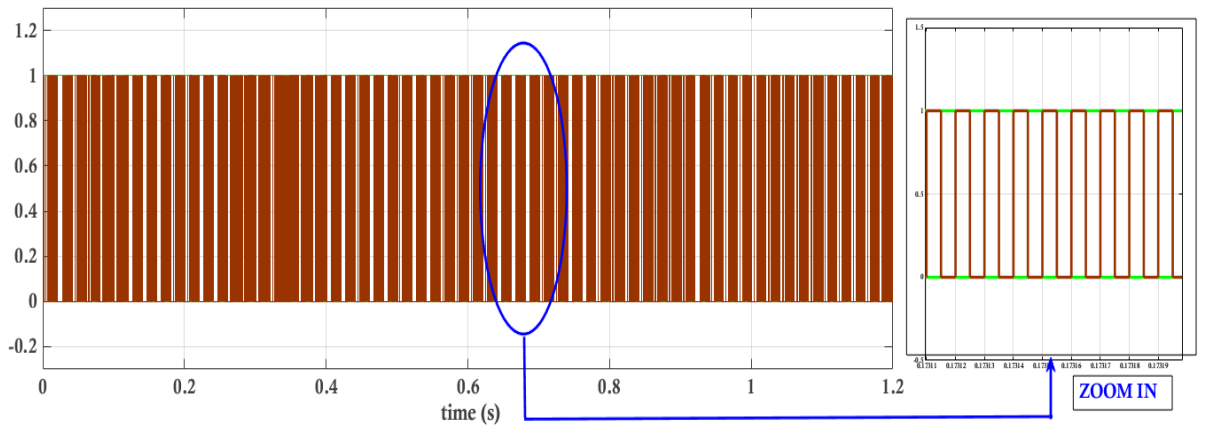


Figure III.3. Switching Pulse Waveforms of Switches A1 and A3 under MPC Control

III.3.3 Analysis of Switching Pulses of Switches A2 and A4 under MPC Control

The following waveform illustrates the switching pulse signals associated with switches A2 and A4 of the three-level NPC inverter operating under the proposed MPC strategy. The generated switching sequences demonstrate stable commutation and accurate switching state selection achieved by the predictive controller. The obtained results verify the capability of the

MPC algorithm to ensure proper operation of the lower switching devices while maintaining stable inverter performance and efficient power conversion.

