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Dedication

With deep gratitude and sincere words, I dedicate this humble final year project to:

❖ *To my dear and respectful parents:*

No dedication can truly express my attachment, love, and affection for you. I offer you this modest work as a token of appreciation for all the sacrifices and immense kindness you have always shown me. I hope that one day I can return even a small part of what you have given me. May Almighty God protect you and grant you health and happiness.

❖ *To my dear brothers: Chamseddine, Yacine, and Hocine, for their great love, constant support, and encouragement which have been a real strength throughout this work.*

❖ *To my late grandmother, may Allah have mercy on her and grant her Paradise, whose memory will always remain in my heart and prayers.*

❖

❖ *And to all my family and everyone I love, who have never stopped supporting and encouraging me throughout my journey.*

Ben Moussa Ala Eddine

Dedication

With all meanings of gratitude and appreciation, and after a journey of effort and perseverance, I dedicate this humble work to:

- ❖ *To my dear parents, who have been my first support in life and the source of strength and kindness. They have filled my life with support, sacrifice, and prayers, and after God, they are the reason I have reached this stage. To them, I express all my love, respect, and gratitude.*
- ❖ *To my dear sister Maria, who has been and still is a symbol of love and loyalty, and the companion of my heart whom I deeply cherish having in my life.*
- ❖ *To my cousins: Omar and Abdelkader, who were not just relatives, but true brothers who shared moments with me and supported me sincerely, making their presence an invaluable support.*
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ABSTRACT

Solar energy is one of the leading renewable energy sources that can be harnessed for sustainable and efficient electricity generation. This thesis investigates the integration of photovoltaic (PV) systems into the electrical grid using advanced control strategies to enhance grid performance. The study addresses the fundamental principles of photovoltaic energy conversion and the effects of solar irradiance and temperature on PV system performance. It also explores the application of power electronic converters and Maximum Power Point Tracking (MPPT) techniques to maximize energy extraction.

To improve the performance of grid-connected PV systems, a Model Predictive Control (MPC) strategy integrated with Common-Mode Voltage (CMV) reduction is proposed. Simulation results demonstrate that the proposed controller maintains sinusoidal three-phase currents over an operating frequency range of 50–100 Hz while reducing the inverter CMV from $V_{dc}/2$ to the theoretical minimum of $V_{dc}/6$. The obtained current Total Harmonic Distortion (THD) remained very low, with values of 0.26% for the conventional FCS-MPCC method and 0.35% for the proposed MPC with CMV strategy, confirming high power quality in both cases. Furthermore, the proposed method reduced the computational burden (approximately 2×10^{-7} compared with 3×10^{-7} for the conventional FCS-MPCC at T_{s2}), demonstrating its suitability for real-time implementation. Overall, the proposed control strategy improves the stability, efficiency, and reliability of grid-connected photovoltaic systems.

Keywords: Photovoltaic Systems, Grid Integration, Model Predictive Control (MPC), Common-Mode Voltage (CMV), MPPT, Power Electronics, Inverter Control.

الملخص

تُعد الطاقة الشمسية من أبرز مصادر الطاقة المتجددة التي يمكن استغلالها لتوليد الكهرباء بصورة مستدامة وفعّالة. تهدف هذه الرسالة إلى دراسة دمج الأنظمة الكهروضوئية (PV) مع الشبكة الكهربائية باستخدام استراتيجيات تحكم متقدمة لتحسين أداء الشبكة. كما تتناول المبادئ الأساسية لتحويل الطاقة الشمسية إلى طاقة كهربائية، وتأثير كل من الإشعاع الشمسي ودرجة الحرارة على أداء النظام الكهروضوئي. بالإضافة إلى ذلك، تستعرض استخدام محولات إلكترونيات القدرة وتقنيات تتبع نقطة القدرة العظمى (MPPT) لضمان استخلاص أكبر قدر ممكن من الطاقة.

ولتحسين أداء الأنظمة الكهروضوئية المتصلة بالشبكة، تم اقتراح استراتيجية تحكم تنبؤية (MPC) مدمجة مع تقنية تقليل جهد النمط المشترك (CMV). أظهرت نتائج المحاكاة أن المتحكم المقترح يحافظ على تيارات ثلاثية الطور ذات شكل جيبي ضمن نطاق تردد تشغيلي يتراوح بين 50 و100 هرتز، مع تقليل جهد النمط المشترك (CMV) للعاكس من $V_{dc}/2$ إلى الحد الأدنى النظري $V_{dc}/6$. كما بقيت قيمة التشوه التوافقي الكلي للتيار (THD) منخفضة جداً، حيث بلغت 0.26% للطريقة التقليدية FCS-MPCC و 0.35% للاستراتيجية المقترحة MPC مع CMV، مما يؤكد جودة القدرة العالية في كلتا الحالتين. علاوة على ذلك، حققت الطريقة المقترحة انخفاضاً في العبء الحسابي، إذ بلغ حوالي 2×10^{-7} مقارنةً بـ 3×10^{-7} للطريقة التقليدية FCS-MPCC عند زمن العينة Ts2، مما يبرز ملاءمتها للتطبيقات ذات التنفيذ الآني (Real-Time). وبشكل عام، تسهم استراتيجية التحكم المقترحة في تحسين استقرار الأنظمة الكهروضوئية المتصلة بالشبكة وكفاءتها وموثوقيتها.

الكلمات المفتاحية: الأنظمة الكهروضوئية، الربط مع الشبكة الكهربائية، التحكم التنبؤي بالنموذج (MPC)، جهد النمط المشترك (CMV)، تتبع نقطة القدرة العظمى (MPPT)، إلكترونيات القدرة، التحكم في العاكس.

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INTRODUCTION

INTRODUCTION

In recent decades, the global energy landscape has undergone profound transformations driven by the increasing demand for electricity, the depletion of fossil fuel resources, and the growing awareness of environmental degradation and climate change. In this context, renewable energy sources have emerged as a strategic alternative capable of ensuring sustainable development while reducing greenhouse gas emissions. Among these renewable sources, solar energy has attracted significant attention due to its abundance, accessibility, and environmental compatibility.

Photovoltaic (PV) systems, which convert solar radiation directly into electrical energy, represent one of the most promising technologies in the field of renewable energy. Continuous technological advancements in power electronics, semiconductor materials, and control systems have significantly improved the efficiency and reliability of PV systems, making their integration into electrical grids increasingly feasible. However, the intermittent and variable nature of solar irradiance introduces several technical challenges that affect the stability and quality of power injected into the grid.

This thesis focuses on the integration of photovoltaic systems into electrical power grids through the application of advanced control strategies. The main objective is to improve the performance of grid-connected PV systems by enhancing their efficiency, stability, and power quality under dynamic environmental conditions. Special attention is given to intelligent and predictive control methods that allow better management of energy conversion and grid interaction.

Problem Statement

Despite the significant progress achieved in photovoltaic technology, the integration of PV systems into electrical grids remains a complex engineering challenge. The primary difficulty lies in the inherent intermittency of solar energy, which depends on weather conditions, irradiation levels, and environmental fluctuations. These variations directly impact the stability, continuity, and quality of the electrical power supplied to the grid.

In addition, conventional control methods often struggle to maintain optimal performance under rapidly changing operating conditions. This leads to issues such as voltage fluctuations, reduced energy efficiency, and power quality degradation.

Therefore, the central research question guiding this study is:

How can advanced control strategies be designed and implemented to enhance the performance, stability, and power quality of grid-connected photovoltaic systems while ensuring efficient and reliable energy delivery under variable environmental conditions?

Hypotheses

This research is based on several key hypotheses that aim to guide the analysis and validation process:

First, it is assumed that the implementation of advanced control techniques, particularly Model Predictive Control (MPC), can significantly improve the dynamic response, stability, and robustness of grid-connected photovoltaic systems. MPC offers predictive capabilities that allow the system to anticipate future behavior and optimize control actions accordingly.

Second, the optimization of power electronic converters, combined with improved Maximum Power Point Tracking (MPPT) algorithms, is expected to enhance the efficiency of energy extraction from photovoltaic panels. This optimization reduces energy losses and ensures operation at or near the maximum power point under varying conditions.

Third, it is hypothesized that the integration of advanced predictive control strategies contributes to the reduction of common-mode voltage (CMV) and harmonic distortions, thereby improving the overall quality of power injected into the electrical grid.

Difficulties and Challenges

The integration of photovoltaic systems into electrical grids presents several technical and practical challenges that must be addressed to ensure reliable operation.

One of the main difficulties is the intermittent and unpredictable nature of solar energy. Unlike conventional energy sources, photovoltaic output is highly dependent on

environmental conditions such as cloud cover, temperature variations, and seasonal changes. This variability complicates the task of maintaining a stable power supply.

Another major challenge lies in the design and implementation of advanced control systems capable of operating in real time. Such systems must respond quickly and accurately to changing conditions while maintaining optimal performance, which requires high computational efficiency and robust control algorithms.

Furthermore, maintaining power quality remains a critical issue. Parameters such as Total Harmonic Distortion (THD) and common-mode voltage (CMV) must be minimized to ensure compatibility with grid standards. Achieving this without compromising system efficiency represents a complex engineering trade-off.

Importance of the Study

This research is of significant importance in the context of the global transition toward sustainable and renewable energy systems. As countries seek to reduce their dependence on fossil fuels, photovoltaic energy is expected to play a central role in future power generation systems.

Improving the control and integration of PV systems into electrical grids contributes directly to enhancing energy efficiency, grid stability, and overall system reliability. Moreover, it supports environmental sustainability by reducing carbon emissions and promoting cleaner energy production.

From a technological perspective, this study contributes to the advancement of smart grid systems and intelligent energy management strategies. It also provides insights into the development of more adaptive and efficient control methods suitable for modern power systems.

Objectives

The main objectives of this thesis are structured as follows:

First, to investigate and analyze the role of advanced control strategies, particularly Model Predictive Control (MPC), in improving the stability and dynamic performance of grid-connected photovoltaic systems.

Second, to study the impact of power electronic converters and Maximum Power Point Tracking (MPPT) algorithms on optimizing the energy conversion process and maximizing power extraction from photovoltaic panels.

Third, to evaluate the effectiveness of different control approaches in reducing common-mode voltage (CMV), minimizing harmonic distortion, and improving overall power quality in grid-connected systems.

Finally, to provide a comprehensive assessment of how intelligent control strategies can contribute to the development of more efficient, stable, and reliable photovoltaic energy systems.

Reasons for Choosing This Topic

The selection of this research topic is motivated by both scientific and practical considerations. On a global scale, the increasing demand for clean and sustainable energy solutions has made the integration of renewable energy sources into electrical grids a critical research area.

Solar energy, in particular, offers immense potential due to its wide availability and environmental benefits. However, its effective utilization requires overcoming several technical challenges related to control, stability, and grid compatibility.

This study aims to address these challenges by focusing on advanced control strategies for photovoltaic systems. It is therefore highly relevant to current developments in renewable energy technologies, smart grids, and sustainable engineering practices. Moreover, it contributes to bridging the gap between theoretical control methods and practical real-world applications in modern power systems.

Chapter 1: Solar Radiation and Photovoltaic Energy

1.1 Introduction

Solar energy is regarded as one of the most significant renewable energy resources, as it is derived from solar radiation incidents on the Earth's surface. Owing to its sustainability and relatively low environmental impact, solar energy has assumed an increasingly important role in modern electrical power generation systems.

Photovoltaic (PV) systems enable the direct conversion of solar radiation into electrical energy by means of semiconductor-based photovoltaic cells operating in accordance with the photovoltaic effect.

This chapter addresses the fundamental principles of solar radiation and photovoltaic systems, with particular emphasis on the mechanisms of electrical energy generation and the effects of geographical location and seasonal variations on system performance, especially in grid-connected photovoltaic applications.

1.2 Overview and Motivation

The increasing global demand for electrical energy, predominantly derived from fossil fuels such as oil and coal, has placed considerable pressure on fossil fuel reserves and has significantly impacted the global environment. The limited supply of fossil fuels, which remain the predominant energy source, results in substantial greenhouse gas emissions, including nitrous oxide (N_2O), carbon dioxide (CO_2), and methane (CH_4), that are key contributors to climate change (IPCC, 2007).

Furthermore, the use of fossil fuels for transportation and the ongoing expansion of industrial activities have led to severe air pollution, compounding environmental challenges [1, 2]. To sustain economic growth while safeguarding natural ecosystems for future generations, it is imperative to transition to alternative, sustainable, and clean energy sources. Achieving these goals necessitates coordinated global efforts, as emphasized in international frameworks like the Kyoto Protocol [3].

In response to these challenges, renewable energy sources (RES) have been increasingly promoted as an alternative for power generation. Over the past few decades, the contribution of renewable energy to electricity grids has grown substantially due to policy measures aimed at combating climate change and ensuring a sustainable energy

supply (World Energy Outlook). In 2023, RES accounted for over 33% of the global power generation capacity, as illustrated in Figure 1.1, demonstrating their rising significance in the energy mix [4]. Unlike fossil fuels, renewable energy sources such as wind, solar, biomass, and hydroelectric power produce energy without emitting greenhouse gases, thereby contributing to the mitigation of climate change and a reduction in air pollution.

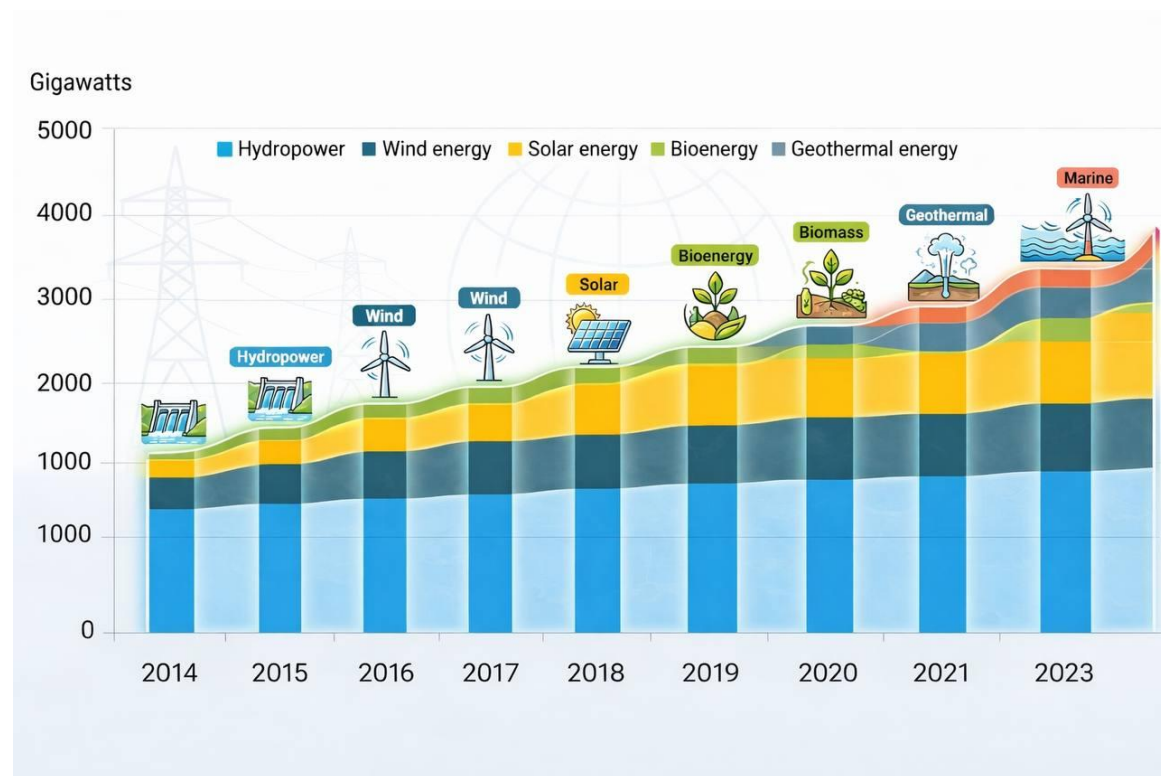


Figure 1.1. Global power generating capacity.

Among renewable energy technologies, solar photovoltaic energy and wind power have experienced substantial growth, outpacing other forms of RES. As shown in Figure 1.2, photovoltaic systems (PV) and wind power constitute approximately 33% and 28% of new renewable energy installations, respectively. This trend underscores the potential of these technologies to play a leading role in decarbonizing the energy sector. The geographical potential for solar energy, in particular, varies significantly by region, as illustrated in Figure 1.3[5].

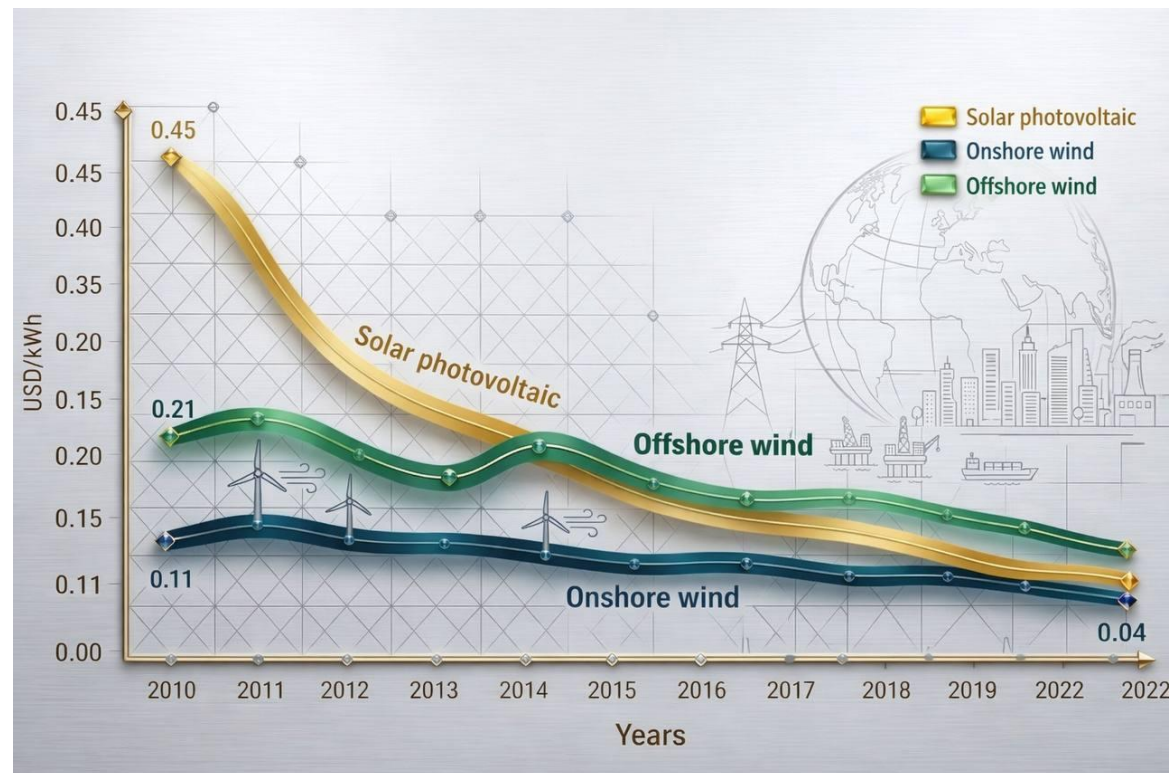


Figure 1.2. Levelized cost of electricity from newly commissioned solar PV, onshore wind power and offshore wind power, 2010-2022.

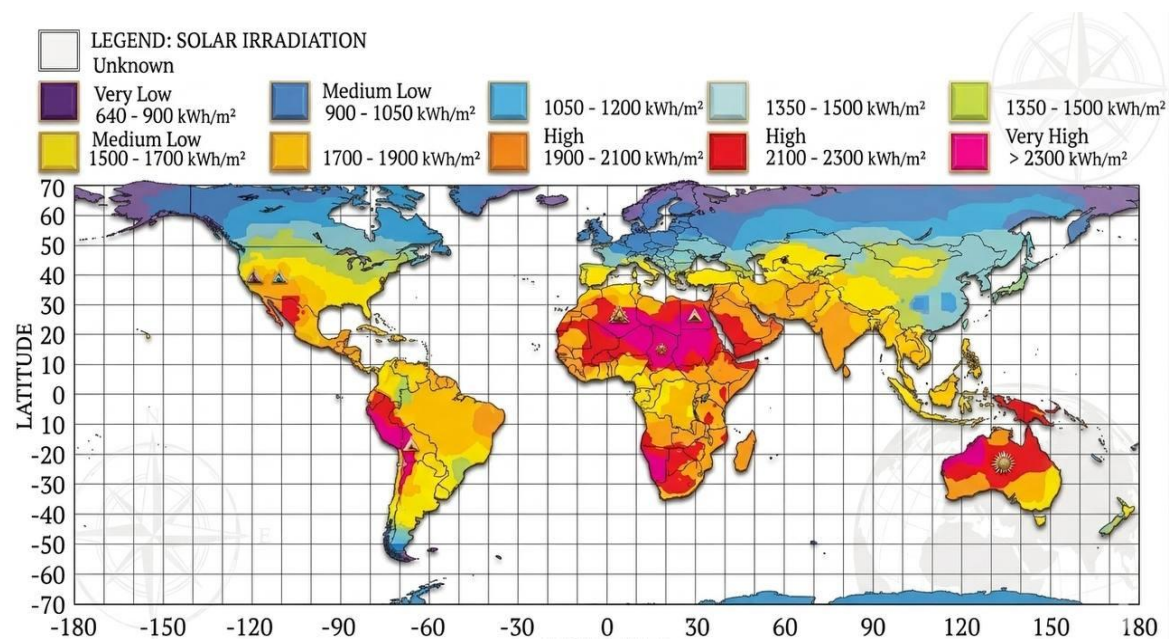


Figure 1.3. Solar irradiation map of the world from photovoltaic guidenr

The levelized cost of electricity (LCOE) associated with renewable energy technologies has experienced a substantial decline in recent years. Among these, onshore wind energy has exhibited the most pronounced reduction, with the global average LCOE decreasing by 50% between 2010 and 2022 to reach USD 0.033 per kilowatt-hour (kWh). Similarly, solar

photovoltaic (PV) systems have observed a significant cost reduction, with the global average LCOE recorded at USD 0.049 per kWh in 2022. In contrast, offshore wind energy remains comparatively more expensive, with an LCOE of USD 0.081 per kWh (refer to Figure 1.2).

Despite these advancements in cost-efficiency, the integration of renewable energy sources, particularly solar PV, into the power grid presents notable challenges due to their intermittent nature. The direct current (DC) voltage output from these systems is inherently variable, influenced by fluctuating environmental conditions, which renders direct grid connection impractical. This challenge has catalyzed advancements in power electronic converters (PECs) as a pivotal technological solution.