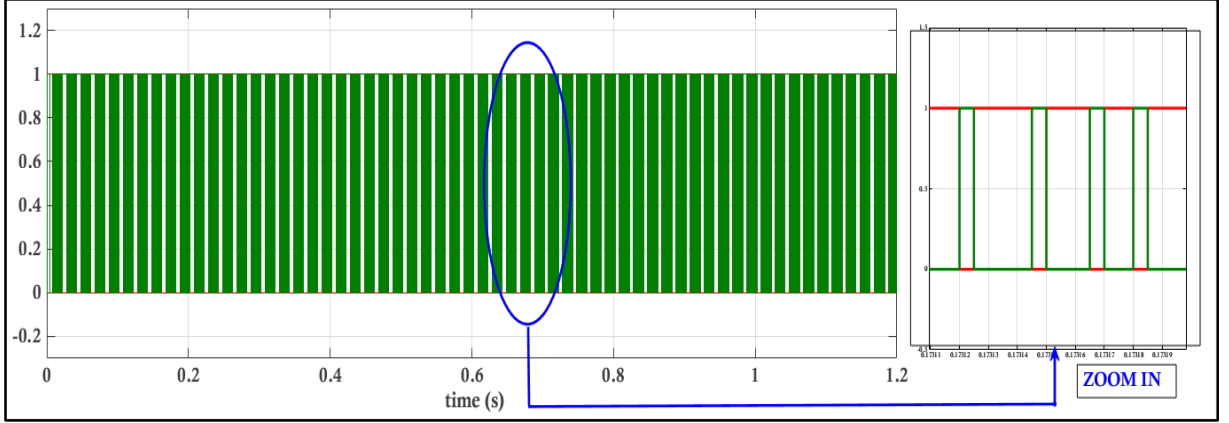


Figure III.4. Switching Pulse Waveforms of Switches A2 and A4 under MPC Control

III.4.1 State Analysis of Output Voltage under MPC Control

Figure 1 illustrates the line-to-line output voltage waveforms V_{ab} , V_{bc} , and V_{ca} produced by the three-level Neutral-Point-Clamped (NPC) inverter operating under the proposed Model Predictive Control (MPC) strategy during constant reference conditions. The results demonstrate that the predictive controller successfully generates balanced and symmetrical three-phase voltages with stable operation throughout the entire simulation interval. The waveform structure clearly reflects the multilevel characteristics of the NPC topology, where multiple discrete voltage levels, including positive, zero, and negative states, are generated to achieve improved voltage synthesis compared with conventional two-level inverters. The staircase-shaped waveform significantly enhances the approximation of a sinusoidal voltage profile, thereby reducing harmonic distortion and minimizing voltage stress across the semiconductor switching devices. Furthermore, the zoomed-in section highlights the rapid and well-coordinated switching transitions selected by the MPC algorithm, confirming the effectiveness of the optimization-based switching strategy in determining the optimal voltage vector at each sampling instant. The absence of irregular oscillations or unstable transitions indicates robust controller performance and accurate predictive operation. In addition, the symmetrical distribution of the voltage levels around the zero axis confirms effective neutral-point voltage balancing, which represents one of the most critical challenges in three-level NPC inverter systems. The obtained results verify that the proposed MPC approach maintains dc-link capacitor voltage balance while simultaneously ensuring high-quality output voltage generation and stable steady-state behavior. Moreover, the reduced waveform distortion and improved voltage quality demonstrate the suitability of the proposed control strategy for

medium- and high-power industrial applications, renewable energy conversion systems, and advanced grid-connected power electronic applications requiring high dynamic performance and enhanced power quality.

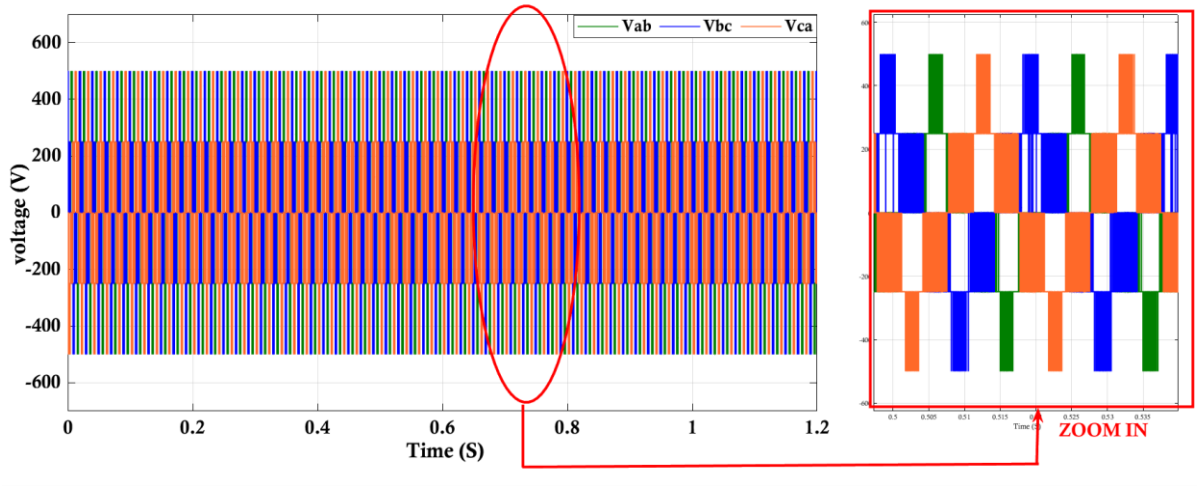


Figure III.5. Output Voltage of the Three-Level NPC Inverter under MPC

III.4.2 Analysis of Phase Output Voltage Waveform under MPC Control

The phase output voltage waveform V_{ca} generated by the three-level NPC inverter under the proposed MPC strategy demonstrates stable and symmetrical multilevel voltage operation during constant reference conditions. The obtained waveform exhibits smooth switching transitions and effective steady-state performance, confirming the ability of the inverter to generate multiple voltage levels that improve waveform quality and reduce harmonic distortion compared with conventional two-level inverters. The zoomed-in section highlights the accurate switching behavior achieved by the MPC controller and verifies the effectiveness of the predictive optimization process in selecting the optimal switching states. In addition, the symmetrical voltage distribution around the zero axis indicates successful neutral-point voltage balancing and stable dc-link capacitor operation. Overall, the results confirm that the proposed MPC strategy achieves high-quality voltage synthesis, enhanced power quality, and reliable performance suitable for advanced medium- and high-power power electronic applications.

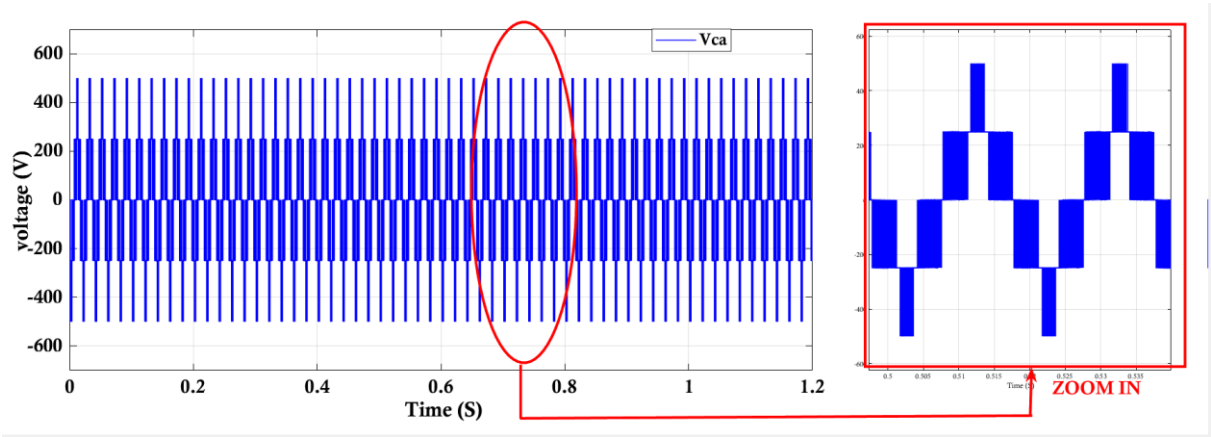


Figure III.6. Phase Output Voltage V_{ca} of the Three-Level NPC Inverter under MPC Control

III.4.3 Analysis of Three-Phase Grid Voltage

As shown in Figure 3, the three-phase grid voltage waveforms V_a , V_b , and V_c exhibit balanced sinusoidal behavior under constant reference conditions. The voltage amplitude is approximately ± 130 V, while the waveforms remain centered around the zero-voltage axis, confirming the absence of dc offset. The zoomed-in view between approximately 0.50 s and 0.54s shows that the three phases are sinusoidal and regularly displaced by about 120° , which confirms proper three-phase grid operation and phase balance. The complete simulation interval from 0 s \ 1.2 s demonstrates stable steady-state performance without noticeable amplitude fluctuation, waveform distortion, or instability. Therefore, as shown in Figure 3, the proposed MPC-controlled three-level NPC inverter maintains accurate grid voltage generation, balanced phase relationships, and high waveform quality, which supports its suitability for grid-connected power electronic applications.