Power electronic converters serve as intermediary devices between renewable energy systems and the electrical grid. These converters address the variability of output voltage by dynamically regulating it, ensuring efficient power conversion, and maintaining a balanced power distribution. Through these functions, PECs enhance grid compatibility and ensure the reliable delivery of power generated from renewable sources.

1.3 Power Electronics Converters for Renewable Energy System

Power electronic converters (PECs) are essential in facilitating the integration of renewable energy sources (RES) with the electrical grid or load systems. Their operation critically impacts the overall performance of the system, particularly influencing aspects such as stability, reliability, efficiency, power quality, and the consumption ratio.

To ensure energy conversion processes that are both cost-effective and efficient, various innovative Photo electrochemical (PEC) systems are being developed alongside the increasing practical implementation of renewable energy technologies [4]. Figure 1.4 presents a detailed framework for the integration of Renewable Energy Sources (RES) through the application of Power Electronic Converters (PEC). The incorporation of RES into electrical systems necessitates the deployment of PEC to align the outputs of RES with the requirements of the power grid. Consequently, significant advancements have been made in enhancing the efficiency of PEC systems. These improvements can be achieved through two primary approaches: (a) the development of novel power converter designs or (b) the implementation of advanced control strategies.

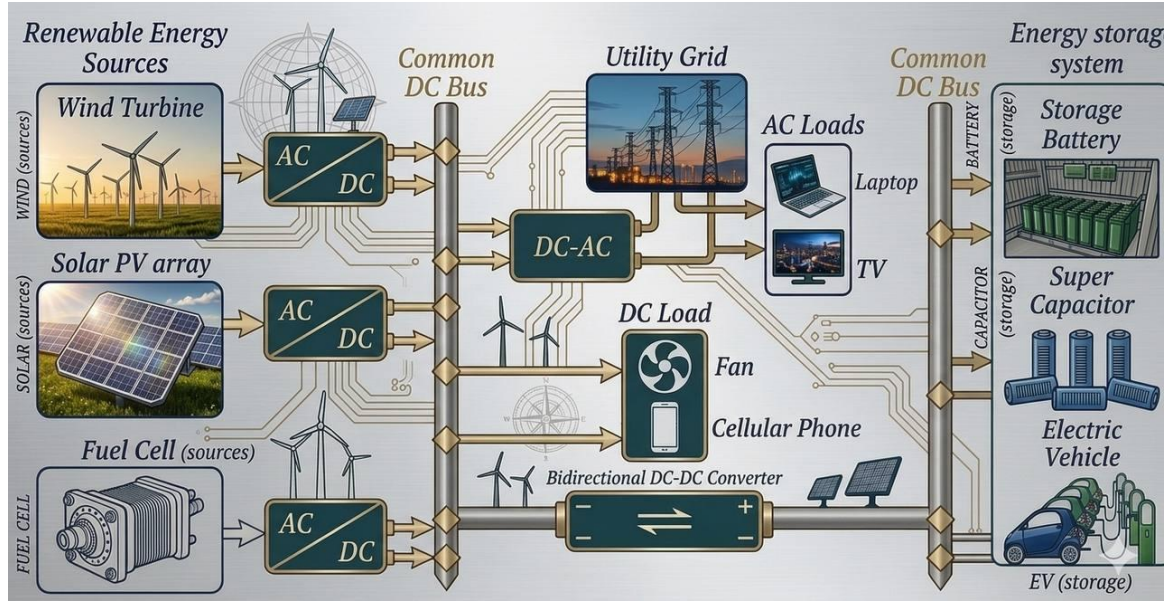


Figure 1.4. Schematic exhibiting the relationship of a RES to the electricity grid.

The classification of converters in renewable energy systems (RES) encompasses two primary categories: galvanic ally isolated and non-isolated variants [6], [7]. Galvanically isolated converters, also known as transformer-based converters, employ a transformer to achieve input-output isolation, as highlighted in the topological analyses of [8],[9], [10]. This isolation mechanism enhances their functional potential. However, the inclusion of transformers introduces notable challenges, including increased financial costs, larger physical dimensions, and reduced operational efficiency. These limitations, absent in non-isolated or transformer-less solutions, are substantiated by empirical findings from case studies [11, 12]. Therefore, non-isolated converters emerge as a more favorable option in power conversion processes when all critical factors are considered.

1.3.1 Review of PV Energy System Applications

Photovoltaic (PV) energy conversion systems play a crucial role in the integration of renewable energy into the utility grid, providing a sustainable and efficient solution for electricity generation. Figure 1.5 illustrates the structural configuration of such a system, beginning with PV arrays that harvest solar irradiance and convert it into direct current (DC) electrical energy, which is subsequently stabilized via DC bus structures. A multilevel power electronics converter serves as the pivotal component, facilitating the conversion of DC power into alternating current (AC) power characterized by high quality and reduced Total Harmonic Distortion (THD). A filtering stage ensures compliance with grid standards by attenuating high-frequency noise, while an optional transformer is incorporated to

perform voltage adaptation and provide electrical isolation between the PV system and the grid. The control unit, incorporating a Maximum Power Point Tracking (MPPT) controller, ensures optimal energy harvesting from the PV arrays and precise regulation of the power electronics converter. Ultimately, the AC power is injected into the utility grid, demonstrating a sophisticated integration of advanced control algorithms and power conversion technologies for efficient solar energy utilization and grid compatibility.

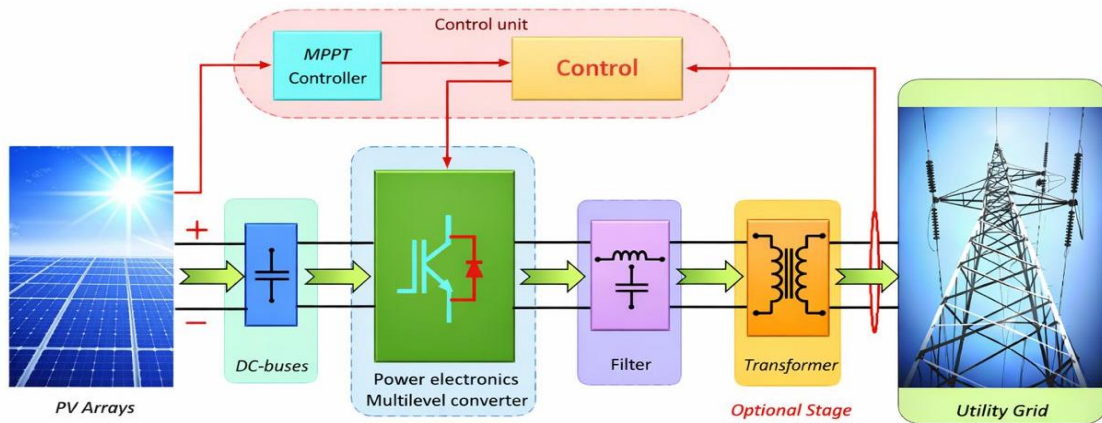


Figure 1.5. A photovoltaic (PV) system with power electronics and the needed control.

1.3.2 Classification of power converters

Power electronic converters have been used in many industrial applications for efficient power conversion and energy conservation. Depending on the type of electric power conversion and the electric power flow, the power converters can be divided into the following four categories:

- **AC-DC rectifiers:** Convert a single-phase or three-phase AC voltage to DC is used as front-end in variable-speed motor drives and wind energy conversion systems.
- **DC-DC converters:** Convert a DC voltage from one level and a certain polarity to a DC voltage of another level and in some applications to another polarity.
- **DC-AC inverters:** Conversion from DC to variable-voltage and variable-frequency AC is used invariable-speed motor drives. Conversion of unregulated or regulated DC to fixed AC is used in grid-connection of renewable energy sources.
- **AC-AC cycloconverters:** Convert an AC voltage of one level, frequency and number of phases to an AC voltage of a different level, frequency, and in some applications to different number of phases.

1.3.3 Classification of DC–DC converters

Many researchers have addressed different types of DC–DC converters for renewable energy applications and storage to improve and enhance efficiency whilst overcoming the weaknesses of converters. DC–DC converters are categorized into three major technologies based on their operation modes, as shown in Figure 1.6 [13-15]. They are linear mode, hard switching mode, and soft switching mode. The linear mode has features such as simplicity, low noise with good regulation, and quick response. On the other hand, its drawback is low efficiency due to power losses in various working conditions. Hard switching mode converters can be sub-categorized into non-isolated and isolated converters based on galvanic isolation. The buck, boost, buck–boost, and Cuk converters are typical examples of the hard switching mode topologies that are without galvanic isolation (non-isolated) and identified as chopper circuits. However, galvanic isolation (transformer) is necessary for safety causes when the converters are supplied by the utility grid. Power converters (PCs), with their control techniques, help regulate voltages of nodes in microgrid with different types of loads such as resistive, inductive, nonlinear, constant power, or critical loads. However, constant power loads (CPLs) affect the stability of the voltage in the output of PCs and are usually difficult to regulate with traditional control techniques [16, 17].

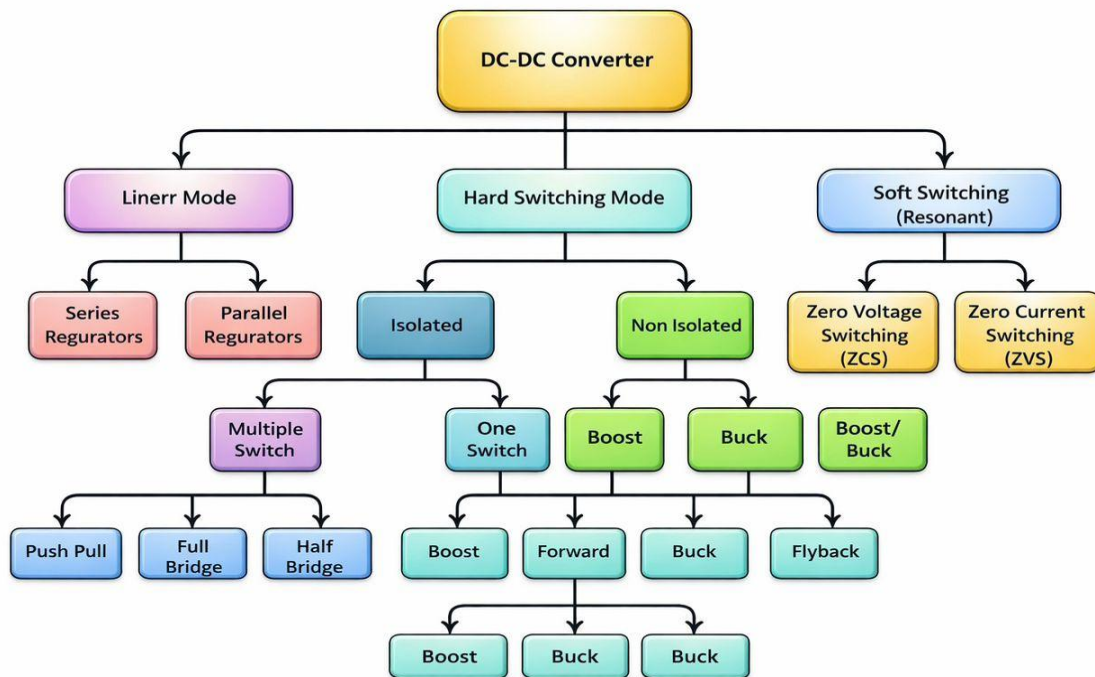


Figure 1.6. Classification of DC–DC converters.

1.4 Solar Radiation

Solar radiation refers to the entirety of the radiation emitted by the Sun. In addition to cosmic rays, particles characterized by extremely high speed and energy, the Sun emits electromagnetic waves that extend from the radio wave spectrum to gamma rays, passing through visible light.

The emission of electromagnetic waves by the Sun is accurately modelled by a black body at 5800 Kelvin, as described by Planck's law. The emission peak is in the yellow spectrum ($\lambda=570$ nm), with radiation distribution roughly evenly split between visible light and infrared, and 1% in ultraviolet. Upon reaching sea level, after traversing the entire Earth's atmosphere, solar radiation undergoes several "filtering" processes. Notably observable in the spectrum are the ozone absorption bands (known to absorb a significant portion of ultraviolet radiation), oxygen, carbon dioxide, and water [1] .

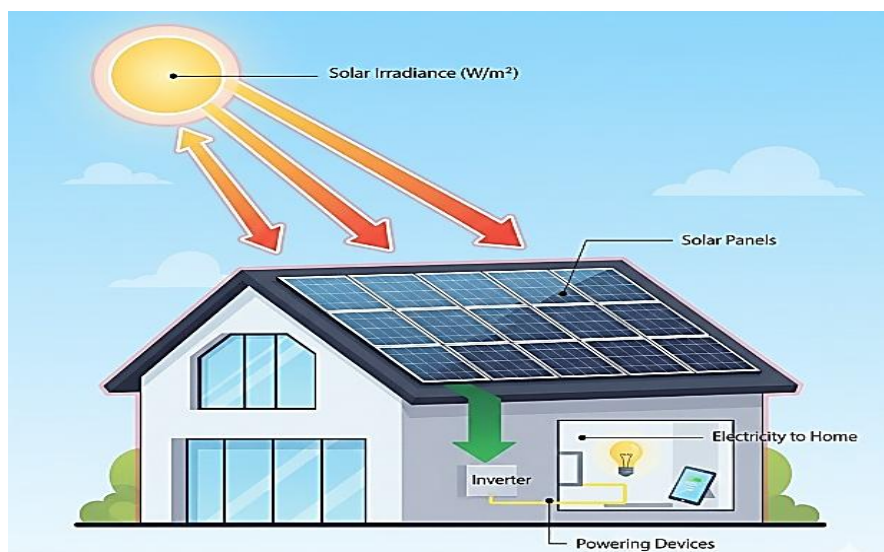


Figure 1.7. Representation of Solar Radiation

1.4.1 Radiation Spectrum

Although the notion of solar energy may appear abstract, it essentially corresponds to the heat and light emitted by the Sun. The development of photovoltaic cells in the previous century enabled the direct utilization of solar radiation as a practical energy source for

electricity generation. Through photovoltaic solar panels, incident light energy is transformed into electrical energy by means of an electronic conversion process.

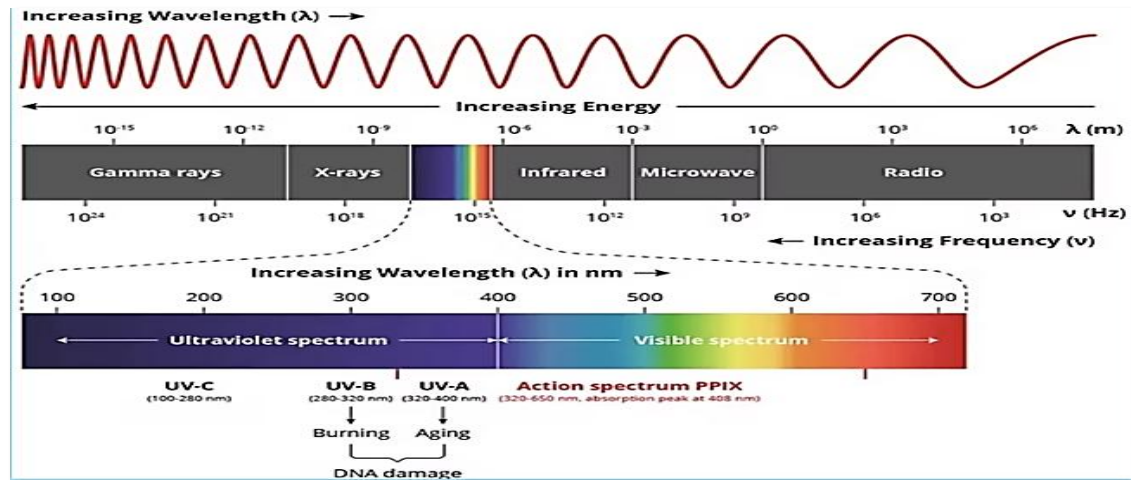


Figure 1.8. Solar Radiation Spectrum

Although the electromagnetic spectrum spans a wide range of wavelengths, nearly 99.8% of the solar radiant energy is concentrated within a relatively narrow wavelength interval ranging from 20 to 2500 nanometers. Only a limited portion of this solar radiation is able to penetrate the Earth's atmosphere and reach the surface, extending from radio waves with wavelengths of several decameters to the longest ultraviolet wavelengths. The remaining radiation is either absorbed or reflected by the atmospheric layers and the ionosphere [2].

Figure (1.9) illustrates the solar radiation spectrum. The composition of solar energy is approximately 5% ultraviolet light; 42% visible light and 53% near infra-red radiation.

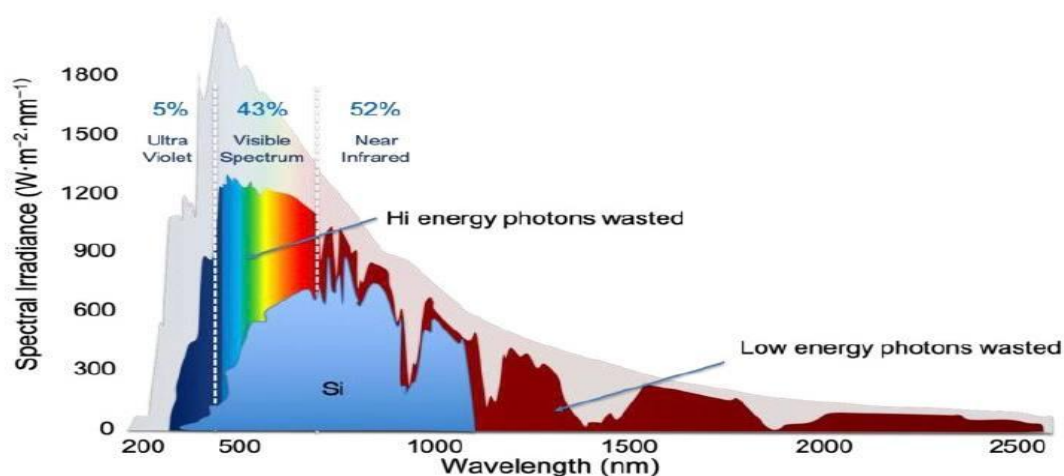


Figure 1.9. Representation of Solar Radiation Spectrum

1.5 Conversion of Solar Radiation by PV Effect

A PV cell consists of two layers of silicon; these two layers are doped to be polarized. To make one of the layers positive ("P layer"), a certain number of boron atoms are incorporated, and to make the other layer negative ("N layer"), a certain number of phosphorus atoms are incorporated. This creates a potential barrier. When a photon with sufficient energy is absorbed by this semiconductor, it breaks a valence bond and releases an electron, creating a positive "hole". This is what is called the photovoltaic effect: it is the potential difference between these two layers. By connecting the two layers, there is a movement of electrons from one layer to the other, thus creating an electric current [1].

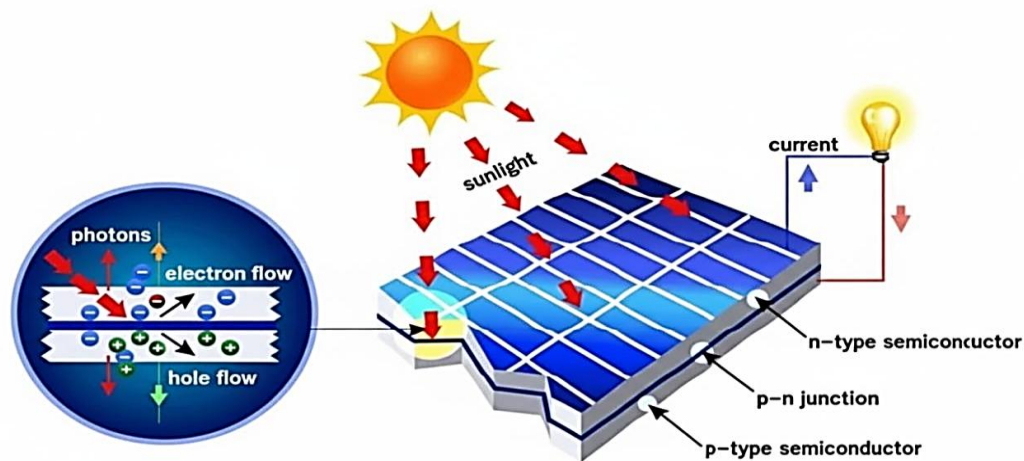


Figure 1.10. Solar Radiation Conversion by PV Effect

1.6 Photovoltaic Generator

A photovoltaic generator is defined by its electrical characteristics, mainly the current–voltage (I–V) relationship, as shown in Figure 1.11 . This electrical model is widely employed to predict the output behaviour of the photovoltaic device, namely the generated voltage and current, as a function of two main input parameters: the operating temperature and the level of incident solar irradiance.

The current output of a photovoltaic module at a specific voltage is primarily determined by the illumination intensity and the cell temperature. When these two parameters remain constant, the performance and efficiency of the solar cell are strongly affected by the electrical load connected to the circuit. In the case of an open-circuit condition ($R_c \rightarrow \infty$, I

= 0, $V = V_{oc}$) or a short-circuit condition ($R_c = 0$, $I = I_{sc}$, $V = 0$), no electrical power is delivered to the external load. Between these two operating limits, there exists an optimal load resistance, denoted as R_{opt} , at which the photovoltaic cell supplies its maximum output power. This maximum power is expressed as

($P = V_{max} \times I_{max}$) provided by the solar cell to the load resistance is maximal, thus reaching P_{max} [2].

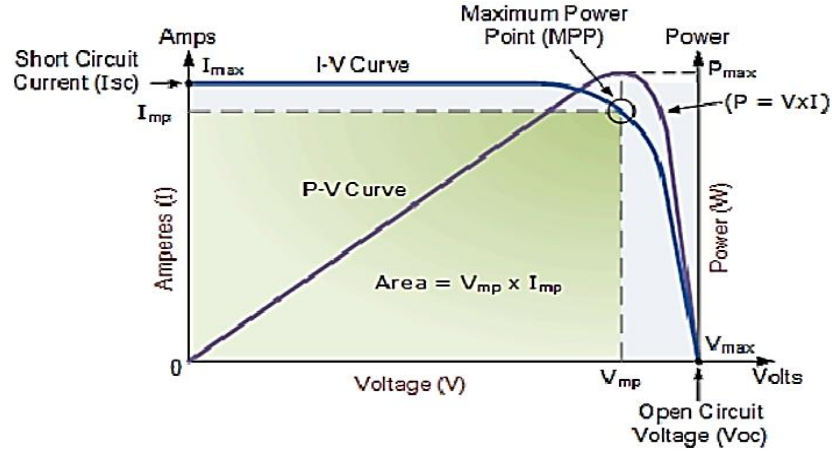


Figure 1.11. Typical Characteristics of a PV Generator

The energy efficiency of the solar cell is defined as $\eta = P/P_{\gamma}$, where P_{γ} represents the incident solar power received on the surface of the cell. When the load resistance reaches its optimal value R_c , the solar cell operates at its highest efficiency, expressed as $\eta_{max} = P_{max}/P_{\gamma}$. The value of R_{opt} is not an intrinsic constant of a given photovoltaic cell; rather, it varies according to the spectral distribution of the incoming radiation and the operating temperature of the p–n junction. As the cell temperature increases, its efficiency generally decreases. This thermal sensitivity has motivated the development of hybrid photovoltaic–thermal (PV/T) systems, which combine solar cells with thermal collectors. Such hybrid systems enable simultaneous electrical energy generation and hot water production, while improving photovoltaic efficiency through active cell cooling.