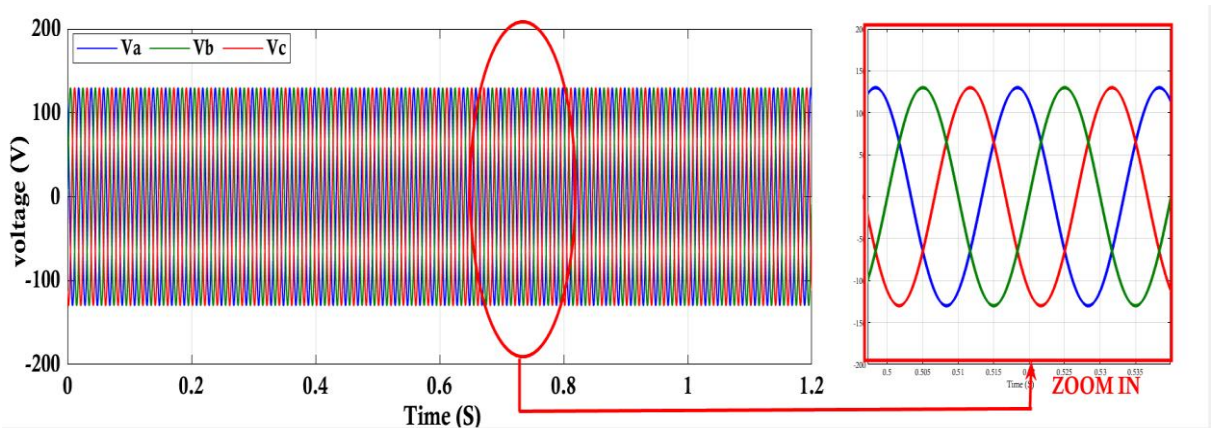


Figure III.7. Three-Phase Output Grid Voltage

III.4.4 State Analysis of DC-Link Capacitor Voltage Balancing

As shown in Figure 4, the dc-link capacitor voltages V_{dc1} and V_{dc2} remain properly balanced around the reference value of approximately 250 V throughout the entire simulation interval from 0 s\ 1.2 s. Both capacitor voltages exhibit only small ripple variations within a narrow operating range of approximately 249.8 V to 250.2 V, indicating effective neutral-point voltage regulation and stable dc-link operation. The zoomed-in section around 0.46 s clearly demonstrates that the voltage fluctuations are minimal and well-controlled despite the high-frequency switching behavior introduced by the MPC strategy. Furthermore, the close overlap between V_{dc1} and V_{dc2} confirms that the proposed predictive controller successfully maintains capacitor voltage balance, which represents one of the major operational challenges in three-level NPC inverter topologies. The absence of significant voltage drift or imbalance verifies the effectiveness of the MPC optimization process in selecting appropriate switching states to preserve neutral-point stability while ensuring reliable inverter performance. Therefore, the obtained results confirm that the proposed MPC-controlled three-level NPC inverter achieves stable dc-link voltage regulation, reduced capacitor voltage imbalance, and enhanced steady-state performance suitable for advanced grid-connected and medium-voltage power electronic applications.

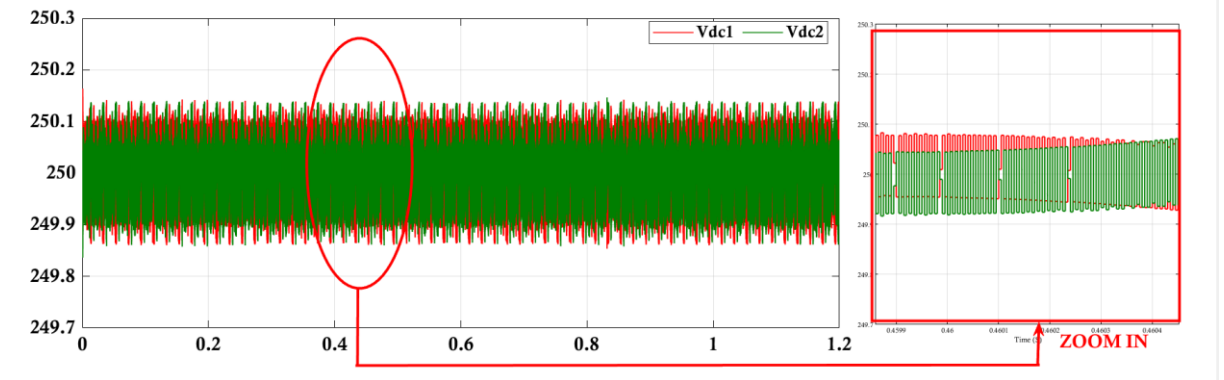


Figure III.8. DC-Link Capacitor Voltages V_{dc} and V_{dc2} under Constant Reference Conditions

III.5 variable reference current

III.5.1 Dynamic Analysis of Three-Phase Output Currents under MPC Control

As shown in Figure 5, the three-phase output currents I_a , I_b , and I_c exhibit balanced sinusoidal behavior under variable reference current conditions. During the initial operating interval, the current amplitude is maintained at approximately 14 A. At around 0.45 s, a

dynamic reference change is introduced, causing the current amplitude to increase rapidly to approximately 20 A. The obtained results demonstrate that the proposed MPC-controlled three-level NPC inverter successfully tracks the variable reference current with fast dynamic response and minimal transient distortion. The zoomed-in section clearly illustrates the transient behavior during the reference variation, where the currents remain smooth and balanced despite the sudden amplitude change. In addition, the three phases preserve the required 120° phase displacement throughout the transition process, confirming stable three-phase operation and effective predictive current regulation. The absence of significant oscillations, overshoot, or instability after the reference variation indicates the robustness of the MPC algorithm and its capability to ensure rapid tracking performance while maintaining waveform quality. Therefore, the results verify that the proposed MPC strategy provides accurate current control, excellent transient response, and stable dynamic performance suitable for advanced grid-connected and high-performance power electronic applications.