The power provided by the solar cell ($P = I \times V$) and its efficiency depend on the material used and the manufacturing technology (amorphous silicon, polycrystalline silicon, monocrystalline silicon), the junction geometry (layer thickness, multilayers, etc.), and

external parameters (temperature, spectrum and power of the incident radiation, external electrical circuit connected to the cell, etc.).

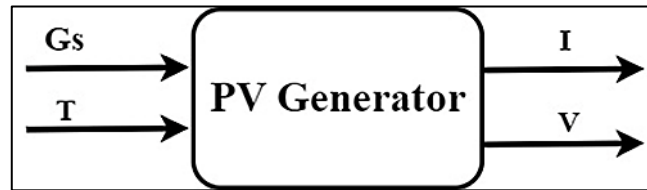


Figure 1.12. Block Diagram of a PV Generator

1.6.1 Photovoltaic Cell

Photovoltaic modules are composed of multiple solar cells electrically interconnected to achieve the desired electrical output. These cells are typically embedded in a protective resin and encapsulated either between two tempered glass layers, forming double-glass modules, or between a glass layer and a Tedlar back sheet in glass/Tedlar configurations. The assembled structure is generally mounted within an anodized aluminium frame to provide mechanical strength and durability. However, frameless modules are also manufactured for building-integrated photovoltaic (BIPV) applications, where aluminium profiles are directly incorporated into façades or roofing systems. The electrical power output of a photovoltaic module is primarily determined by its active surface area and the level of incident solar irradiation. This power is commonly expressed in peak watts (W_p), which corresponds to the maximum power delivered by the module under standard test conditions, notably an irradiance of 1000 W/m^2 .

The voltage delivered by a module depends on the number of cells connected in series. For low-power modules ($< 75 \text{ W}_p$), the operating voltage is generally between 12 and 15 volts. Higher power modules are obtained by increasing the number of cells in series, which results in an "increase in voltage," and by increasing the number of cell branches in parallel, which causes an "increase in current value." The physical dimensions of photovoltaic modules vary across manufacturers, with surface areas generally ranging from 0.5 to 1 m^2 , and potentially reaching up to 3 m^2 for special designs or large-scale production. Multiple interconnected modules form a photovoltaic panel, and several panels connected together constitute a photovoltaic array. By configuring modules in series and/or parallel combinations, a wide range of output voltages and power levels can be achieved to meet specific application needs [1].

1.6.2 Modelling of a PV Cell

The operation of a photovoltaic module is described by the "standard" one-diode model, established by Shockley for a single photovoltaic cell, and then generalized to a photovoltaic module by considering it as a set of identical cells connected in series or parallel.

In the literature, a photovoltaic cell is often described as an electrical current generator whose behavior is equivalent to a current source shunted by a diode. To account for physical phenomena at the cell level, the model is supplemented by two series resistances R_s and R_{sh} , as illustrated in the equivalent circuit diagram in Figure 1.13.

The series resistance represents the internal resistance of the cell and depends mainly on the resistance of the semiconductor used, the contact resistance of the collecting grids, and the resistivity of these grids. The shunt resistance is due to leakage current at the junction and depends on how it was made.

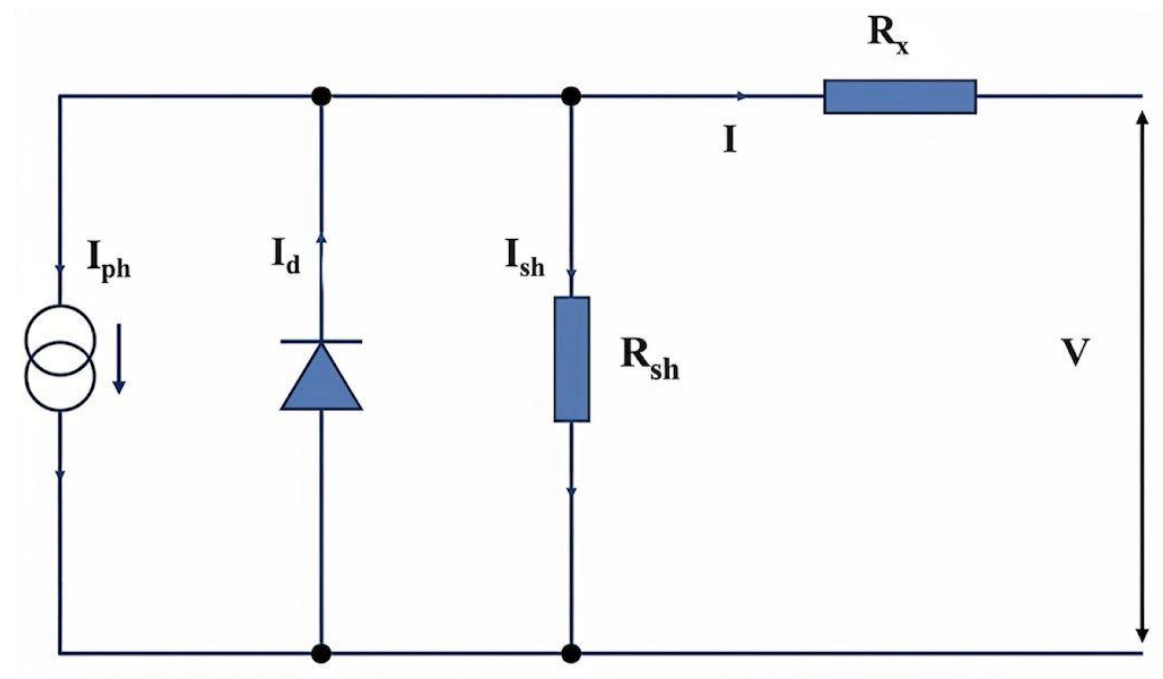


Figure 1.13. Equivalent Circuit of a PV Cell

1.6.3 Types of Photovoltaic Cells :

Photovoltaic solar panels are made up of photovoltaic cells and vary according to type:

1. Monocrystalline Cells: Monocrystalline silicon results from the cooling of molten silicon. Once solidified, it transforms into a uniform crystal that is cut into thin slices to form the photovoltaic cell. The color of this material is blue, without any trace of crystals or other impurities.

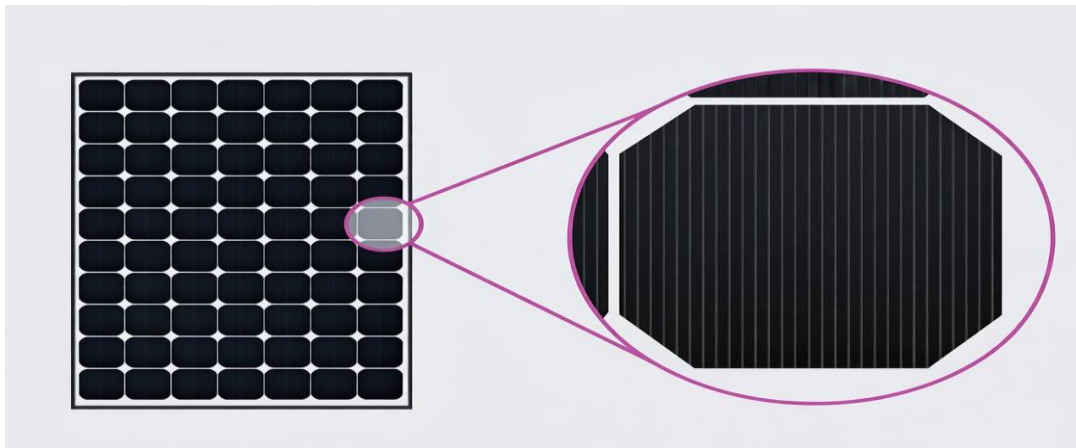


Figure 1.14. Monocrystalline Cells

2. Polycrystalline Cells: Polycrystalline silicon is obtained by melting silicon in a square and elongated metal mold, called an ingot. The color of this type of cell is blue and speckled with patterns left by the crystals. This characteristic allows us to easily recognize this photovoltaic cell.

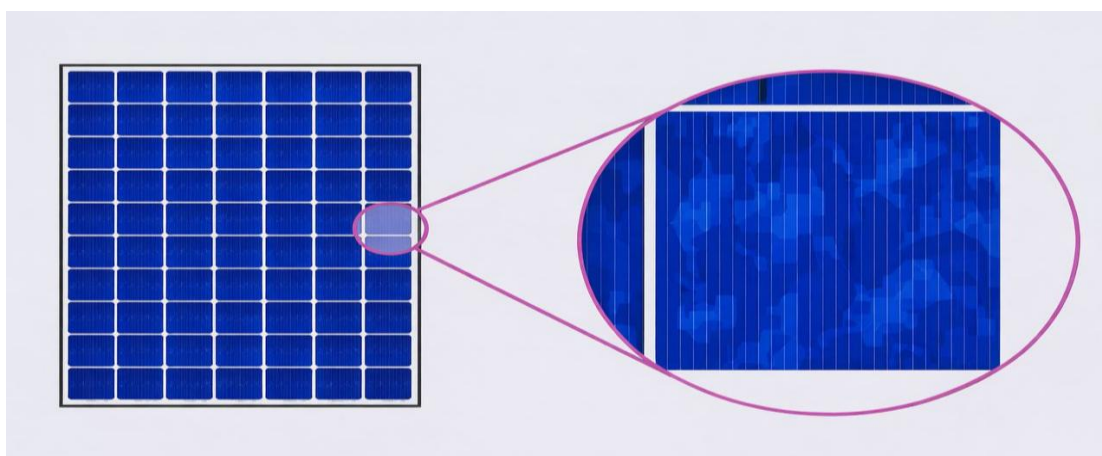


Figure 1.15. Polycrystalline Cells

3. Hydrogenated Amorphous Cells: Hydrogenated amorphous silicon is produced from silicon-based gas through a vacuum deposition technique. During this process, the vaporized gas is deposited onto various substrates such as glass, flexible polymer materials, or metal surfaces. Photovoltaic cells fabricated using this technology typically exhibit a dark gray appearance.



Figure 1.16. Hydrogenated Amorphous Cells

1.7 The Impact of Temperature on Solar Panel

Temperature has a significant impact on the performance of solar panels. Here's how:

- **Reduction in Efficiency:** An increase in the operating temperature of photovoltaic panels leads to a decline in their conversion efficiency. As solar panels convert incident solar radiation into electrical energy, elevated temperatures negatively affect this energy conversion process.
- **Voltage Decrease:** The output voltage of a solar panel decreases with rising temperature. This phenomenon is attributed to the reduced charge carrier mobility in the semiconductor material at higher temperatures.
- **Power Output Reduction:** Elevated temperatures result in a reduction of the electrical power generated by photovoltaic panels, as both efficiency and voltage degradation directly affect the overall power output.
- **Thermal Degradation:** Prolonged exposure to high temperatures can induce thermal degradation of photovoltaic materials, leading to a gradual reduction in both performance and operational lifespan.

- **Operating Temperature Range:** Photovoltaic modules are designed to function within a specified temperature range. Exceeding this range can significantly impair their performance and reliability.
- Overall, while solar panels still generate electricity on hot days, their efficiency decreases as temperatures rise, impacting their overall performance and output.

1.8 Advantages and Disadvantages of PV Energy

1.8.1 Advantages

- **Renewable Energy:** Solar energy represents a plentiful and universally accessible renewable energy source, ensuring its sustainability for long-term energy production.
- **Low Greenhouse Gas Emissions:** Photovoltaic energy generation does not emit greenhouse gases during operation, contributing to the reduction of carbon emissions and supporting efforts to combat climate change.
- **Decreasing Costs:** Technological advancements and large-scale deployment have led to a substantial decrease in the cost of photovoltaic systems, enhancing their competitiveness with conventional energy sources.
- **Energy Independence:** Photovoltaic installations enable users to generate their own electrical power, thereby decreasing reliance on external energy providers and minimizing exposure to energy price volatility.
- **Low Maintenance:** Once installed, photovoltaic systems require limited maintenance, which helps reduce operational and long-term maintenance expenses.

1.8.2 Disadvantages

- **Sunlight Variability:** Photovoltaic power generation relies on the availability of solar irradiance, which is inherently variable and intermittent, often necessitating the use of energy storage systems or hybrid integration with other energy sources.
- **High Initial Costs:** Despite the significant reduction in photovoltaic technology costs, the upfront capital required for system installation remains relatively high.

- **Environmental Impact:** Although photovoltaic energy is classified as a clean energy source during operation, the manufacturing processes and end-of-life disposal of solar panels may have environmental impacts.
- **Space Requirement:** Photovoltaic installations typically require substantial surface areas, either on land or rooftops, which can be challenging in densely populated regions or locations with limited available space.
- **Dependency on Weather Conditions:** The performance of photovoltaic systems is influenced by meteorological factors such as cloud cover, rainfall, and snowfall, which can temporarily reduce energy conversion efficiency.

1.9 Conclusion

This chapter presented the fundamental principles of solar radiation and photovoltaic energy conversion, emphasizing the operation of solar cells and the modelling of photovoltaic generators. It highlighted the effects of temperature and load conditions on system performance, reviewed the main types of photovoltaic cells and module components, and provided a theoretical foundation for the analysis of photovoltaic systems in subsequent chapters.

Chapter 2: Modeling and control of photovoltaic systems integrated into the electrical grid

2.1 Introduction

With the growing demand for renewable energy sources, photovoltaic (PV) systems have emerged as a key technology for sustainable electricity generation. Nevertheless, their effective integration into the electrical grid requires accurate modeling, advanced control strategies, and efficient power conversion techniques to ensure system reliability and optimal performance.

This chapter presents the fundamental principles of grid-connected PV systems, highlighting the main components involved in the conversion and control process. It begins with an overview of PV system modeling, followed by an analysis of DC–DC converters and their role in voltage regulation. The discussion then addresses Maximum Power Point Tracking (MPPT) techniques for maximizing energy extraction from solar modules. Subsequently, the operation and control of Voltage Source Inverters (VSI) are examined, emphasizing their importance in DC–AC conversion and stable grid integration. Finally, grid synchronization methods are introduced to ensure seamless and reliable operation within the power network.

2.2 Architecture of a photovoltaic module

2.2.1 Grouping cells in series

A single photovoltaic (PV) cell functions as a low-power energy source and cannot independently satisfy the requirements of most residential or industrial loads. Consequently, practical PV generators are constructed by interconnecting numerous cells in series and/or parallel to achieve the desired voltage and current levels.

A series connection of (N_s) cells increases the voltage of the photovoltaic generator. The cells are traversed by the same current, and the resulting characteristic of the series connection is obtained by adding the voltages of the individual cells, as represented in Figure II.1.

Equation (1.3) summarizes the electrical characteristics of a series connection of (N_s) cells:

$$V_{ocN_s} = N_s \times V_{oc}; I_{ccN_s} = I_{cc} \quad \text{II.1}$$

V_{ocN_s} : The sum of the open-circuit voltages of the (N_s) cells in series.

I_{ccN_s} : The short-circuit current of the (N_s) cells in series.

This connection system is generally the most commonly used for commercial photovoltaic modules.

With the increase in cell area and technological advancements, the generated current increases while the voltage remains low; therefore, series connection is used to raise the overall voltage and consequently enhance the total power output.

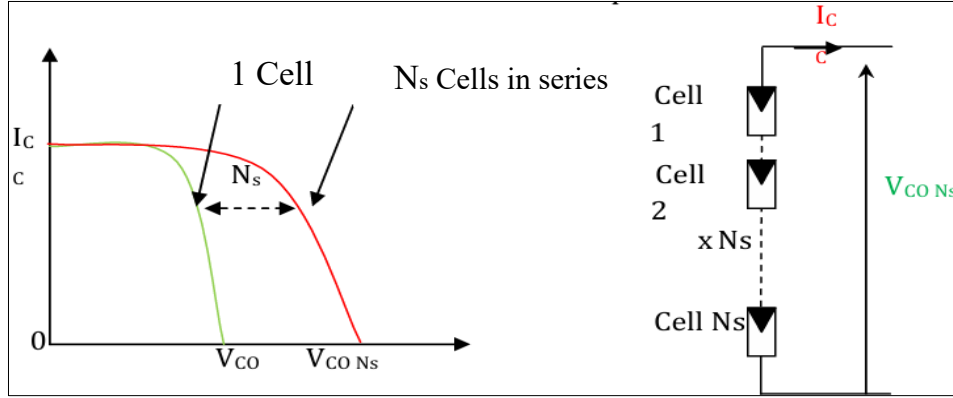


Figure 2.1. Resulting characteristic of a series connection of (N_s) cells.

2.2.2 Parallel Connection of Cells

A parallel connection of (N_p) cells is possible and allows for an increase in the output current of the generator thus created. In a grouping of identical cells connected in parallel, the cells are subjected to the same voltage, and the resulting characteristic of the grouping is obtained by adding the currents.

Figure 2.2 summarize the electrical characteristics of a parallel connection of (N_p) cells.

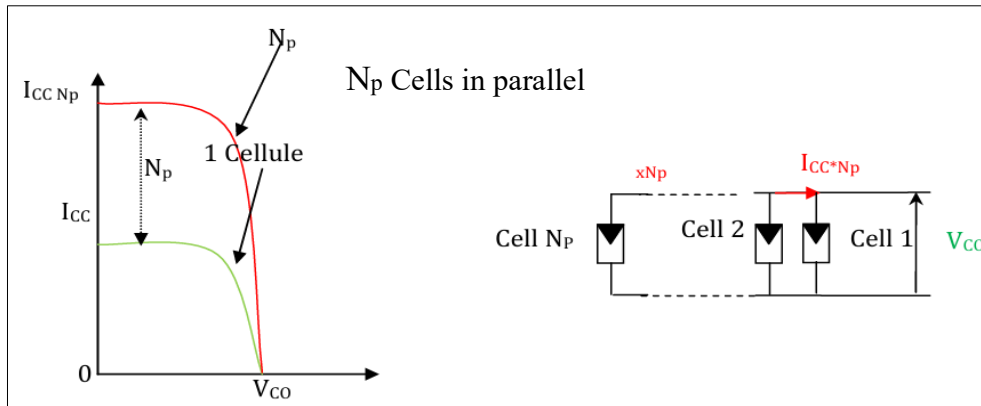


Figure 2.2. Resulting characteristic of a parallel connection of (N_p) cells.

$$I_{ccN_p} = N_p \times I_{cc} \quad \text{II.2}$$

$$V_{ocN_p} = V_{oc} \quad \text{II.3}$$

I_{ccN_p} : The sum of the short-circuit currents of (N_p) cells connected in parallel.

V_{ocN_p} : The open-circuit voltage of (N_p) cells connected in parallel.

2.2.3 Hybrid Connection of Cells (Series & Parallel)

Depending on the series and/or parallel connection of these cells, the values of the total short-circuit current and the total open-circuit voltages are given by the following relations:

$$I_{cc}^t = N_p \times I_{cc} \quad \text{II.4}$$

$$V_{oc}^t = N_c \times V_{oc} \quad \text{II.5}$$

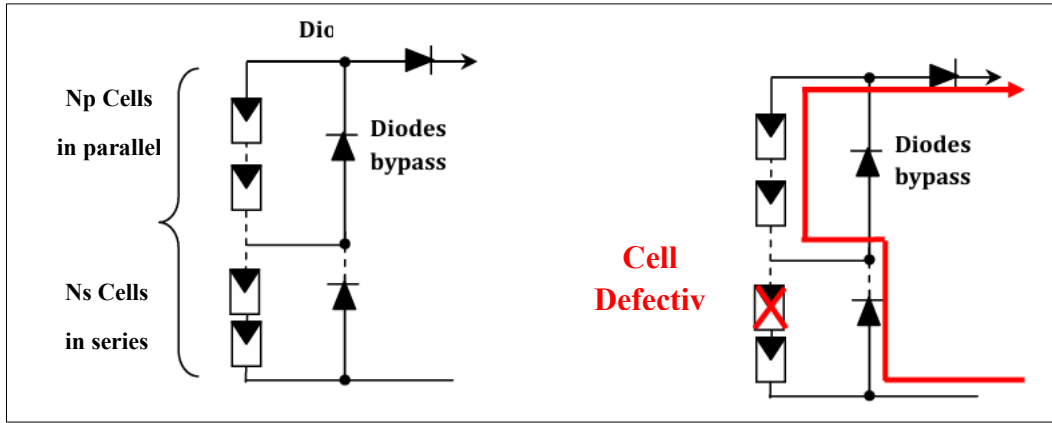


Figure 2.3. Resulting characteristics of a hybrid connection of ($N_s \times N_p$) cells.

Where:

N_c : Number of cells connected in parallel.

N_p : Number of cells connected in series.

I_{cc}^t : Total short-circuit current.

V_{oc}^t : Total open-circuit voltage.

Thus, the characteristic $I_p V_p$ of a photovoltaic generator can be considered the result of a network of $N_s \times N_p$ cells connected in series/parallel. The overall characteristic can also vary depending on illumination, temperature, cell aging, shading effects, or illumination inhomogeneity. Furthermore, even single shading or degradation of a cell in a series connection can cause a significant reduction in the current produced by the photovoltaic module.

If the load current exceeds the current generated by a poorly illuminated cell, the cell becomes reverse-biased and dissipates excessive power, which may cause damage. This phenomenon is known as the hot spot effect.

To prevent damage, PV modules use bypass diodes that divert current around faulty cells and block reverse currents. However, this protection reduces the module's voltage and power output.

The degradation of a cell renders the group of cells associated with the defective cell, and protected by the bypass diode, incapable of producing power.

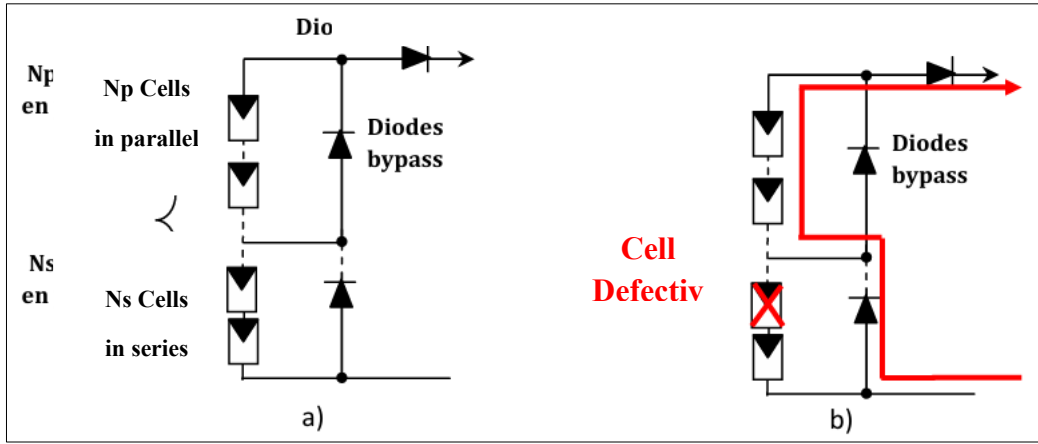


Figure 2.4. a) Classical architecture of a photovoltaic module with protective diodes.

b) Failure of one of the PV module cells and activation of the bypass diode, highlighting the circulation current pv.

This phenomenon of partial power loss should be compared to the total loss of a module in the event of a problem with a single cell in a module operating without protections.

2.3 Modeling of Photovoltaic Installation Elements

2.3.1 Conversion of Light into Electricity

A photovoltaic generator converts light into electrical energy using semiconductor devices called photovoltaic cells, typically made of silicon. [3].

The photovoltaic generator, or "solar field," consists of photovoltaic panels interconnected in series (N_{ps}) and/or in parallel (N_{pp}) to produce the required power.

These panels are mounted on a metallic frame that supports the solar field at a specific tilt angle.

The photovoltaic panel itself is made up of (N_{cs}) cells in series and (N_{cp}) in parallel, encapsulated under glass. Series connections of multiple cells increase the voltage for a given current, while parallel connections increase the current while maintaining the voltage.

2.3.2 Single-Diode Model

The (I–V) characteristic of an elementary cell is represented by the equivalent circuit shown in Figure 2.5, which consists of a current source and a diode connected in parallel, along with a series resistance (R_s) and parallel (shunt) resistance (R_{sh}), to account for dissipative phenomena at the cell level [4, 5].

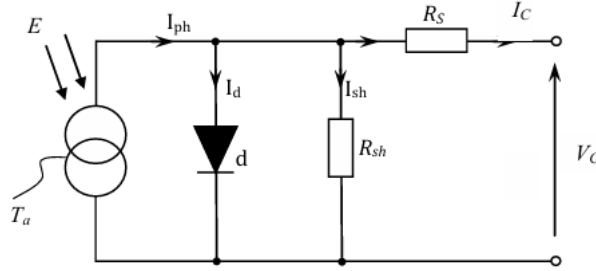


Figure 2.5. Equivalent electrical schematic of the PV cell with a single diode.

With:

I_c : Current delivered by the cell.

I_{ph} : Photocurrent generated by the cell (proportional to the incident radiation)

I_d : Current of the diode.

I_{sh} : Shunt current.

$$I_{ph} = P_1 \cdot E_G \cdot [1 + P_2 \cdot (E_G - E_{ref}) + P_3 \cdot (T_j - T_{jref})] \quad \text{II.6}$$

$$T_j = T_a + E_G \left(\frac{N_{oct} - 20}{800} \right) \quad \text{II.7}$$

$$I_d = I_s \left[\exp \left(\frac{q}{A \cdot K \cdot T_j} (V_c R_{s-p} \cdot I_c) \right) - 1 \right] \quad \text{II.8}$$

$$I_s = P_4 \cdot T_j^3 \exp \left(\frac{-E_G}{K \cdot T_j} \right) \quad \text{II.9}$$

$$I_{sh} = \frac{V_c}{R_{sh}} \quad \text{II.10}$$

$$I_c = I_{ph} - I_d - I_{sh} \quad \text{II.11}$$

With:

E_G : Solar irradiation.

P_1, P_2, P_3, P_4 : Constants dependent on the nature of the cell material, determined experimentally by the manufacturer.

T_a : Ambient temperature.

T_{ref} : Reference temperature (298 K).

T_j : Temperature of the cell.

N_{oct} : Nominal operating temperature of the solar cell, as provided by the manufacturer (45°C).

E_{ef} : Reference illumination (1000 W/m²).

I_s : Saturation current of the diode.

E_g : Energy gap for crystalline silicon (1.12 eV).

A : Ideal factor of the junction ($1 < A < 3$).

R_{sp} : Series resistance of a photovoltaic panel.

R_{sh-p} : Equivalent resistance of a photovoltaic panel.

q : Electron charge (1.6×10^{-19} C).

K : Boltzmann constant (1.38×10^{-23} J/K).

V_c : Voltage across the cell terminals.

2.3.3 Two-Diode Model

The two-diode model adds a second diode to better represent recombination effects in the semiconductor, improving accuracy. However, it is more complex and requires four parameters under standard irradiance and temperature conditions, which are usually provided by the manufacturer or obtained through module testing: short-circuit current (I_{sc}), open-circuit voltage (V_{oc}), maximum voltage (V_{max}), and maximum current (I_{max}) at the point of maximum power.

Temperature coefficients are also necessary in this modeling technique to account for the effect of temperature on the critical parameters of the solar cell.

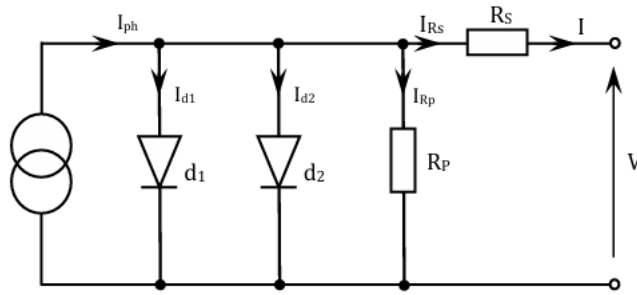


Figure 2.6. Electrical two-diode equivalent model of a photovoltaic cell.

$$I_{d1} = I_{s1} \left[e^{\frac{q(V+IR_s)}{n_1 kT}} - 1 \right] \quad \text{II.12}$$

Avec :

$$I_{d2} = I_{s2} \left[e^{\frac{q(V+IR_s)}{n_2 kT}} - 1 \right] \quad \text{II.13}$$

Ainsi :

$$\begin{aligned} I_{ph} &= I + I_{d1} + I_{d2} + I_{Rp} \\ I &= I_{ph} - I_{d1} - I_{d2} - I_{Rp} \end{aligned} \quad \text{II.14}$$

Alors :

$$I = I_{ph} - I_{s1} \left[e^{\frac{q(V+IR_s)}{n_1 kT}} - 1 \right] - I_{s2} \left[e^{\frac{q(V+IR_s)}{n_2 kT}} - 1 \right] - \frac{V + IR_s}{R_p} \quad \text{II.15}$$

n_1, n_2 : Ideality factors of diodes d_1 and d_2 (ranging between 1 and 2, depending on the technology).

The photocurrent depends on the temperature, and its expression is:

$$I_{ph}(T) = I_{ph}(T = 298K) [1 + (T - 298K) \cdot (5 \cdot 10^{-4})]$$

I_{s1} , I_{s2} : These are the saturation currents of diodes $d1$ and $d2$, respectively, and they depend on the temperature:

$$\begin{aligned} I_{s1} &= K_1 T^3 e^{\frac{-E_g}{KT}} \\ I_{s2} &= K_2 T^{\frac{5}{2}} e^{\frac{-E_g}{KT}} \end{aligned} \quad \text{II.16}$$

Where:

E_g : Energy, with

$K1=1.2A/cm^2 T^3 K1$ and $K2=2.9 \times 10^5 A/cm^2 T^5/2$.

For a solar panel consisting of z cells connected in series, and considering the model in Figure II.6, the equation describing this panel is:

$$I = I_{ph} - I_{s1} \left[e^{\frac{q(V+IzR_s)}{zn_1 kT}} - 1 \right] - I_{s2} \left[e^{\frac{q(V+IzR_s)}{nz_2 kT}} - 1 \right] - \frac{V + IzR_s}{R_p} \quad \text{II.17}$$

- The Three-Diode Model: The third diode is included in the equivalent schematic to account for effects not considered in the other models (e.g., leakage current related to the diodes).

The current and voltage across the terminals of a photovoltaic panel are given by:

$$\begin{aligned} I_P &= N_{cp} I_c \\ V_P &= N_{cs} V_c \end{aligned} \quad \text{II.18}$$

Whereas the current and voltage across the terminals of a photovoltaic generator are given by:

$$\begin{aligned} I_g &= I_{Pv} = N_{pp} I_P = N_{pp} N_{cp} I_c \\ V_g &= V_{Pv} = N_{ps} V_P = N_{ps} N_{cs} V_c \end{aligned} \quad \text{II.19}$$

The current generated by the photovoltaic generator at a given voltage depends solely on the illumination and the temperature of the cell.

2.3.4 Simulation results

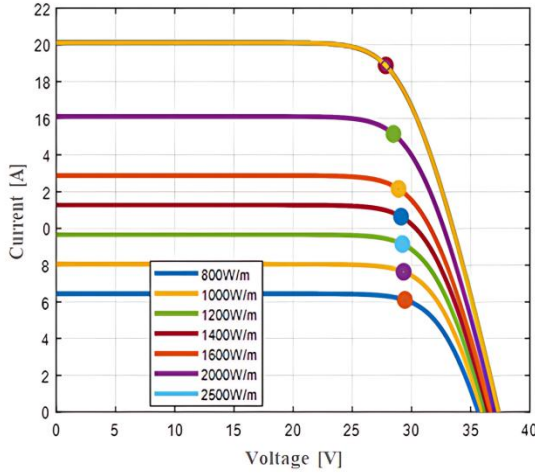


Figure 2.7. I-V characteristics, variation of irradiance at constant temperature.

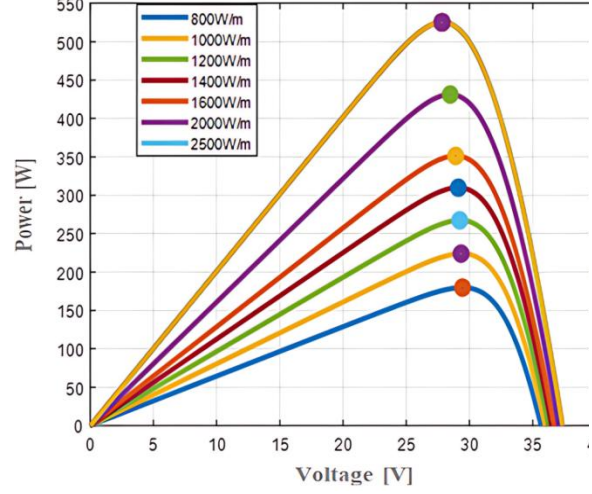


Figure 2.8. P-V characteristics, variation of irradiance at constant temperature.

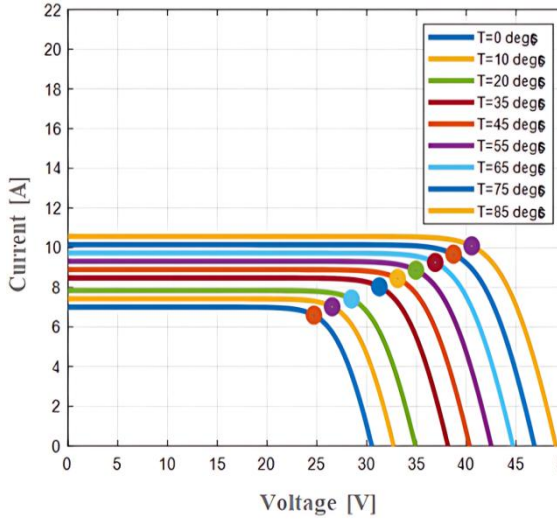


Figure 2.9. I-V characteristics, temperature variation at constant solar radiation.

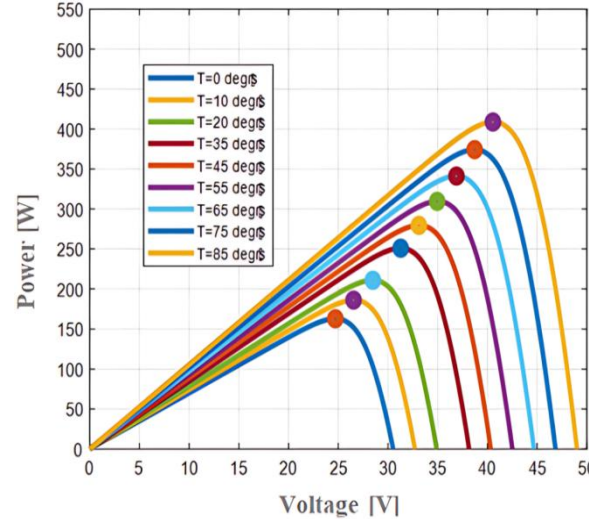


Figure 2.10. P-V characteristics, temperature variation at constant solar radiation

The behavior of a photovoltaic (PV) module is highly influenced by variations in irradiance (G) and temperature (T) due to their significant impact on the module's power output. Figure 2.7 depicts the variations in current (I_{pv}) and voltage (v_{pv}) with respect to voltage for different illumination levels, while maintaining a constant temperature of 25°C . Multiple $P(V)$ curves are shown, representing the maximum power points (v_{mp}, I_{mp}). According to Figure 2.8, the open circuit voltage and short circuit current vary proportionally to the illumination. In Figure 2.9, with constant illumination ($1000\text{w}/\text{m}^2$) and increasing temperature, the open circuit voltage (v_{oc}) decreases while the short circuit current (I_{sc}) remains relatively stable. Therefore, the operation of a PV module

is primarily dependent on the surrounding environmental conditions. It is crucial to consider these factors when sizing a PV system to achieve the desired power output.

The impact of irradiance on a solar PV module is illustrated by the I-V and P-V characteristic curves in Figure 2.7 and Figure II.8, where the irradiance intensity ranges from 100 W/m^2 to 1000 W/m^2 at a fixed temperature of 25°C . The current remains constant as voltage increases up to 30 V, after which it starts to decrease. Additionally, the current increases with higher irradiance intensity, demonstrating the significant effect of irradiance on the short circuit current. Conversely, the open circuit voltage shows minimal change. The proof of maximum power can be found in the power performance curves.

Observing the figure, when the temperature varies from 0 to 80°C , it is evident that increasing temperature leads to a decrease in power (W) with voltage variations (V).

2.4 Modeling of DC-DC Converters

DC-DC converters are a significant part of the conversion chain. They are widely used in connections to storage batteries, photovoltaic systems, wind turbines, and hybrid systems. These converters are used to adjust the input voltage of a system to match the desired output voltage [30].

2.4.1 Types of DC-DC Converters

The three primary categories of DC-DC converters include the Buck converter, the Boost converter, and the Buck-Boost converter.

2.4.1.1 Buck Converter

A Buck Converter is a distinct category of DC-DC converters specifically designed to diminish the amplitude of the input DC voltage via a step-down conversion mechanism. This device operates by converting a constant DC input into a reduced DC output voltage. Fundamentally, its function is to produce a DC output signal with a lower magnitude than the input. It is also commonly known as a Step-down DC-DC Converter, Step-down Chopper, or Buck Regulator.

- **Operating Principle of Buck Converter**

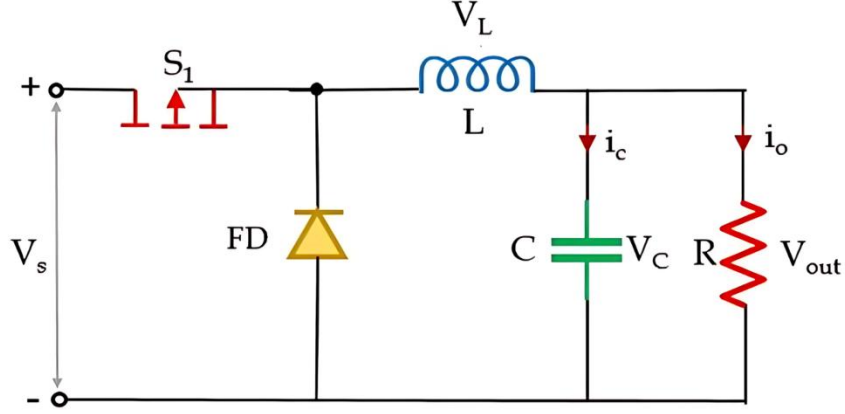


Figure 2.11. The Circuit Representation of Buck Converter

As illustrated in the preceding figure, the circuit consists of a solid-state switching element and a free-wheeling diode connected to a low-pass LC filter, which reduces voltage and current fluctuations to ensure a stable DC output. A resistive element is used as the load. The circuit operates in two modes. In the first mode, the power MOSFET (S_1) is closed, allowing current to flow through it.

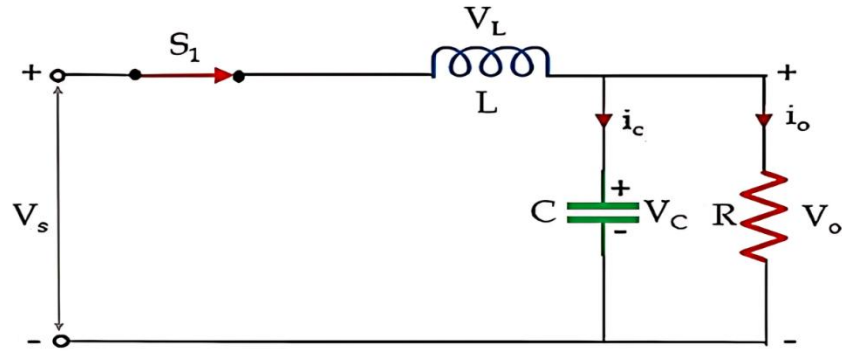


Figure 2.12. Buck Converter When S_1 is Closed

When a steady DC voltage is applied and switch S_1 is closed, current flows through the circuit, storing energy in the inductor as a magnetic field and charging the capacitor. The voltage across the capacitor is then supplied to the load.

According to Lenz's law, the inductor opposes changes in current, generating an induced current and reversing its polarity.

Here the total time period is a combination of T_{on} and T_{off} time.

$$T = T_{on} + T_{off}$$

II.21

The duty cycle is written as:

$$D = \frac{T_{on}}{T} \quad \text{II.22}$$

On applying KVL, in the above-given circuit

$$V_s = V_L + V_{out} \quad \text{II.23}$$

$$V_L = V_s - V_{out} \quad \text{II.24}$$

Also,

$$V_L = L \frac{di_L}{dt} = V_s - V_{out} \quad \text{II.25}$$

$$\frac{di_L}{dt} = \frac{V_s - V_{out}}{L} \quad \text{II.26}$$

When S1 is in closed condition then $T_{on} = DT$ thus $\Delta t = DT$. Therefore, we can write

$$\frac{\Delta i_L}{\Delta t} = \frac{V_s - V_{out}}{L} \quad \text{II.27}$$

$$\frac{\Delta i_L}{DT} = \frac{V_s - V_{out}}{L} \quad \text{II.28}$$

Hence,

$$\Delta i_t = \left(\frac{V_s - V_{out}}{L} \right) DT \quad \text{II.29}$$

The aforementioned equation demonstrates the fluctuation in current throughout the circuit following the activation of switch S1.

In the second mode, switch S1 is open and S2 (the freewheeling diode) conducts automatically. When S1 opens, the inductor acts as a power source, releasing the energy stored in the previous phase. Due to polarity reversal in the inductor, the diode becomes forward biased, allowing current to flow in the indicated direction:

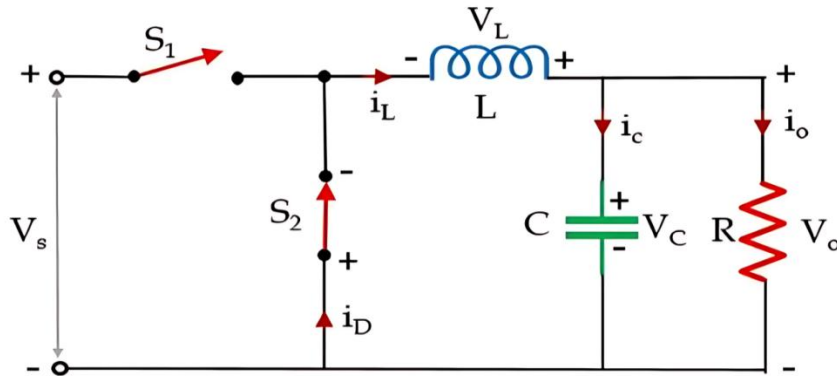


Figure 2.13. Buck Converter Behavior under S2 Closed Condition

The flow of current persists until the inductor has entirely released its stored energy. Upon full depletion of the inductor's charge, the diode transitions into a reverse-biased state, leading to the deactivation of switch S_2 . As a result, switch S_1 engages, initiating the recurrence of the cycle.

Now, let us apply KVL, in the above circuit

$$0 = V_L + V_{out} \quad \text{II.30}$$

$$V_L = L \frac{di_L}{dt} = -V_{out} \quad \text{II.31}$$

Since, we know,

$$T = T_{on} + T_{off} \quad \text{II.32}$$

$$T = DT + T_{off} \quad \text{II.33}$$

$$T_{off} = T - DT \quad \text{II.34}$$

$$T_{off} = (1 - D)T \quad \text{II.35}$$

$$V_L = L \frac{\Delta i_L}{\Delta t} = -V_{out} \quad \text{II.36}$$

$$T_{off} = \Delta t = (1 - D)T \quad \text{II.37}$$

$$L \frac{\Delta i_L}{(1 - D)T} = -V_{out} \quad \text{II.38}$$

So,

$$\Delta i_L = -\frac{V_{out}}{L} (1 - D)T \quad \text{II.39}$$

This equation represents the rate of change of the current flowing through the inductor when switch S_1 is in the open state.