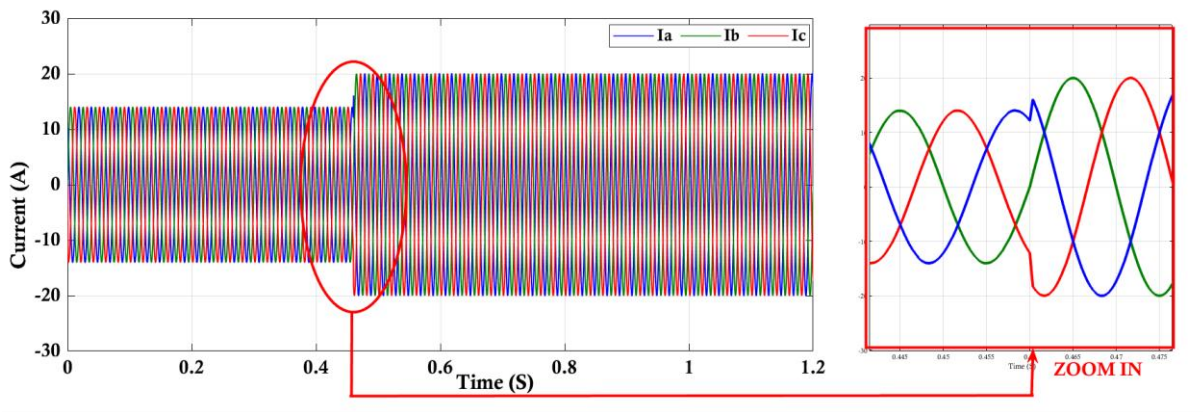


Figure III.9. Three-Phase Output Currents under Variable Reference Current Conditions

III.5.2 Dynamic Analysis of Output Voltage under MPC Control

As shown in Figure 6, the output voltage waveforms V_{ab} , V_{bc} , and V_c remain balanced and stable under variable reference current conditions. The generated voltages exhibit symmetrical multilevel switching behavior with voltage levels extending approximately between -500 V- and $+500$ V. Around 0.45 s, the system experiences a reference current variation; however, the proposed MPC-controlled three-level NPC inverter maintains stable voltage generation without noticeable instability or waveform degradation. The zoomed-in section clearly illustrates the detailed switching transitions and confirms that the predictive controller continues selecting the appropriate voltage vectors during the transient operating condition. In addition, the multilevel stepped waveform structure remains preserved throughout

the dynamic transition, which contributes to reducing harmonic distortion and improving output voltage quality. The balanced distribution of the three line voltages around the zero axis further confirms stable inverter operation and effective predictive switching control. Moreover, the absence of excessive overshoot, oscillations, or voltage imbalance demonstrates the robustness and fast dynamic response capability of the MPC strategy under changing operating conditions. Therefore, the obtained results verify that the proposed predictive control approach achieves reliable voltage regulation, stable multilevel voltage synthesis, and high dynamic performance suitable for advanced medium- and high-power grid-connected power electronic applications.

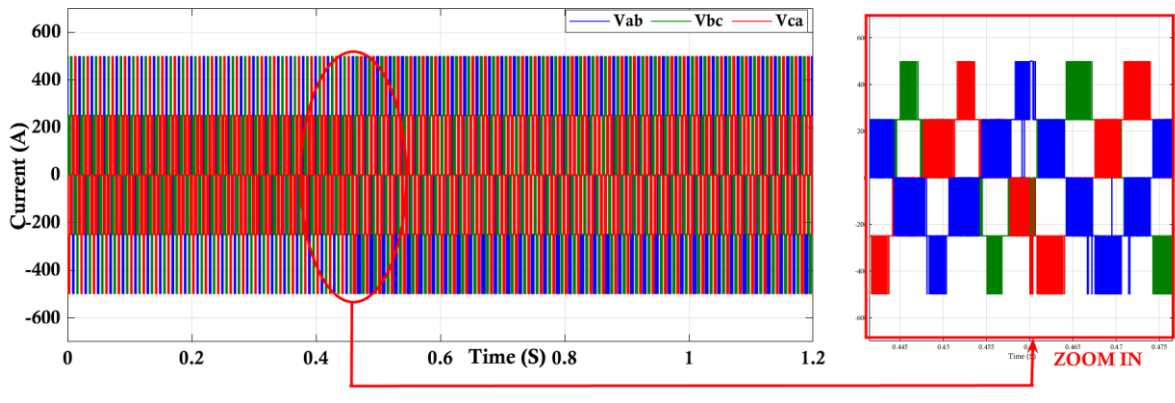


Figure III.10. Output Voltage Waveforms under Variable Reference Current Conditions