It is well established that the net change in the current flowing through the inductor over a complete cycle is zero. Consequently,

$$\Delta i_{L(s1-closed)} + \Delta i_{L(s1-open)} = 0 \quad \text{II.40}$$

$$\frac{V_s - V_{out}}{L} DT + \left\{ -\frac{V_{out}}{L} (1 - D)T \right\} = 0 \quad \text{II.41}$$

On simplifying,

$$\frac{V_s DT}{L} - \frac{V_{out} DT}{L} - \frac{V_{out} T}{L} + \frac{V_{out} DT}{L} = 0 \quad \text{II.42}$$

$$\left(\frac{V_s DT}{L} \right) = \frac{V_{out} T}{L} \quad \text{II.43}$$

$$V_{out} = DV_s \quad \text{II.44}$$

The figure given below represents the waveform representation of Buck Converter:

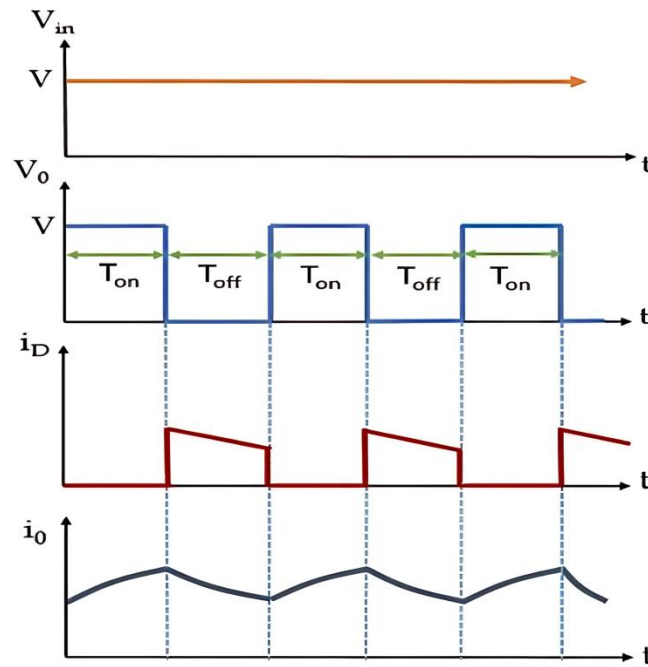


Figure 2.14. Waveform Representation

Buck converters are employed to generate a reduced dc output from a constant dc input.

2.4.1.2 Boost Converter

Boost converters, also referred to as step-up DC-DC converters, are a category of chopper circuits designed to deliver an output voltage greater than the supplied input voltage. In these converters, the process of DC-to-DC conversion results in an output voltage with a higher magnitude compared to the input voltage. The term 'boost' is used to describe these converters due to their ability to increase the output voltage above the level of the input.

- **Fundamental Operating Mechanism of the Boost Converter**

The schematic presented below depicts the circuit arrangement of the boost converter:

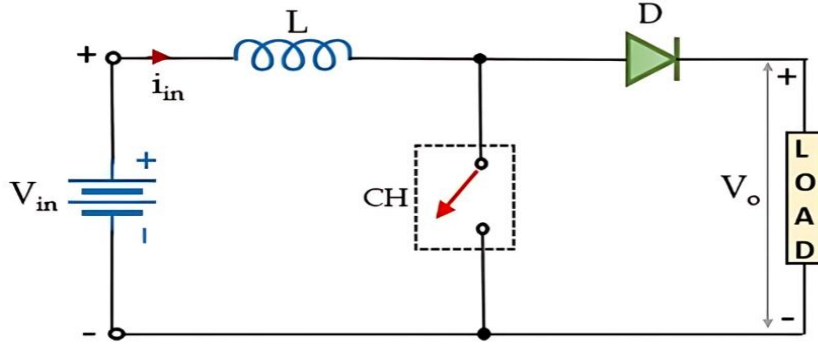


Figure 2.15. Elementary Circuit of Boost Converter

This circuit embodies a fundamental structure of a step-up DC-DC converter, necessitating the integration of a substantial inductor (L) in series with the voltage source. The primary objective of this system is to maintain the stability of the output voltage, thereby ensuring the delivery of a well-regulated DC signal.

To analyze the functionality of the proposed circuit, the focus is placed on enhancing the direct current signal supplied to the load. Initially, when the chopper (CH) is switched to the 'on' state, the application of the DC power source facilitates the current flow within the closed circuit, specifically traversing the inductor, as depicted in the subsequent figure.

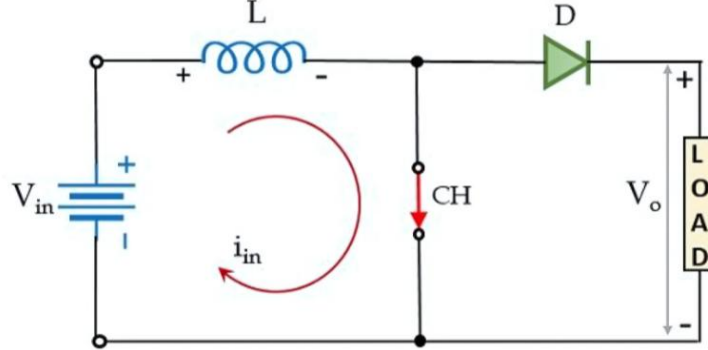


Figure 2.16. The Chopper CH is in on State

In this context, the polarity of the inductor will align with the direction of current flow. Specifically, the diode in the given configuration is reverse-biased, preventing current from flowing through that segment of the circuit when the DC-DC converter is in the "on" state. Consequently, the voltage across the DC-DC converter will be present across the load.

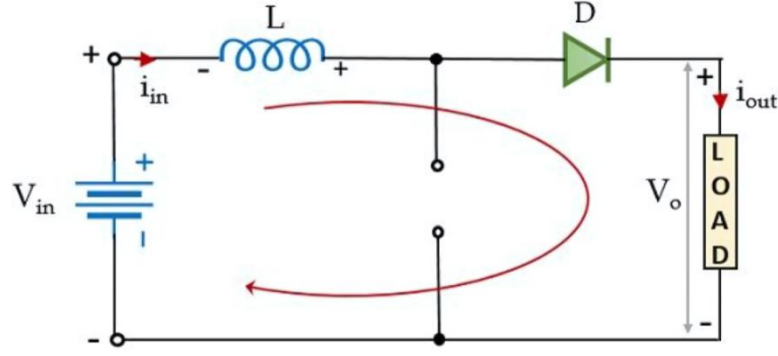


Figure 2.17. The Chopper CH is in Off State

When the chopper (CH) is off, the previously conducting part of the circuit becomes inactive. However, the inductor continues supplying current because it stores energy in its magnetic field. According to Lenz's law, the inductor reverses its polarity, forward-biasing the diode and allowing current to flow through the load even when the chopper is off T_{off} . The current flowing through the inductor gradually decreases over time and eventually stops. Therefore, the total voltage applied to the load can be expressed accordingly :

$$V_{out} = V_{in} + V_L \quad \text{II.45}$$

This implies that the output voltage surpasses the input voltage, thereby achieving a step-up conversion. This process occurs as the energy accumulated in the inductor during the T_{on} phase is discharged during the T_{off} period.

During the T_{on} period, the voltage across the inductor will be given as:

$$V_L = L \frac{di}{dt} \quad \text{II.46}$$

Let us examine the waveform depiction of the step-up chopper illustrated below:

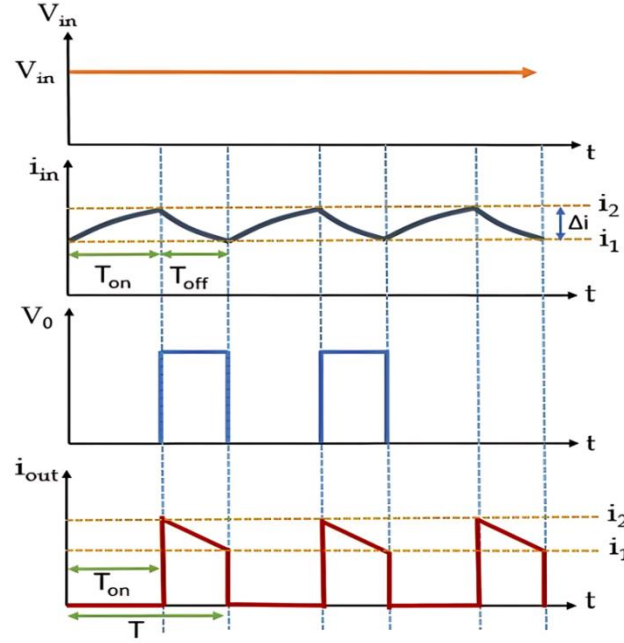


Figure 2.18. Waveform Representation.

During the T_{on} period, the current flowing through the inductor will transition from i_1 to i_2 , as illustrated above. Conversely, during the T_{off} period, the current passing through the inductor transitions from i_2 to i_1 . Concerning the voltage, during the activation phase, the potential difference across the inductor corresponds to the supplied input voltage. Conversely, when the CH is deactivated, employing Kirchhoff's Voltage Law (KVL) to the given circuit diagram leads to the following outcome,

$$V_L - V_0 + V_{in} = 0 \quad \text{II.47}$$

This means,

$$V_L = V_0 - V_{in} \quad \text{II.48}$$

The energy provided by the source to the inductor during the activation of CH is considered as the input energy, under the assumption of a linear change in the output current:

$$W_{on} = (\text{voltage across the inductor})(\text{average current through the inductor})T_{on}$$

$$W_{on} = V_{in} \left(\frac{i_1 + i_2}{2} \right) T_{on} \quad \text{II.49}$$

The energy released by the inductor to the load when the CH is off can be expressed as follows:

$W_{\text{off}} = (\text{voltage across the inductor}) (\text{average current through the inductor}) T_{\text{off}}$

$$W_{\text{off}} = V_{\text{out}} - V_{\text{in}} \left(\frac{i_1 + i_2}{2} \right) T_{\text{off}} \quad \text{II.50}$$

For a lossless system, comparing the two energies, we will have,

$$\begin{aligned} V_{\text{in}} \left(\frac{i_1 + i_2}{2} \right) T_{\text{on}} \\ = V_{\text{out}} - V_{\text{in}} \left(\frac{i_1 + i_2}{2} \right) T_{\text{off}} \end{aligned} \quad \text{II.51}$$

On simplifying,

$$V_{\text{in}} T_{\text{on}} = V_{\text{out}} T_{\text{off}} - V_{\text{in}} T_{\text{off}} \quad \text{II.52}$$

$$V_{\text{out}} T_{\text{off}} = V_{\text{in}} T_{\text{on}} + V_{\text{in}} T_{\text{off}} \quad \text{II.53}$$

$$V_{\text{out}} T_{\text{off}} = V_{\text{in}} (T_{\text{on}} + T_{\text{off}}) \quad \text{II.54}$$

Since we know, $T = T_{\text{on}} + T_{\text{off}}$, therefore,

$$V_{\text{out}} T_{\text{off}} = V_{\text{in}} T \quad \text{II.55}$$

$$V_{\text{out}} = V_{\text{in}} \frac{T}{T_{\text{off}}} \quad \text{II.56}$$

$$V_{\text{out}} = V_{\text{in}} \frac{T}{T - T_{\text{on}}} \quad \text{II.57}$$

$$V_{\text{out}} = V_{\text{in}} \frac{1}{\left(\frac{T}{T} - \frac{T_{\text{on}}}{T} \right)} \quad \text{II.58}$$

Since, we know, duty cycle i.e., $\alpha = T_{\text{on}} / T$

$$V_{\text{out}} = V_{\text{in}} \frac{1}{(1 - \alpha)} \quad \text{II.59}$$

The average load voltage can therefore be increased by modifying the duty cycle.

2.4.1.3 Buck-Boost Converter

The buck-boost converter is a DC-DC converter capable of producing an output voltage either higher or lower than the input voltage. Like a flyback converter but using a single inductor, it can operate as both a step-up and step-down converter depending on the duty cycle (D). A typical Buck-Boost converter circuit is shown below:

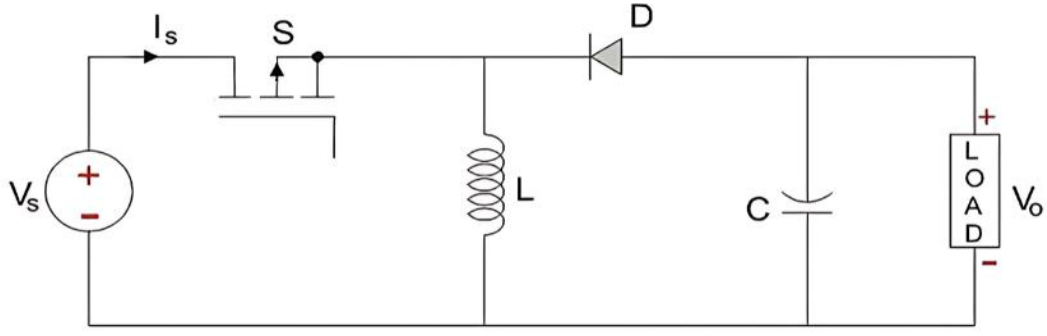


Figure 2.19. The Circuit Representation of Buck-Boost Converter.

The Buck-Boost converter consists of an input voltage source connected to a solid-state switch and a diode acting as a second switch in the opposite direction of power flow, along with a capacitor and load connected in parallel. The switch is controlled using PWM, typically time-based due to its fixed frequency and simplicity.

The converter operates in two modes, with the first mode occurring when the switch is closed and current flows through it.

Mode I: Switch is ON, Diode is OFF

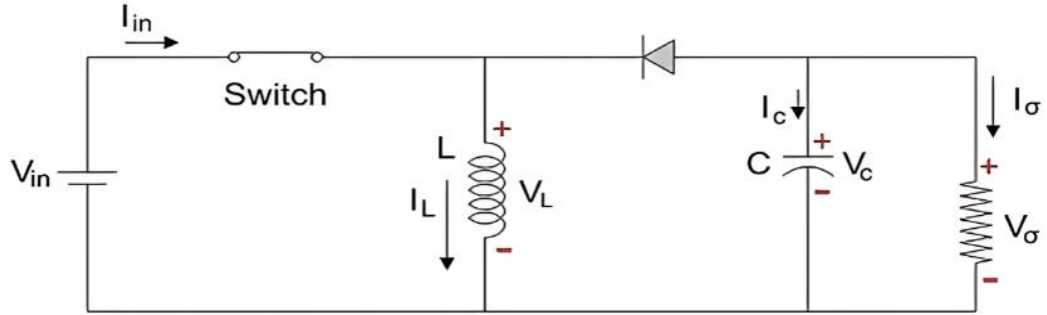


Figure 2.20. The Equivalent Circuit of Mode I.

When the switch is closed, it acts as a short circuit, allowing current to flow through the switch and inductor back to the DC source, while the inductor stores energy. When the switch opens, the inductor reverses its polarity, enabling current to flow through the diode and load, maintaining continuous current through the inductor.

Let us say the switch is on for a time T_{ON} and is off for a time T_{OFF} .

We define the time period, T , as:

$$T = T_{ON} + T_{OFF}$$

II.60

And the switching frequency:

$$f_{\text{switching}} = \frac{1}{T} \quad \text{II.61}$$

Let us now define another term, the duty cycle:

$$D = \frac{T_{\text{ON}}}{T} \quad \text{II.62}$$

We will now examine the Buck-Boost converter under steady-state conditions for this mode by applying Kirchhoff's Voltage Law (KVL).

$$\begin{cases} V_{in} = V_L \\ V_L = L \frac{di_L}{dt} = V_{in} \\ \frac{di_L}{dt} = \frac{\Delta i_L}{\Delta t} = \frac{\Delta i_L}{DT} = \frac{V_{in}}{L} \end{cases} \quad \text{II.63}$$

Since the switch is closed for a time $T_{\text{ON}} = DT$ we can say that $\Delta t = DT$.

$$(\Delta i_L)_{\text{closed}} = \left(\frac{V_{in}}{L} \right) DT \quad \text{II.64}$$

To ensure a comprehensive analysis of the Buck-Boost converter, it is essential to consider the following aspects

- To ensure continuity in the inductor current, it is essential to choose an appropriate inductance (L) value.
- In the steady-state condition, the current through the inductor increases with a positive slope until it reaches its maximum during the ON state, after which it decreases back to the initial value, following a negative slope. As a result, the overall change in the inductor current over one full cycle is null.

Mode II: Switch is OFF, Diode is ON

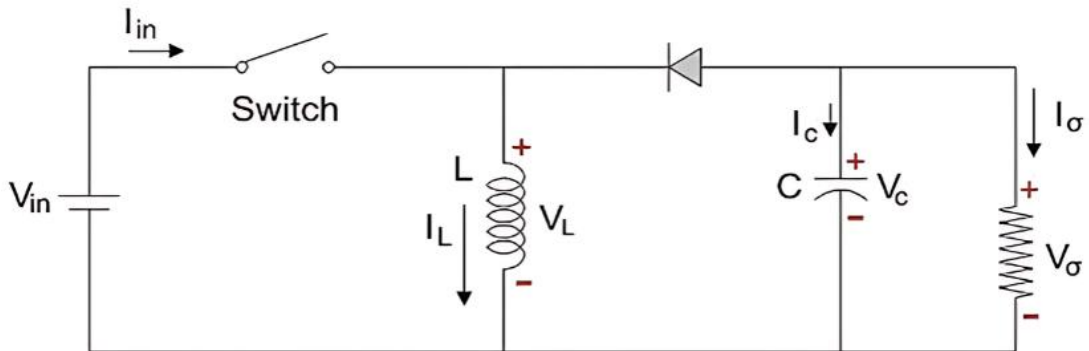


Figure 2.21. The Equivalent Circuit of Mode II

In this configuration, the inductor reverses its polarity and releases its stored energy to the load, maintaining continuous current flow, The output voltage increases as the inductor

acts as an additional source with the input, For analysis, the original conventions are kept to apply Kirchhoff's Voltage Law (KVL).

- **Buck Boost Converter Formula**

Let us now analyse the Buck Boost converter in steady state operation for Mode II using KVL.

$$V_L = V_o \quad \text{II.65}$$

$$V_L = L \frac{di_L}{dt} = V_o \quad \text{II.66}$$

$$\frac{di_L}{dt} = \frac{\Delta i_L}{\Delta t} = \frac{\Delta i_L}{(1-D)T} = \frac{V_o}{L} \quad \text{II.67}$$

Since the switch is open for a time

$$T_{OFF} = T - T_{ON} = T - DT = (1-D)T \quad \text{II.68}$$

we can say that

$$\Delta t = (1-D)T \quad \text{II.69}$$

$$(\Delta i_L)_{\text{open}} = \left(\frac{V_o}{L}\right)(1-D)T \quad \text{II.70}$$

It is already established that the net change of the inductor current over any one complete cycle is zero.

$$(\Delta i_L)_{\text{closed}} + (\Delta i_L)_{\text{open}} = 0 \quad \text{II.71}$$

$$\left(\frac{V_o}{L}\right)(1-D)T + \left(\frac{V_{in}}{L}\right)DT = 0 \quad \text{II.72}$$

$$\frac{V_o}{V_{in}} = \frac{-D}{1-D} \quad \text{II.73}$$

It is established that the value of D lies within the range of 0 to 1. When D exceeds 0.5, the output voltage surpasses the input voltage. Conversely, if D is less than 0.5, the output voltage is reduced compared to the input. However, when D is exactly 0.5, the output voltage equals the input voltage.

2.4.1.4 Comparison of Converter Types

Table 2.1 summarizes the voltage gains and switch stresses of different converters and shows how voltage gain varies with the duty cycle. Although several converters can operate as boost types when the duty cycle exceeds 0.5, the conventional boost converter provides voltage gain across the entire duty cycle range. For example, at $D = 0.5$ it produces twice

the input voltage, while other boost-derived converters only match the input voltage at this point and approach boost performance only as D nears 1.

Table 2.1. Comparison of Converter Types.

Converter /Parameters	Voltage Gain $\frac{V_{out}}{V_{in}}$	Voltage Controls $V_{k,max} = V_{d,max} $	Current Controls $i_{k,max} = V_{d,max} = i_{d,max}$
Boost	$\frac{1}{1-\alpha}$	$\frac{V_{in}}{1-\alpha} + \frac{\Delta V_{out}}{2}$	$\frac{I_{out}}{1-\alpha} + \frac{\Delta I_L}{2}$
Buck	$\frac{\alpha}{1-\alpha}$	$\frac{V_{in}}{1-\alpha} + \frac{\Delta V_{out}}{2}$	$\frac{V_C}{1-\alpha} + \frac{\Delta V_{out}}{2}$
Buck-Boost	α	V_{in}	$i_L + \frac{\Delta I_L}{2}$

2.5 Maximum Power Point Tracking:

To enhance photovoltaic (PV) system efficiency, the operating point must be optimized to ensure maximum power output. This is achieved using a DC-DC converter for impedance matching and applying Maximum Power Point Tracking (MPPT) techniques. MPPT algorithms determine the optimal operating point by measuring and multiplying voltage and current to locate the true maximum power point (MPP). Several methods exist, such as constant voltage, constant current, incremental conductance, and perturb and observe (P&O), with the P&O method selected due to its simplicity of implementation.

2.5.1 working principle of MPPT

MPPT control strategies are used to ensure devices, particularly photovoltaic (PV) systems, operate at their maximum power point (MPP), even though this point is not fixed and may vary. These methods continuously search for the MPP while maintaining optimal matching between the generator and the load to maximize power transfer.

To achieve this, a DC load and a DC-DC converter (four-port system) are used, providing the flexibility needed to adapt the PV generator to the load and ensure maximum power (P_{MAX}) is efficiently delivered.

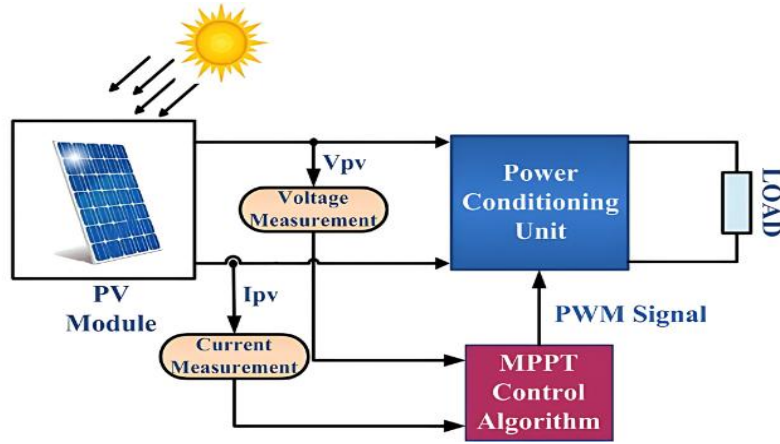


Figure 2.22. Block Diagram of The PV System

The most commonly adopted control approach relies on the automatic adjustment of the duty cycle to ensure that the photovoltaic generator operates at the maximum power point (MPP), particularly in the presence of sudden load variations. Disturbances resulting from changes in solar irradiance, load conditions, or temperature cause the operating point to deviate from the MPP. In all cases, the control system must intervene to track a new optimal operating point, with faster dynamic response required for irradiance and load variations compared to temperature changes.