III.5.3 Dynamic Analysis of Reference Current Tracking under MPC Control

As shown in Figure 7, the actual output current I_a accurately follows the reference current I_{ref} under variable reference conditions, demonstrating the excellent tracking capability of the proposed MPC-controlled three-level NPC inverter. During the initial operating interval, the current amplitude remains approximately within ± 14 A, while at around 0.45 s, the reference current amplitude increases to approximately ± 20 A. The obtained results indicate that the controller rapidly responds to the reference variation with minimal transient error and without significant overshoot or oscillatory behavior. Furthermore, the zoomed-in section clearly shows the close overlap between I_a and I_{ref} , confirming the high tracking accuracy achieved by the predictive control strategy during both steady-state and transient operating conditions. The smooth sinusoidal waveform and the absence of noticeable distortion demonstrate the effectiveness of the MPC optimization process in selecting the appropriate switching states to ensure fast dynamic response and stable current regulation. Therefore, the results verify that the proposed MPC approach provides excellent reference tracking performance, high dynamic

stability, and reliable operation suitable for advanced grid-connected and high-performance power electronic applications.

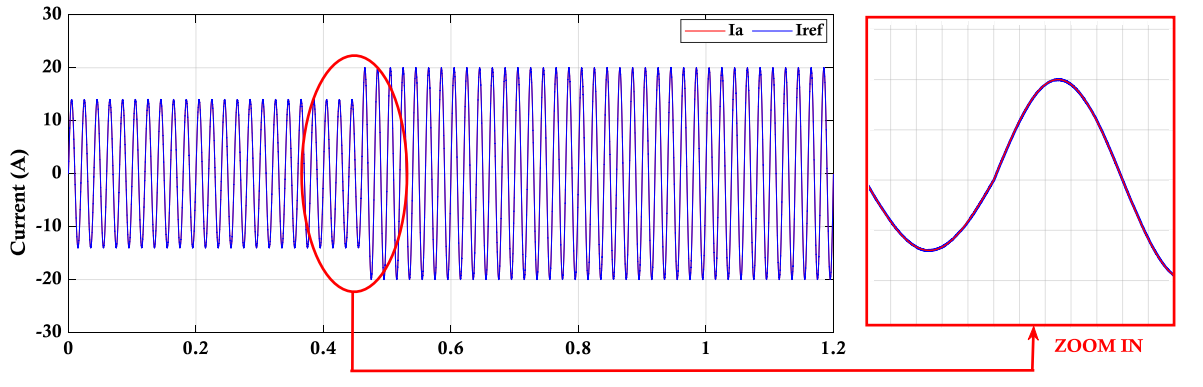


Figure III.11. Reference Current Tracking Performance under Variable Reference Conditions

III.5.4 Dynamic Analysis of DC-Link Capacitor Voltage Balancing under MPC Control

As shown in Figure 8, the dc-link capacitor voltages V_{dc1} and V_{dc2} remain closely regulated around the reference value of approximately 250 V under variable reference current conditions. During the initial operating interval, both capacitor voltages exhibit small ripple variations within a narrow range of approximately 249.85 V to 250.15 V, indicating stable steady-state operation and effective neutral-point voltage balancing. At around 0.45 s, a variation in the reference current is introduced, resulting in a temporary increase in voltage ripple amplitude due to the dynamic load transition. However, the proposed MPC-controlled three-level NPC inverter rapidly stabilizes the capacitor voltages without significant imbalance or voltage drift. The zoomed-in section clearly illustrates the transient response of the capacitor voltages, where V_{dc1} and V_{dc2} remain tightly controlled despite the sudden operating condition change. Furthermore, the close voltage tracking between the two capacitors confirms the effectiveness of the predictive optimization strategy in maintaining neutral-point stability, which is one of the major operational challenges in three-level NPC inverter topologies. The absence of severe oscillations or long transient settling time demonstrates the robustness and fast dynamic response capability of the MPC algorithm. Therefore, the obtained results verify that the proposed control strategy successfully maintains dc-link voltage regulation, minimizes capacitor voltage imbalance, and ensures reliable dynamic performance suitable for advanced medium- and high-power grid-connected power electronic applications.