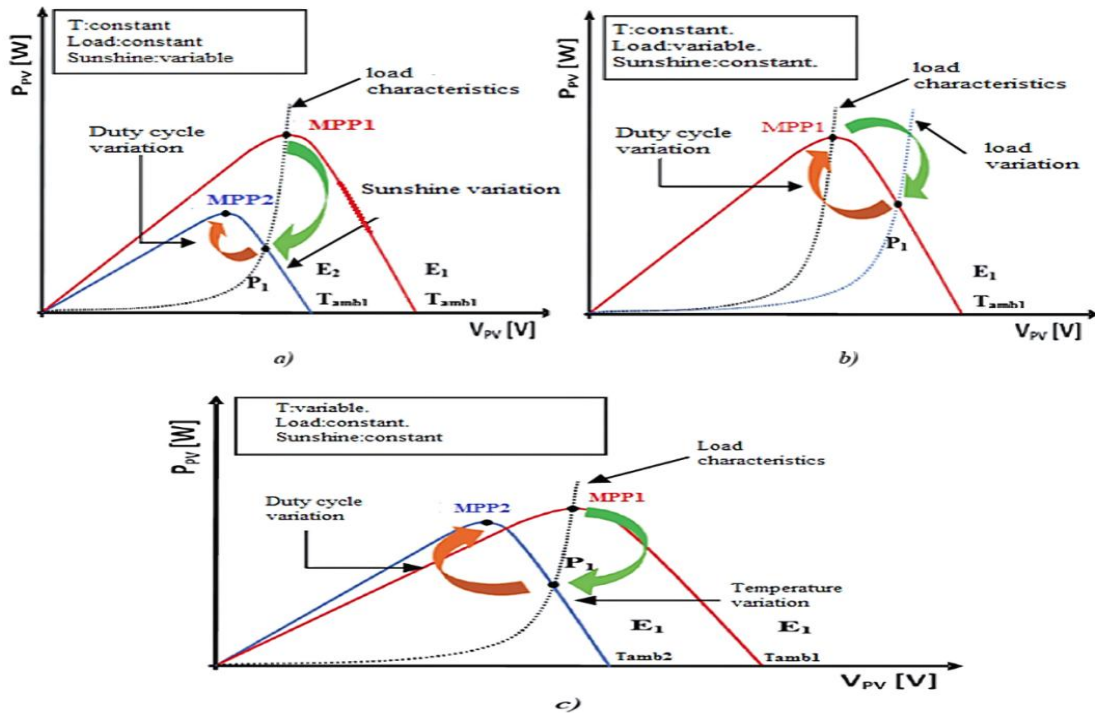


Figure 2.23. Search and Recovery of MPP.

2.5.2 MPPT Control with High-Performance Algorithms

The examination of different Maximum Power Point Tracking (MPPT) algorithms reveals that, in practical applications, their performance and the trade-offs in accuracy are generally comparable. A range of experiments documented in the literature suggests that this type of control can be efficient under specific circumstances, yet no conclusive evidence exists to demonstrate the superiority of one tracking method over others. This variability can be attributed to discrepancies in the testing environments and the values assigned to the increment variables.

The categorization of MPPT algorithms is primarily influenced by factors such as implementation complexity, cost, and algorithm efficiency. The table below presents a summary of various MPPT techniques:

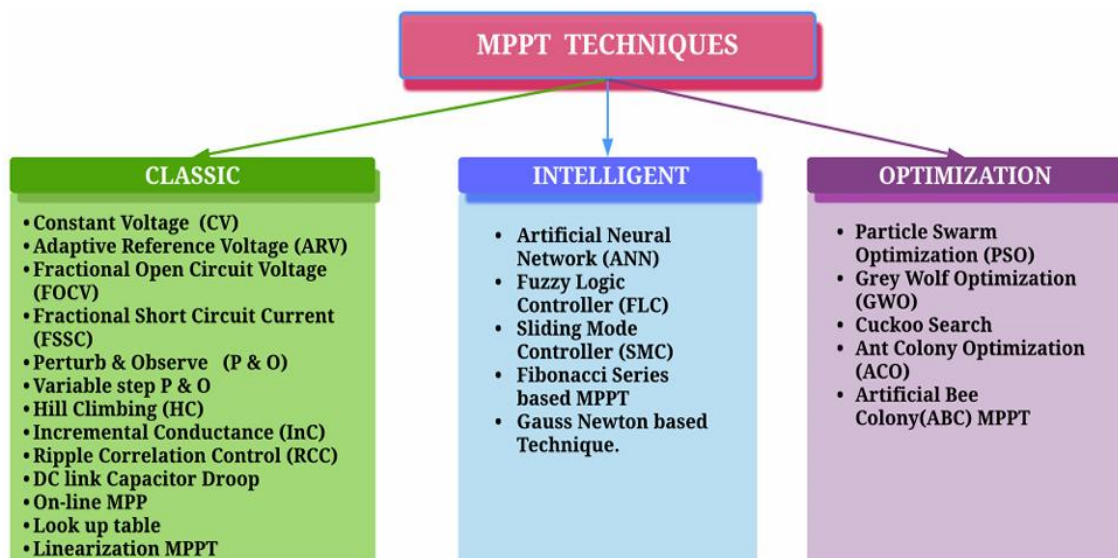


Figure 2.24. Basic classification of tracking techniques

2.5.2.1 Algorithm Perturb and Observe (P&O):

The MPPT strategy based on Perturb and Observe (P & O) operates by perturbing the voltage (VPV) around its initial value with small amplitude and monitoring the resulting power variation (PPV). As depicted in Figure 2.25, it can be inferred that if an increase in voltage VPV leads to a rise in power PPV, the system is operating to the left of the maximum power point (MPP). Conversely, if the power decreases, it indicates that the system has surpassed the MPP.

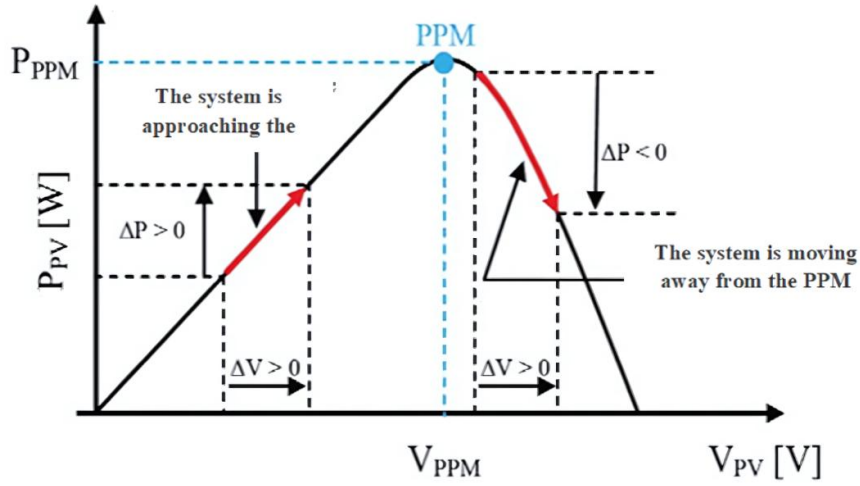


Figure 2.25. P_{pv} VS V_{pv} Characteristic of a Solar Panel

The algorithm depicted in Figure 2.26 corresponds to a traditional Maximum Power Point Tracking (MPPT) method of the Perturb and Observe (P & O) type. This algorithm analyzes the power changes after each voltage perturbation. To assess the power of the solar generator at any given moment, two sensors-measuring current and voltage-are required.

The Perturb & Observe approach is widely employed due to its simplicity of implementation. However, it presents challenges, particularly oscillations around the Maximum Power Point (MPP) in steady-state conditions. This occurs because the MPP search is periodically repeated, leading to continuous oscillations around the MPP.

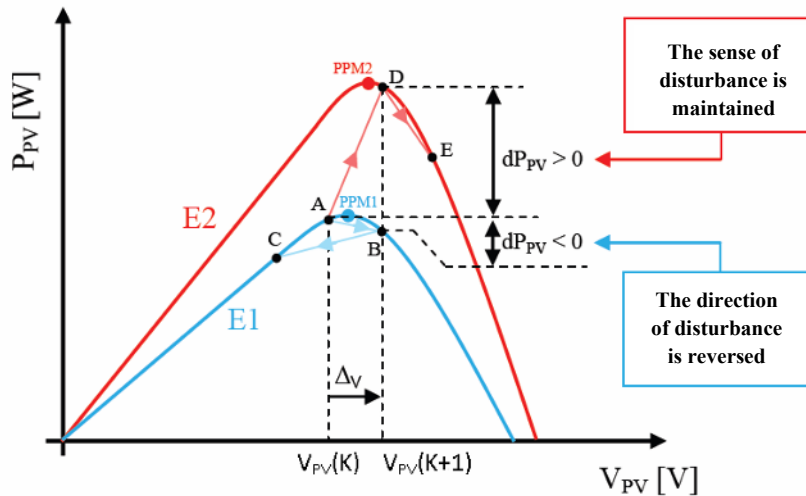


Figure 2.26. Divergence of The P & O Command Due to Radiation Variation.

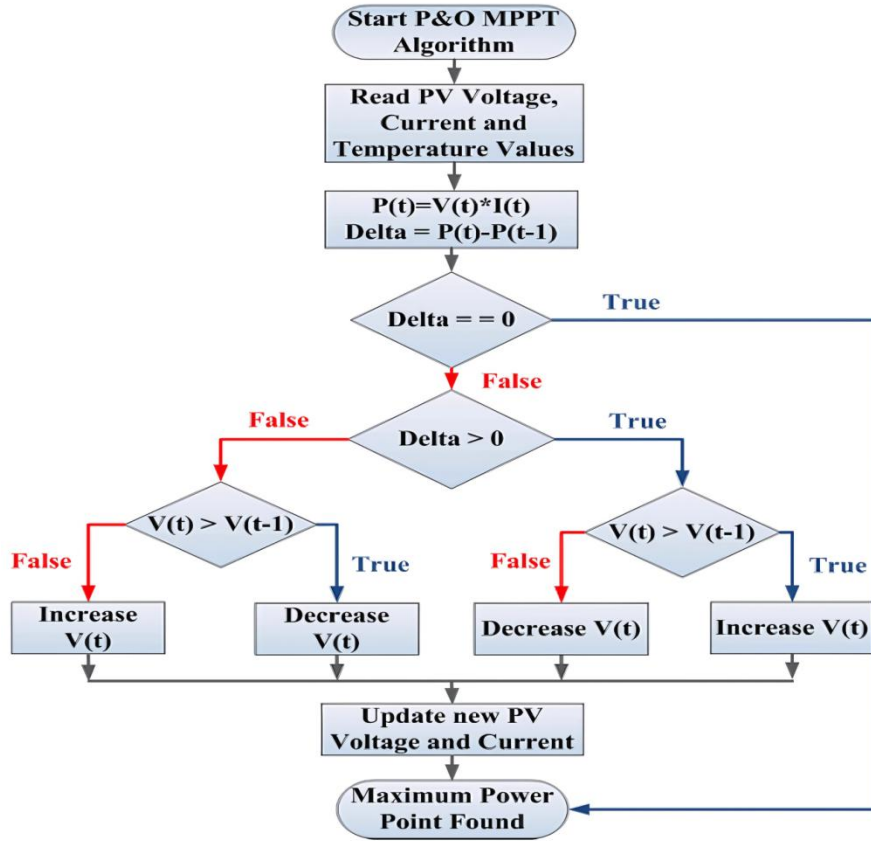


Figure 2.27. Algorithm of The P & O Type of Command.

At an initial irradiance E_1 , the system operates at point A. A voltage disturbance (ΔV) shifts the operating point to B, where a negative power derivative causes the control to reverse the disturbance direction, leading to oscillations around the Maximum Power Point (MPP) between points B and C. Power losses depend on how far B and C are from A. When irradiance changes from E_1 to E_2 , the operating point moves from A to D, reflecting an increase in power output.

2.6 Modeling of the DC/AC (Inverter)

Voltage inverters are devices in power electronics that convert DC bus voltage into alternating voltages. These converters find applications across various fields. Their considerable advancement can be attributed to two key factors: first, progress in semiconductor technology, leading to components that are fully controllable, powerful, robust, and fast; and second, the extensive adoption of pulse width modulation (PWM) techniques.

2.6.1 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.

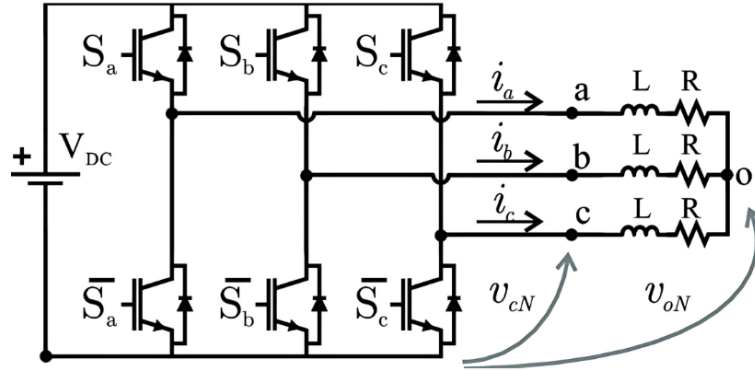


Figure 2.28. Structure of the two-level three-phase voltage inverter.

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:

$$S_a = \begin{cases} 1 & \text{if } S_1 \text{ on and } S_2 \text{ off} \\ 0 & \text{if } S_1 \text{ off and } S_2 \text{ on} \end{cases} \quad \text{II.74}$$

$$S_b = \begin{cases} 1 & \text{if } S_3 \text{ on and } S_4 \text{ off} \\ 0 & \text{if } S_3 \text{ off and } S_4 \text{ on} \end{cases} \quad \text{II.75}$$

$$S_c = \begin{cases} 1 & \text{if } S_5 \text{ on and } S_6 \text{ off} \\ 0 & \text{if } S_5 \text{ off and } S_6 \text{ on} \end{cases} \quad \text{II.76}$$

The dynamic Behavior of the load current for each phase can be described by utilizing the variable definitions shown in Figure 2.28. This formulation for each phase is expressed as follows.

$$U_{an} = L \frac{di_a}{dt} + Ri_a + e_a + U_{nN} \quad \text{II.77}$$

$$U_{bn} = L \frac{di_b}{dt} + Ri_b + e_b + U_{nN} \quad \text{II.78}$$

$$U_{cn} = L \frac{di_c}{dt} + Ri_c + e_c + U_{nN} \quad \text{II.79}$$

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

2.6.2 Voltage Source Inverter-Based Techniques for Digital Control

Connecting a distributed generation system to the grid is extremely important, as any delay in establishing this connection may lead to problems such as grid instability and disturbances. Therefore, developing an appropriate controller is essential to address these challenges. This section reviews the most effective control strategies according to their specific applications. Research highlights both single-loop and multi-loop control techniques for power control, as well as voltage and current regulation. In these systems, the inner loop is responsible for current regulation, while the outer loop mainly handles voltage regulation [6–8]. The classification of classical and advanced control techniques is clearly illustrated in Figure 2.29.

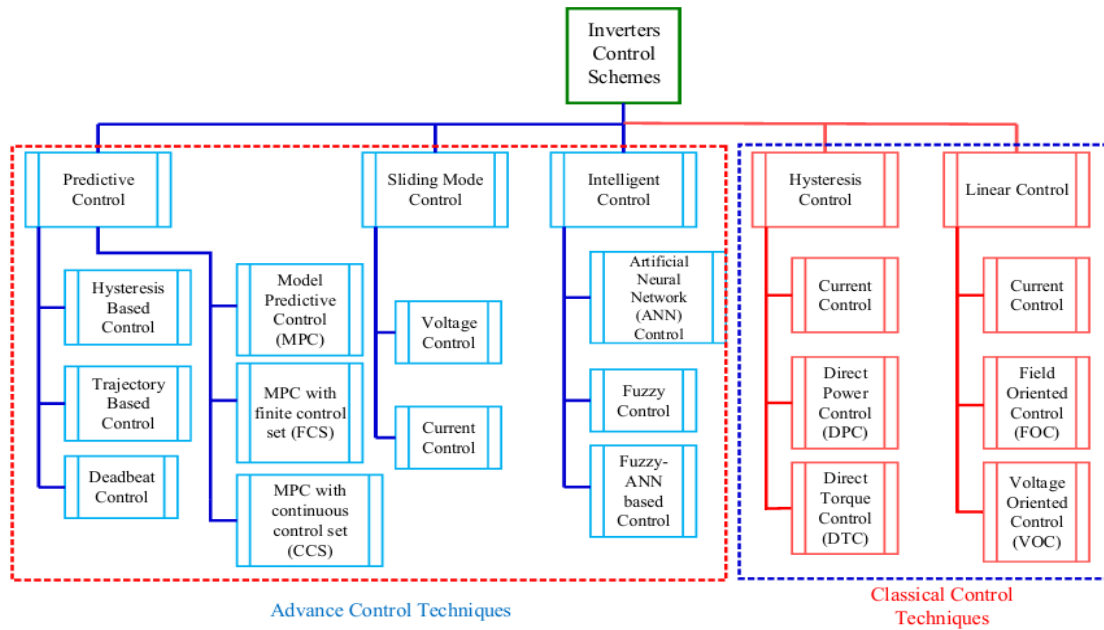


Figure 2.29. Classification of control techniques for VSIs.

2.6.2.1 Classical Control Techniques

Conventional controllers are designed to modify a specific variable and apply the required adjustments to the system. This category includes (P), (PI), (PID), and (PD) controllers. They are considered fundamental components in industrial applications for managing linear systems and are regarded as the foundation of control theory. Numerous studies in the current literature have focused on these controllers [9–19]. Their main advantages include simple design and the ability to adapt to the system's specific requirements, in addition to their wide use in commercial applications and easy availability. However, compared to advanced modern controllers, their performance is relatively weaker in terms of tracking accuracy, response speed, and stability in error management.

A diagram is also presented illustrating a digital PI controller used to regulate a three-phase VSI with an LC filter operating in stand-alone mode.

In Figure 2.30, 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.

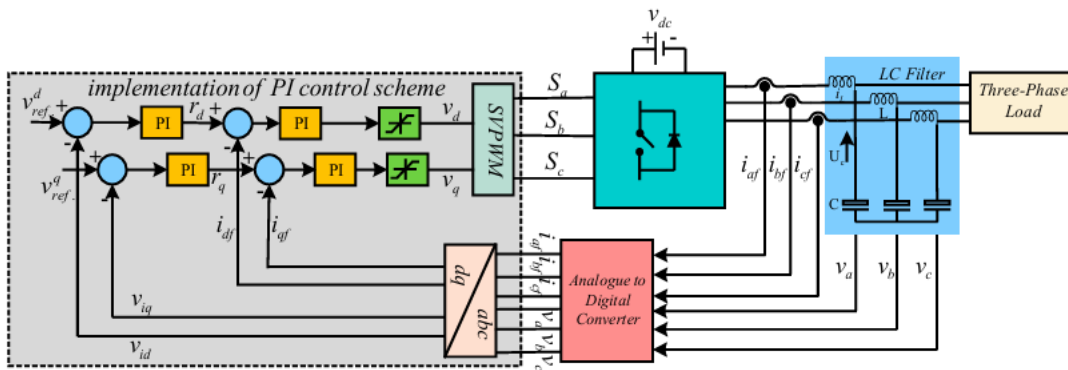


Figure 2.30. Diagrammatic Representation of a PI Control Algorithm for a VSI.

2.6.2.2 Hysteresis Control Technique

Hysteresis control is considered a nonlinear method [20–27] used to monitor the difference between the reference and actual currents, where switching signals are generated according to the tracking error. The hysteresis bandwidth is adjusted to ensure accurate

reference tracking. This approach does not require a modulator; however, the switching frequency depends on operating conditions, the hysteresis band, and the filter parameters [28].

The main drawback is the irregular switching frequency. Nevertheless, research efforts have led to the development of techniques such as Direct Torque Control (DTC) [21, 22, 29, 30] and Direct Power Control (DPC) [31–34]. In DPC, active and reactive powers are directly controlled, whereas in DTC, torque and flux are regulated using hysteresis controllers and lookup tables.

When implemented digitally, high-frequency operation is required to maintain the variables within the hysteresis band limits (Figure 2.31). Moreover, the high switching losses make this method unsuitable for high-power applications.

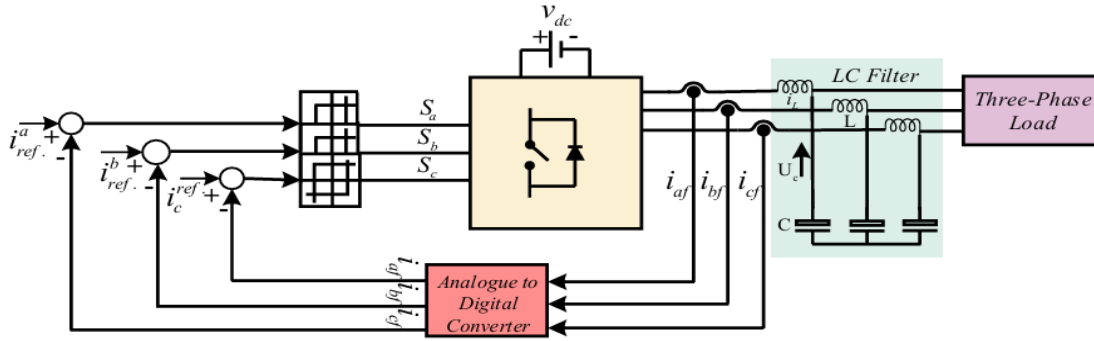


Figure 2.31. A Hysteresis-Based Control Method for VSI.

2.6.2.3 Repetitive Control

Repetitive Control (RC) is based on the Plug-In Scheme (PIS) and the Internal Model (IM) principle, using a periodic signal model to achieve accurate reference tracking and strong disturbance rejection. Its performance in periodic applications depends on closed-loop behavior and the internal model's response, especially under frequency variations and system uncertainties.

RC minimizes tracking errors by predicting and correcting them using past information, but it has limited noise rejection capability. Therefore, techniques such as Low-Pass Filter (LPF) and Kalman filtering are used to reduce noise [35–38]. Figure 2.32 shows the general structure of the repetitive controller.

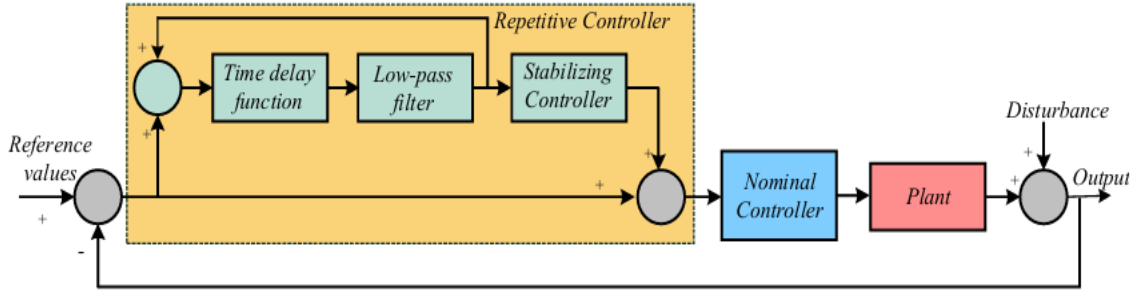


Figure 2.32. Schematic Representation of the Repetitive Control Algorithm.

2.6.2.4 Fuzzy Control

This approach belongs to intelligent control systems, where the conventional PI controller is replaced by a fuzzy logic controller, as shown in Figure (2.33), with v_{fz} representing the fuzzified output voltage. The controller receives the load current tracking error and its derivative as inputs, and its design largely depends on the designer's expertise.

Due to the inherent nonlinearity of power converters, system stability can be maintained despite parameter variations, even without an accurate model. Fuzzy logic controllers, classified as nonlinear controllers, are considered effective solutions within this category [39–42]. However, the fuzzification process requires strong assumptions and substantial expertise, relying on predefined rules established during the design phase.

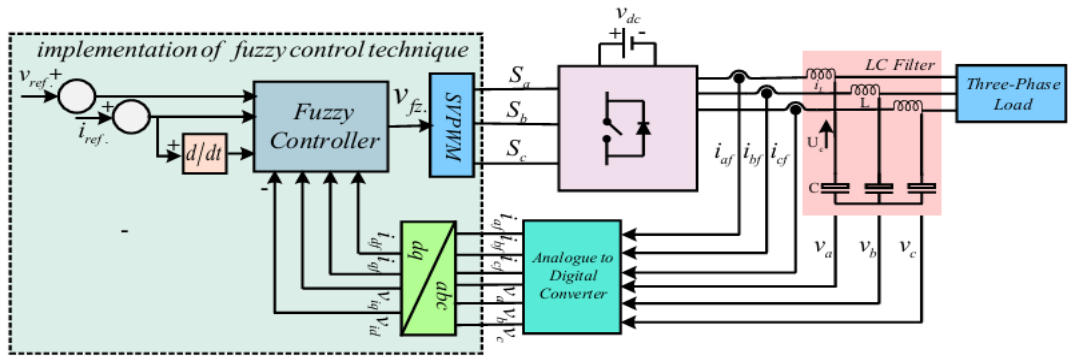


Figure 2.33. A Topological Framework for Fuzzy Control Algorithms in VSI.

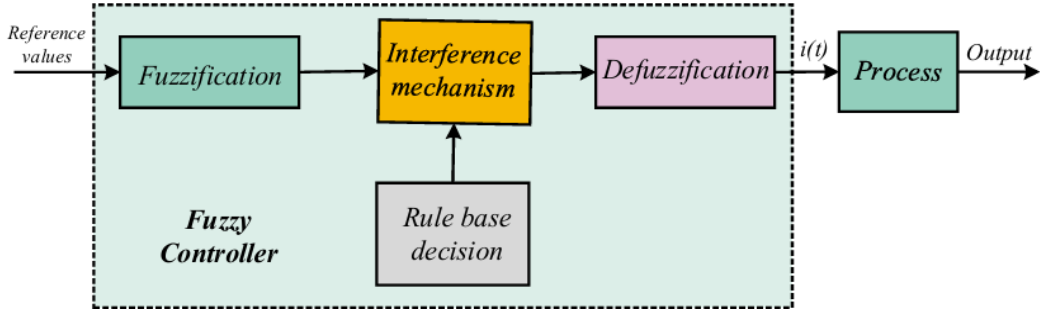


Figure 0.34. Schematic Representation of the Fuzzy Control Algorithm.

2.6.2.5 Artificial Neural Network Control

ANN-based controllers are designed to mimic human cognitive functions using interconnected artificial neurons. The reference tracking error, scaled by a gain factor (S), is fed into the ANN to generate switching signals for power converters, ensuring uniform switching operation. ANNs can operate in both online and offline modes and are highly fault-tolerant due to their function approximation capability. The system topology is shown in Figure 2.35.

Combining Fuzzy Logic with ANN further enhances control performance in power converters [39–41]. Although ANNs do not require an explicit converter model, effective design demands a thorough understanding of the converter's operating characteristics.

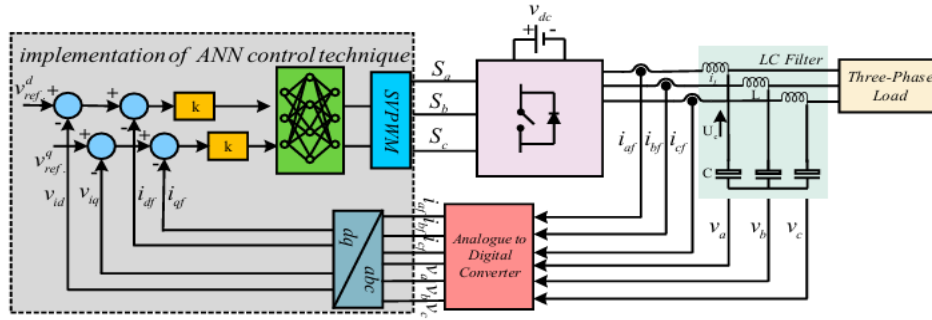


Figure 2.35. Diagram of Artificial Neural Network-based Control for VSIs.

2.6.3 Predictive Controllers

Predictive controllers have emerged as an effective method for controlling electronic inverters. They rely on an accurate system model to predict the future behavior of control variables according to predefined criteria. This approach is relatively simple in structure, performs well in multivariable systems, and can handle constraints and nonlinearities.

It is preferred for its fast static and dynamic response and good steady-state error management. However, it involves more complex computational analysis compared to traditional controllers. Predictive control is mainly classified into Deadbeat Control and Model Predictive Control (MPC) [43–46]. A comparison of these methods, including their advantages and disadvantages, is provided in Table 2.2.

Table 2.2. Description of predictive controllers on the basis of their pros. & cons.

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.

2.6.3.1 Deadbeat Control

Deadbeat control is considered a reliable and efficient method due to its low total harmonic distortion (THD), fast transient response, and wide bandwidth. It operates by discretizing the system's differential equations and predicting the control signal for the next sampling period to ensure accurate reference tracking and strong dynamic current control.

A key feature is error compensation; however, its main limitation is high sensitivity to network parameters and the need for precise mathematical filter modeling [6, 47–57]. The system structure (Figure 2.36) includes a disturbance observer, state estimator, and digital deadbeat controller to regulate voltage and current in a Voltage Source Inverter (VSI),

where the coefficient $\hat{d}$ represents the disturbance observer output containing both voltage and current components. However, $\hat{v}_d$ and $\hat{v}_q$ represent the controlled voltage across the d-axis and q-axis, respectively.

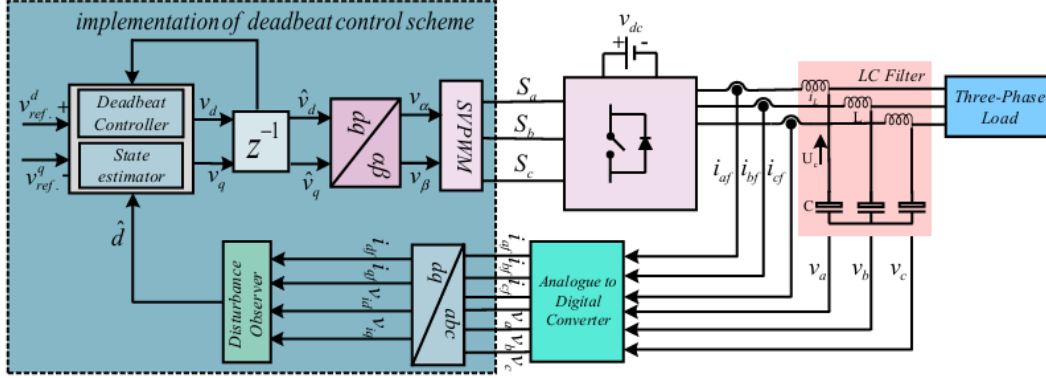


Figure 0.36. Deadbeat control topology for VSIs.

2.6.3.2 Model Predictive Control

Model Predictive Control (MPC) predicts system behavior using a mathematical model and applies a cost function to determine the optimal control action. The controller selects switching states by minimizing this cost function, improving reference tracking and reducing prediction errors.

MPC effectively handles system constraints, nonlinearities, and multi-input multi-output (MIMO) systems. It uses present control actions to predict future states and determine the required control moves. However, similar to deadbeat control, MPC is sensitive to variations in system parameters [58, 59]. The implementation structure for a VSI is shown in Figure 2.37 along with its control diagram is shown in Figure 2.38.

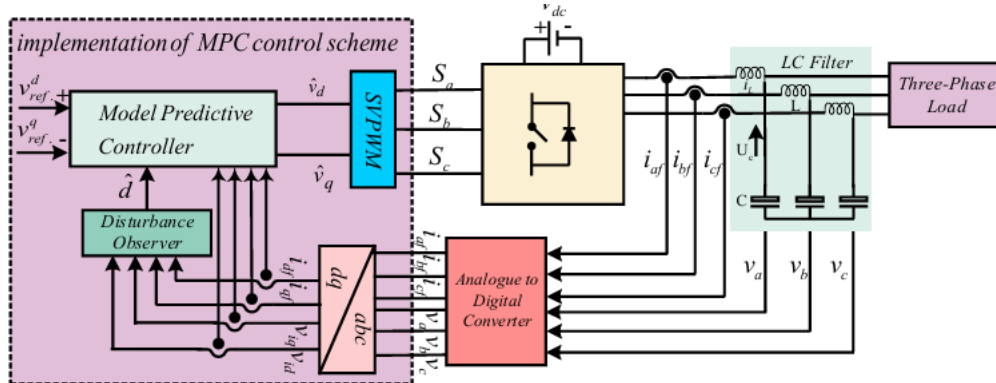


Figure 2.37. Topological Approach to Model Predictive Control for VSIs.

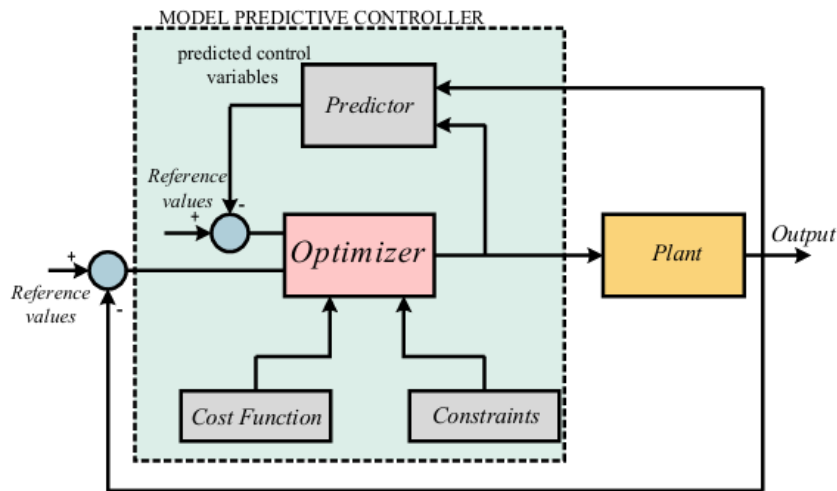


Figure 2.38. Diagrammatic Representation of the Model Predictive Control Algorithm.

2.7 Computer-Based Control System

Digital control systems operate in the discrete-time (z-domain) framework, requiring signal sampling and quantization. Their implementation must consider finite computational precision and possible coefficient errors from A/D and D/A conversions. The controller output is based on current and past input/output samples, which requires data storage.

Digital controllers are cost-effective, flexible, and easy to reconfigure. They are less sensitive to external disturbances than analog controllers and support advanced applications such as logic control and MIMO systems. Their key advantages include flexibility, scalability, accuracy, and noise immunity.

However, they face limitations such as lower processing speed, restricted dynamic range, and sometimes less user-friendly interfaces.

The implementation of digital controllers involves a range of technologies, which can be categorized into three distinct groups, as outlined 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]

Digital Signal Processing (DSP) is used in digital control systems with fixed- and floating-point operations. Microprocessors suit low-speed applications, while Field-Programmable Gate Arrays (FPGAs) are preferred for high-speed control due to their flexibility and reliability.

Figure II.38 shows a grid-connected closed-loop system with inner and outer control loops, a voltage source inverter (VSI), and an output filter. The AC bus connects at the Point of Common Coupling (PCC), and a phase angle (PH) is used for the abc-to-dq transformation.

This system also illustrates the phase-locked loop (PLL). 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} denote the reference voltages within the dq frame. The Space Vector Pulse Width Modulation (SVPWM) technique is utilized to generate control signals for voltage source inverters.

The voltage across the capacitors u_c , and the current through the inductors i_L , are measured and then transformed into a synchronized dq reference frame. The input voltage in the dq frame is derived from the reference voltage v_{ref} of the three-phase reference frame. The calculated values are subsequently converted from the spinning dq frame to the abc reference frame. A suitable PWM approach is ultimately chosen based on the obtained results.

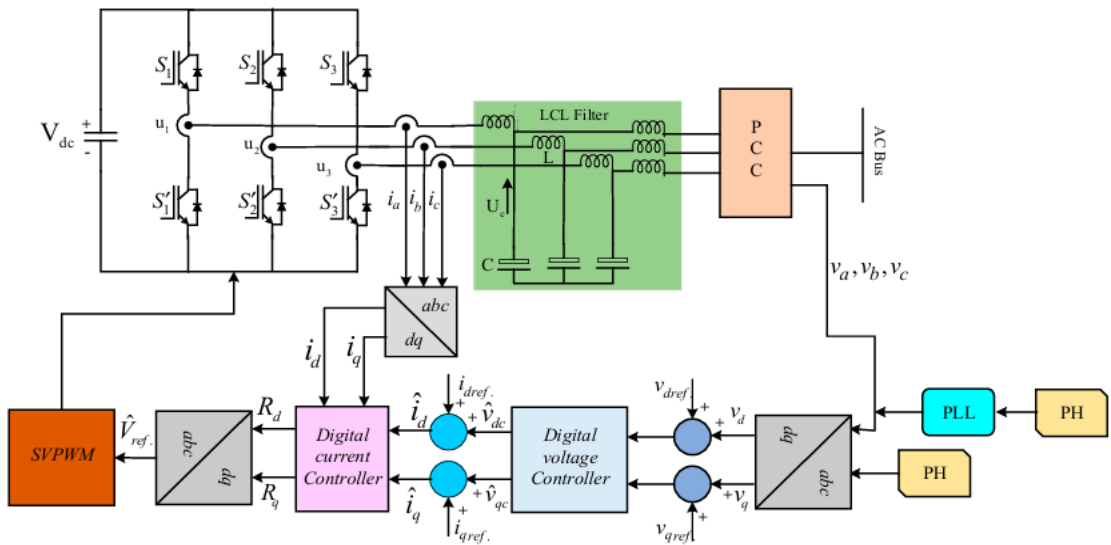


Figure 2.39. Schematic diagram of a controlled three-phase grid connected VSI with a digital controller.

2.8 Output Filters for Inverters

Harmonic reduction is a fundamental concern for researchers in the design of power electronics or electrical systems. An output filter is commonly utilized to resolve this issue. These filters employ the regulated switching characteristics of semiconductor devices to reduce harmonics. Numerous filter topologies have been presented in the literature, which integrate inductors (L) and capacitors (C), including L, LC, and LCL filters, with inverters at their output.

2.8.1 L-Filter

Inverters functioning at elevated switching frequencies generally employ a first-order L-filter, deemed the most suitable option. The incorporation of inductance leads to a diminution of the overall system dynamics.

2.8.2 LC-Filter

An LC filter is categorized as a second-order filter and demonstrates superior damping characteristics compared to an L-filter. This specific filter architecture provides a more straightforward design procedure by balancing inductance and capacitance values. The cut-off frequency is predominantly determined by the inductance value; however the quality of voltage can be improved by augmenting the capacitance. The resonant frequency is dictated by the grid impedance when the system is included into the grid supply. LC filters are generally preferred in independent arrangements.

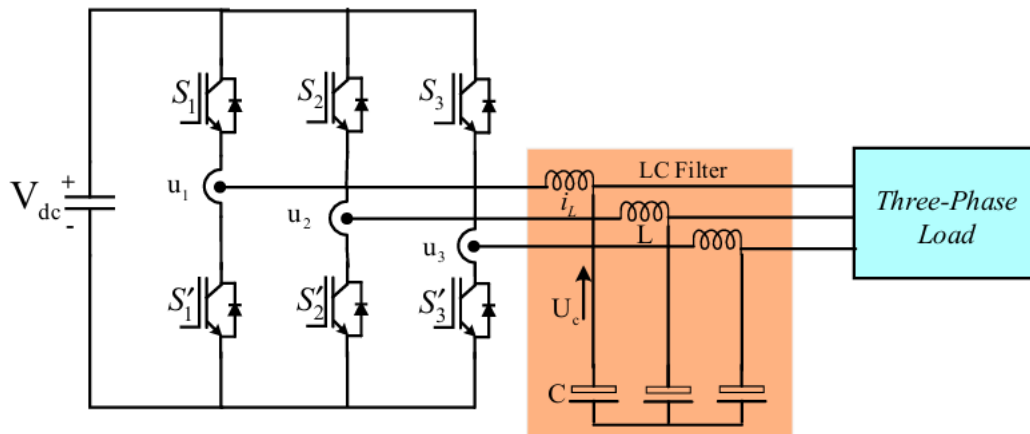


Figure 2.40. Two-level three Phase VSI with an Output LC Filter.

Figures 2.40 illustrate two-stage, three-phase, four-leg voltage source inverters, each featuring an integrated LC filter.

2.8.3 LCL-Filter

An LCL filter is a third-order filter widely used in grid-connected inverters, especially effective at low frequencies. It improves decoupling between the filter and grid impedance. However, proper design is crucial, as inappropriate inductance values may cause resonance and instability, while lower inductance can enhance current ripple attenuation.

A three-phase voltage source inverter (VSI) incorporating an LCL filter is depicted in Figure 2.41, where V_{th} and Z_{th} denote the Thevenin voltage and Thevenin impedance, respectively. Nevertheless, the use of more complex filter configurations leads to a substantial increase in the complexity of the control system, potentially impacting the dynamic performance of the inverter. Consequently, these topologies are generally best suited for high-power applications that operate at low switching frequencies.

Figures 2.42 and 2.43 show the one-leg diagrams of single-phase and three-phase grid-connected systems. Here, K_{pwm} represents the pulse width modulation characteristic of the system, whereas $u_g, u_i, u_c, L_g, L_i, i_i$, and i_g represent, The parameters include the grid-side voltage, inverter-side voltage, capacitor voltage, grid-side inductance, inverter-side inductance, inverter-side current, and grid-side current.

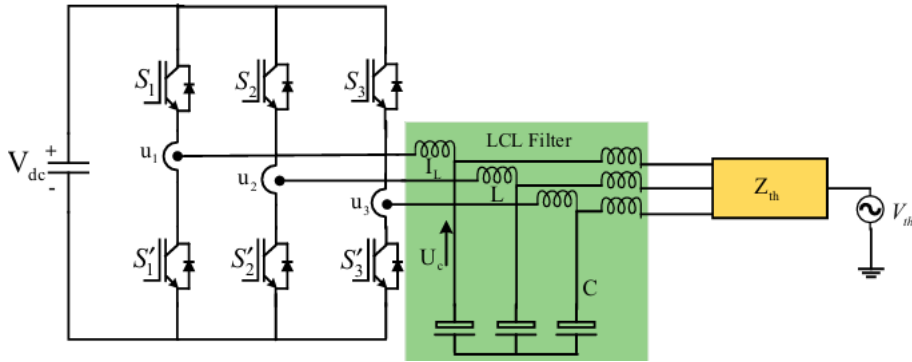


Figure 2.41. A Three-Phase VSI Operating in Grid-Connected Configuration.

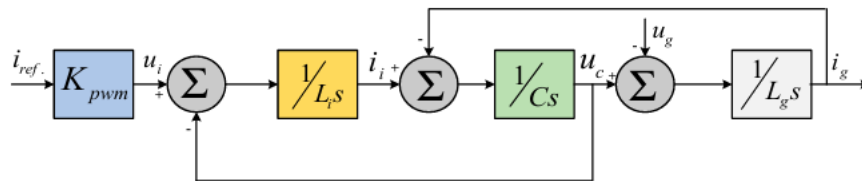


Figure 2.42. Single-Phase Grid-Connected System with One-Leg Block Representation.

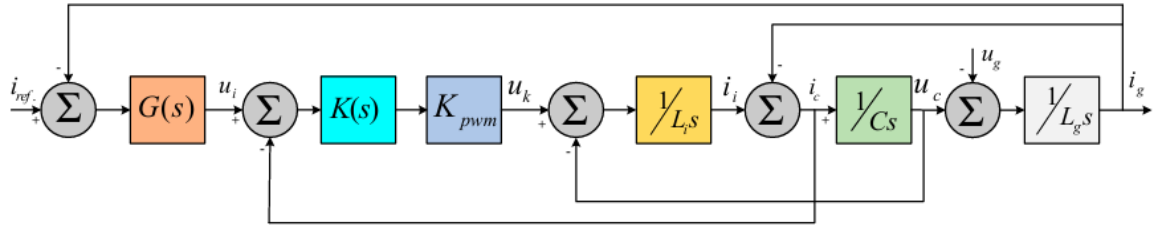


Figure 2.43. One-leg block diagram of a dual-loop current control strategy for VSI.

2.9 Damping Techniques for Grid-Connected VSIs

In grid-connected systems, the LCL filter reduces harmonic distortion and regulates voltage at the Point of Common Coupling (PCC) to control active and reactive power, However it introduces resonance that may cause instability, leading to damping methods classified as (i) Passive damping and (ii) Active damping [61, 62].

2.9.1 Passive Damping

Passive damping reduces the resonant peak by adding passive components to the filter [63] without modifying the control strategy, However, it decreases filter attenuation and increases power losses [64], A common method is adding a series resistor with the capacitor [65], but it leads to higher losses, lower attenuation, and larger filter size [61], Figure 2.44 shows the passive damping method for a grid-connected voltage source inverter (VSI).