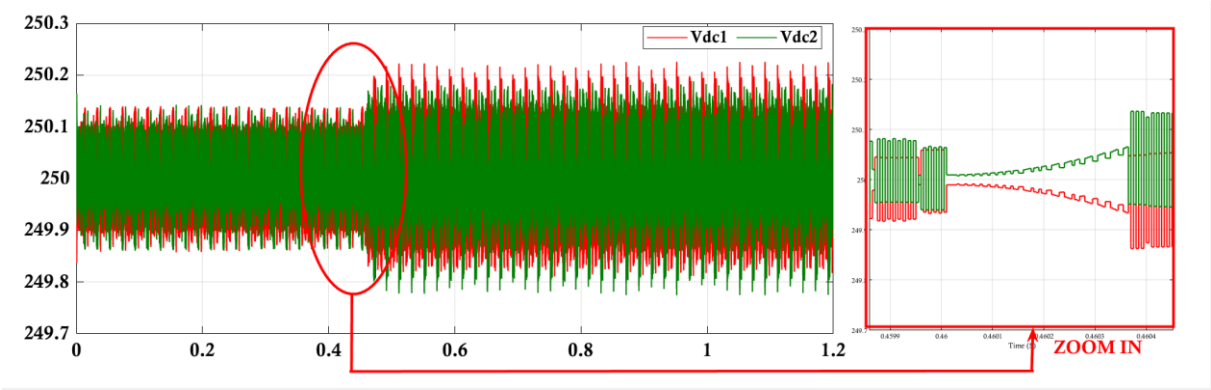


Figure III.12. DC-Link Capacitor Voltage Response under Variable Reference Current Conditions

III.6 Conclusion

In this chapter, the simulation performance of the proposed Model Predictive Control (MPC) strategy for the three-level Neutral-Point-Clamped (NPC) inverter has been successfully analyzed and evaluated using MATLAB/Simulink. The obtained results confirmed the effectiveness of the predictive controller in generating appropriate switching signals, maintaining stable inverter operation, and ensuring accurate control of the output electrical variables.

The analysis of the switching pulse waveforms demonstrated the capability of the MPC algorithm to provide precise switching state selection with stable commutation behavior. In addition, the three-phase output current waveforms i_a , i_b , and i_c exhibited balanced sinusoidal profiles with low harmonic distortion and accurate reference tracking performance. The voltage waveforms also confirmed the proper multilevel operation of the NPC inverter and the ability of the controller to manage the switching states efficiently.

Overall, the simulation results verified that the proposed MPC strategy offers fast dynamic response, improved power quality, reduced harmonic content, and reliable operation for three-level NPC inverter systems. These results demonstrate that Model Predictive Control represents an effective and flexible solution for advanced multilevel power electronic applications.

General Conclusion

This work has presented a detailed study on the modeling, control, and simulation of a three-level Neutral-Point-Clamped (NPC) inverter based on Model Predictive Control (MPC) for grid-connected photovoltaic applications. The study first introduced the fundamental concepts of renewable energy systems, photovoltaic integration, power electronic converters, and multilevel inverter topologies, highlighting the importance of advanced control techniques in improving power quality and system performance.

The theoretical analysis of predictive control demonstrated that MPC represents an efficient and flexible control strategy capable of handling multivariable systems while ensuring fast dynamic response and accurate control performance. Special attention was given to the operating principles of the three-level NPC inverter, including switching states, voltage vector generation, current regulation, and dc-link capacitor voltage balancing.

To validate the proposed control approach, a complete simulation model was developed in MATLAB/Simulink. The obtained simulation results confirmed the effectiveness of the MPC strategy in achieving accurate current tracking, balanced three-phase operation, stable output voltage generation, reduced harmonic distortion, and proper neutral-point voltage balancing under both constant and variable reference conditions. Furthermore, the controller demonstrated excellent dynamic response and stable behavior during transient operating conditions.

Overall, the obtained results verify that the proposed MPC-controlled three-level NPC inverter provides high performance, reliable operation, and improved power quality, making it a suitable solution for modern grid-connected renewable energy and medium- to high-power power electronic applications. Future work may focus on experimental implementation, optimization of the predictive algorithm, and the integration of additional objectives such as switching loss minimization and fault-tolerant operation.

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