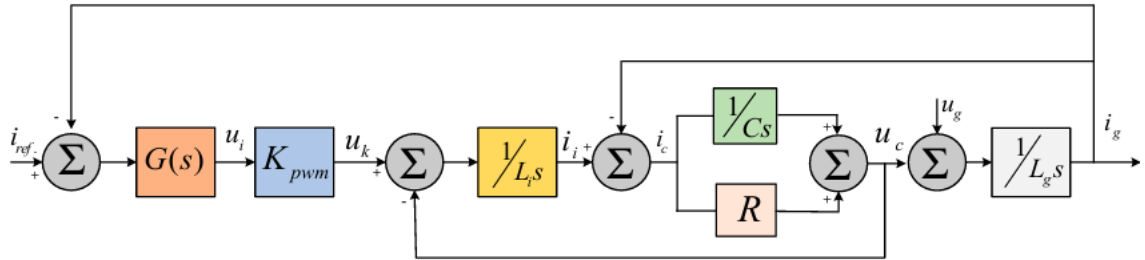


Figure 2.44. A Single-Leg Block Diagram for a Passive Damping Control Strategy in a Grid-Connected VSI.

2.9.2 Active Damping

Active damping approaches have been created to address the limitations of passive damping systems. These techniques entail modifications to the control policy to facilitate closed-loop damping. Active damping techniques are typically classified into three separate categories:

- 1) single loop,
- 2) multi-loop, and

3) Complex controllers.

Single-loop techniques mitigate LCL filter resonance without additional measurements, including the low-pass filter method, virtual flux estimation (sensor-less), splitting capacitor method, notch-filter method, and grid current feedback. They are generally robust against parameter uncertainties and grid inductance variations [66].

Multi-loop schemes use extra measurements such as capacitor current feedback, capacitor voltage feedback, and weighted average current control. A third category relies on advanced control systems, providing optimal and robust dynamic response [67], including predictive control, state-space controllers, adaptive controllers, sliding mode controllers, and vector control.

With an LCL filter, current regulation can be based on either grid current or converter current. Despite many proposed methods, no clear consensus exists in the literature, making careful selection necessary. A comprehensive active damping method combining damping resistance and a harmonic compensator is presented in [68]. Figure 2.45 shows the generalized active damping control approach for a grid-connected voltage source inverter (VSI).

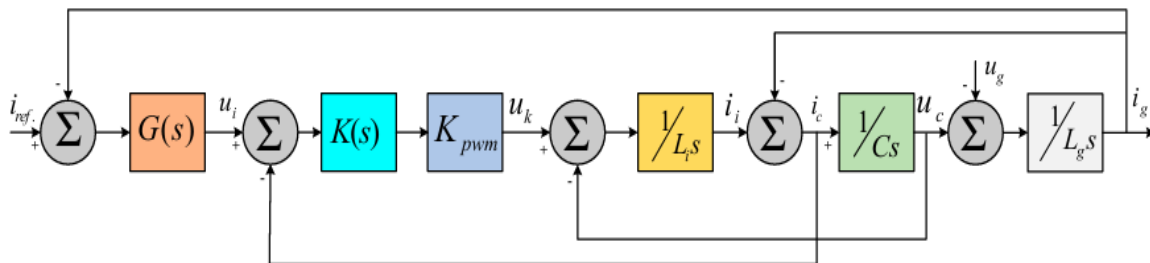


Figure 2.45. Block Diagram of a Single-Leg Active Damping Control Strategy for Grid-Connected VSI.

2.10 Grid Synchronization Techniques

To achieve optimal output in a utility network, it is essential to synchronize the grid voltage with the injected current. In the synchronization process, the phase of the grid voltage vector is taken into account, and control variables, such as grid voltages and currents, are aligned accordingly. Numerous methods for phase angle extraction have been presented in the literature [69]. Below, we examine some widely adopted techniques from reputable studies:

2.10.1 Zero-Crossing Technique

The Zero-Crossing method is considered the simplest approach for implementation. Nevertheless, it is hardly employed in extensive applications owing to the suboptimal performance results documented in the literature. This problem is especially evident during voltage swings, resulting in substantial harmonics and notches.

2.10.2 Filtering of Grid Voltages

The grid voltages can be filtered both in the dq and $\alpha\beta$ reference frames. Voltage filtering enhances the effectiveness of the zero-crossing method [69]. However, extracting the phase angle from the utility voltage, particularly under fault conditions, proves to be a complex task. This technique utilizes the arctangent function to determine the phase angle. Typically, a delay is encountered in signal processing when employing the filtering method. As a result, the design of the filter must be approached with careful consideration.

2.10.3 Phase Locked Loop Technique

The Phase-Locked Loop (PLL) is widely used to determine the grid voltage phase angle in the dq -synchronous reference frame. It performs an abc -to- dq transformation, setting the reference voltage $\hat{u}_d$ to zero for phase locking. A Proportional-Integral (PI) controller regulates the reference variable, while a Voltage-Controlled Oscillator (VCO) generates the utility voltage phase angle, which is then used in the $\alpha\beta$ to dq transformation. Figure II.45 shows the basic PLL structure.

Although effective in eliminating harmonics and disturbances, improvements are needed under asymmetrical voltage conditions. Filtering algorithms must isolate the negative sequence to prevent second-order harmonics from affecting phase estimation, and accurate positive-sequence phase detection under unbalanced conditions is essential [69].

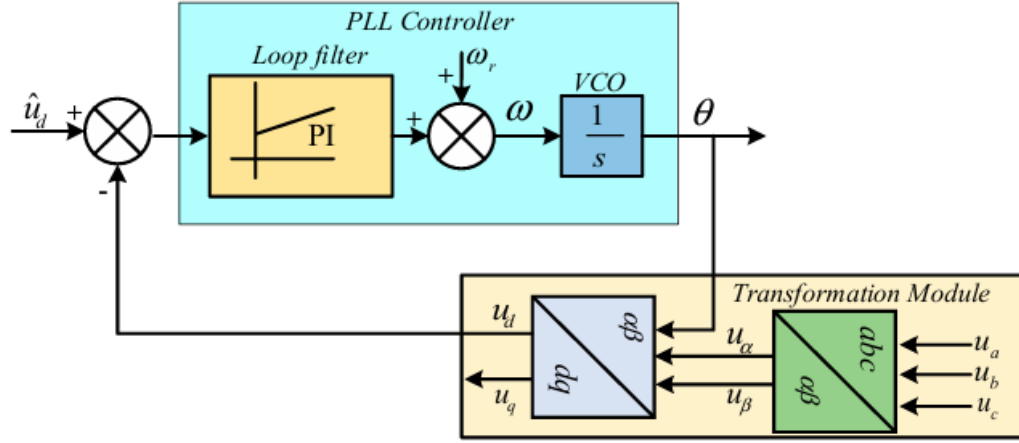


Figure 2.46. Overview of the Three-Phase PLL Technique Structure.

2.11 Controllers Reference Frames

Control systems can be utilized in both single-phase and three-phase synchronous reference frames. The reference frames are aligned using precise formulations to assure compatibility, hence easing the modeling, design, analysis, and transformation of one-phase and three-phase systems. The application of these reference frames, as detailed below, facilitates the simplification of intricate systems, especially in the context of multi-level converters[70] .

2.11.1 Reference Frame: abc

A three-phase system is typically implemented in the abc reference frame without the need for any transformation. For each phase current in the abc frame, a separate controller is utilized. When designing the control system, it is important to account for both delta and star connections. Non-linear controllers are employed in this configuration because of their quick dynamic response.

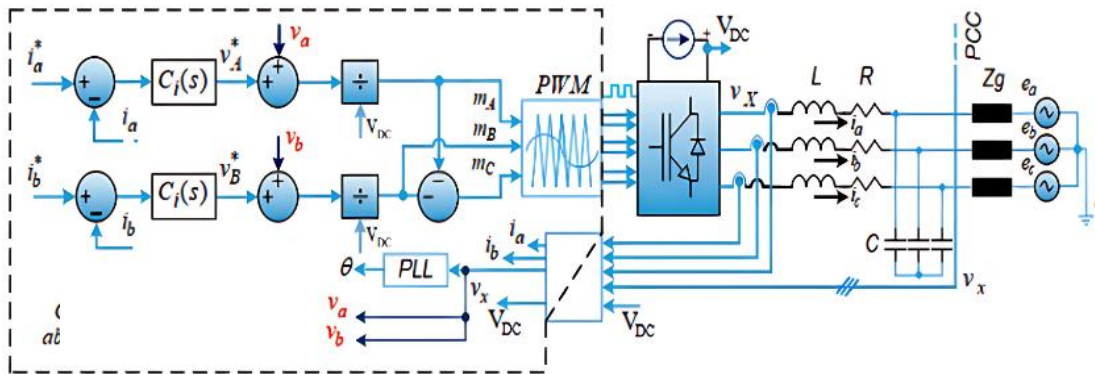


Figure 2.47. Generalized reference frame configuration of abc .

2.11.2 Reference Frame: dq

This framework is applied in three-phase systems. Park's Transformation facilitates the conversion of the abc frame into the dq frame. Through this transformation, the current and voltage waveforms are mapped to a reference frame that rotates in synchrony with the grid voltage. Consequently, the system variables are transformed into direct current (DC) values, making them more manageable for control and filtering when necessary.

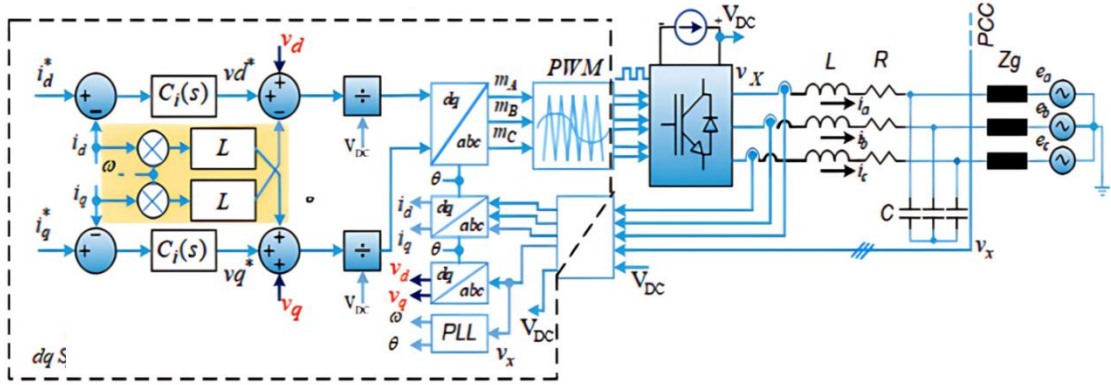


Figure 2.48. Generalized reference frame configuration of dq.

2.11.3 Reference Frame: $\alpha\beta$

This framework is predominantly utilized in three-phase systems and seldom in single-phase systems. The grid current is transformed from the abc or single-phase frame to a stationary reference frame using Clark's transformation. Thus, employing this transformation allows the control variable to be articulated as sinusoidal numbers.

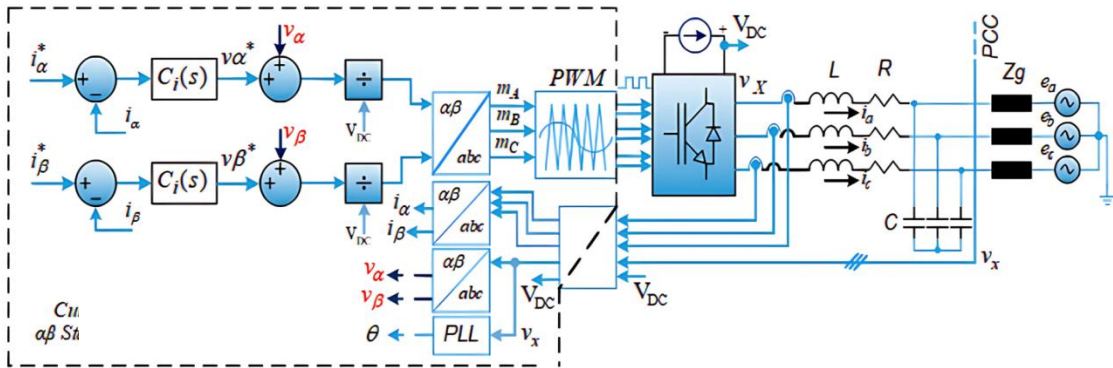


Figure 2.49. Generalized reference frame configuration of $\alpha\beta$.

2.12 Conclusion

This chapter presented a detailed study of the modeling and control of grid-connected PV systems, stressing the importance of precise modeling to ensure optimal energy conversion under varying irradiance and temperature conditions. It explained the role of DC-DC converters (buck, boost, and buck-boost) in regulating and adapting PV voltage, as well as the significance of MPPT techniques such as P&O and InC for maximizing power extraction.

Furthermore, the chapter discussed Voltage Source Inverter (VSI) control strategies, including PI and advanced methods, together with PWM techniques (SPWM, SVPWM) to enhance power quality and reduce harmonics. Finally, PLL-based synchronization was highlighted as a key element for stable and reliable grid integration. Overall, this chapter provides a solid theoretical and practical foundation for advanced research in grid-connected PV systems.

Chapter 3: Case Study, Simulation Results and Discussion

3.1 Introduction

Solar energy has emerged as a preeminent renewable energy solution to mitigate the energy crisis and environmental pollution [1]. This is attributed to its notable advancements, driven by heightened global consciousness regarding climate change and reduced reliance on fossil fuels. Governments across the globe have enacted incentivization measures to promote the utilization of sustainable energy sources, resulting in the widespread adoption of grid-connected photovoltaic (PV) systems [2]. These PV systems facilitate the seamless integration of solar power into the prevailing electrical grid infrastructure, thereby furnishing a dependable and environmentally benign electricity generation paradigm.

The imperative of addressing the energy crisis and mitigating pollution has propelled the rapid advancement of solar energy. This impetus has concurrently fostered the growing penetration of grid-connected photovoltaic (PV) systems [1]. Climate variables, such as temperature and solar radiation, as well as converter and controller design, have an impact on the efficiency of grid-connected PV systems. Weather conditions being uncontrollable, the selection of converter and controller designs becomes crucial for system performance [3]. The power converter facilitates In a grid-connected PV system, energy is transferred between PV panels and the electrical grid. Typically, two main topologies exist, determined by the number and type of converters employed [4].

Incorporating Maximum Power Point Tracking (MPPT) algorithms and advanced inverter control strategies in grid-connected photovoltaic (PV) power generation systems ensures the system's operation at an optimal state, maximizing power output. Through dynamic these control techniques maintain stability and optimize conversion efficiency, enabling the system to operate consistently its maximum power point [5]. When faced with interference and external constraints, meeting the requirements for tracking efficiency becomes challenging [6]. The authors in reference [7]. provide comprehensive literature reviews to facilitate detailed analyses and examinations. And designs a PV-grid connected power system controller using a highly efficient and reliable inverter topology. The study focuses on improving PV system performance through an enhanced HERIC inverter topology for MPPT operation and developing a suitable control system. It includes analysis,

utilization factor derivation, and digital simulations to validate and compare with conventional HERIC inverter systems.

Grid-connected photovoltaic (PV) inverter control technology has emerged as a prominent area of research. Conventional control techniques encompass linear approaches, like PI-based feedforward decoupling control [8]. However, Steady-state current errors arise on the alternating current (AC) side due to the PI controller's exposure to low-frequency fundamental components. In addition to employing PI-controller-based current control techniques for eradicating steady-state errors, several alternative approaches, including hysteresis control, have been suggested to diminish current errors [9].

The inverter establishes the connection between the photovoltaic (PV) system and the electrical grid and holds paramount significance. These inverters incorporate transformers to regulate the direct current (DC) voltage supplied to the inverter and to provide isolation between the PV system and the grid [7]. This proposal presents an advanced adaptive control method for a distributed generation system that uses a 3-phase inverter. The design of this control method is complex and time-consuming, as it involves adjusting the T_s parameter. Additionally, the parameter tuning process needs to account for various operating conditions. To improve system performance and responsiveness, the proposed method incorporates predictive control techniques, such as multi-step testing, rolling optimization, and feedback correction [10]. and model predictive control (MPC) [11]. In [12], [2]. MPC has been successfully implemented in comparable photovoltaic system configurations. Utilizing LC models for MPC offers a significant benefit by presenting a comprehensive description of the converter's dynamic behaviour across all operational states, eliminating the need to explicitly list or assume a predetermined sequence of modes or switching times. And, In [13]. MPC is a powerful approach that effectively addresses the challenges posed by uncertain and nonlinear processes. It can handle multiple constraints associated with spatial state variables. By establishing a predictive model of the system, Choosing the control mode that minimizes the evaluation function will result in optimal control. Also, in [14].

This chapter investigates the performance of a power electronic converter using a finite control set model predictive control (FCS-MPC) technique. Furthermore, the efficacy of the algorithm is evaluated by employing statistical model checking methodologies.

One of the unique characteristics of the conventional FCS-MPC is its ability to handle multiple goals. [15]. As previously indicated, single-phase PV inverters using traditional FCS-MPC perform worse than three-phase inverters, the limited number of switching actions available to single-phase inverters leads to increased output current ripples. Additionally, the injected current into the grid fails to meet standard requirements in terms of quality [16]. Numerous endeavours have been made within scholarly publications to enhance switching sequences and enhance the cost function diminish output ripples [17]. However, for single-phase inverters, the limited availability of switching states presents a greater challenge from a technical and scientific standpoint [18].

This chapter presents a standard procedure for the widely used predictive control method. The technique eliminates the requirement for PWM blocks by using a set switching frequency for 3-phase voltage source inverters. Rather, the suggested approach chooses the best voltage states by taking the reference current's slope into account alone. Using double-loop PI regulation, a popular control strategy for PWM inverters, as the foundation, this method entails creating a feed forward decoupling control scheme. The fundamental elements of this technique are the design of an outside loop with DC voltage, an inner loop with current, and PI regulators.

3.2 Configuration and Dynamic Modeling of the Proposed Energy System

Figure (3.1) show cases the typical configuration of a two-stage photovoltaic (PV) grid-connected system. Wherein an isolation transformer is absent. The system primarily comprises a PV module, a DC-DC converter, and a DC-AC inverter [12]. The load on the grid side is represented by RL. The PV module effectively converts solar energy into direct current (DC), while the DC-DC converter serves to amplify the output voltage of the PV module. This amplification is necessary since the PV module's voltage output is typically low. Subsequently, the DC-AC inverter converts the augmented DC power into alternating current (AC) power, which is then transmitted to the grid via a filter.

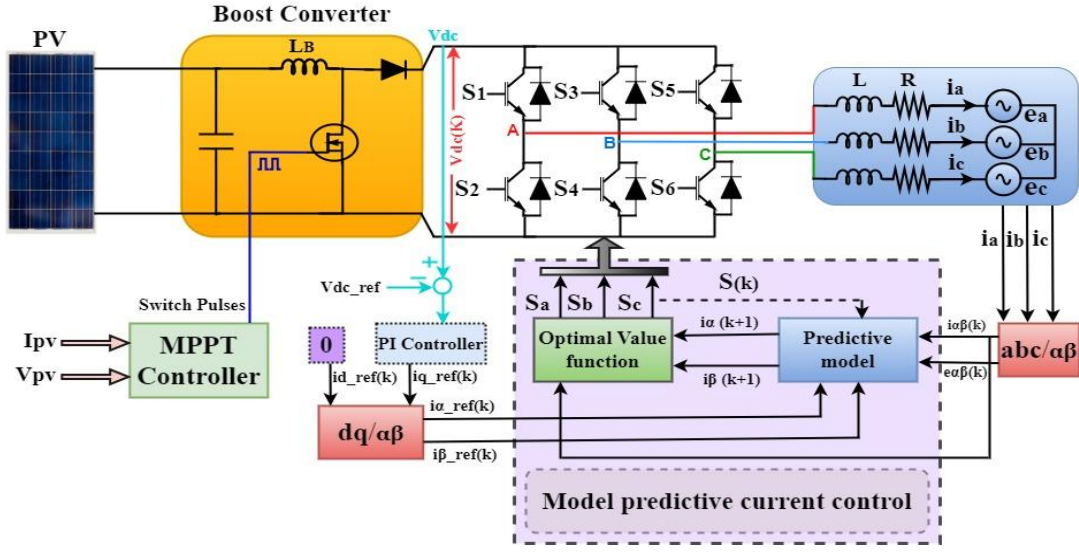


Figure 3.1. FCS-MPC Grid-connected PV power generation system's topological structure.

3.2.1 Proposed System Control

The proposed PV grid-tied system employs three distinct controllers, each serving a specific function. The first controller, known as the Maximum Power Point Tracking (MPPT) controller, is responsible for fine-tuning the operating point of the photovoltaic (PV) system. It achieves this by controlling the duty cycle of the boost converter connected to the PV system, ensuring it closely matches the MPPT conditions. The second controller is designed to regulate the voltage on the DC link, and it accomplishes this by generating a reference grid current. Lastly, the third controller focuses on regulating the grid current of the 3-phase transformer less inverter controller. Detailed analysis of these three control schemes is provided in the subsequent subsections [21].

3.2.1.1 Maximum Power Point Tracking (MPPT)

The optimization of a photovoltaic (PV) system's power extraction is of paramount importance. Achieving maximum power output from the system necessitates its operation at the condition known as the maximum power point (MPP) [22]. The utilization of maximum permissible photovoltaic (PV) power is facilitated through the implementation of the Maximum Power Point Tracking (MPPT) algorithm, specifically employing the incremental conductance (INC) method. This approach offers enhanced monitoring a solar panel's maximum power output and enhanced dynamic performance in situations involving rapid and frequent changes [23]. the attainment of the Maximum Power Point (MPP) can

be determined by monitoring the temporal variations in power (ΔP) and voltage (ΔV). Upon the point where the alteration in power or voltage reaches zero, it signifies the accomplishment of the MPP, according to [24].

$$\begin{cases} \Delta P / (\Delta V) < 0 & \text{the MPPT condition at the curve's right side} \\ \Delta P / (\Delta V) = 0 & \text{at the MPPT condition} \\ \Delta P / (\Delta V) > 0 & \text{the MPPT condition's left side at the curve} \end{cases}$$

The P&O approach is well-known and supported in the literature. It performs extremely well under conditions of constant sun exposure. Nonetheless, the P&O is easily locked at a local maximum when there is partial shade. It is presented here for comparison and validation purposes. The P-V characteristics are the primary determinant of the P&O technique's performance. On the left side of the MPP, the slope of these features is positive, while on the right side, it is negative. [25].

The MPPT algorithm establishes the desired current for the current-regulated boost converter, maintaining optimal conditions for maximum power point tracking, as illustrated in Figure (3.2) Subsequently, the hysteresis controller effectively adjusts the photovoltaic (PV) Repeating Sequence by the MPPT algorithm, achieved by generating a binary ON/OFF state for the boost converter switch

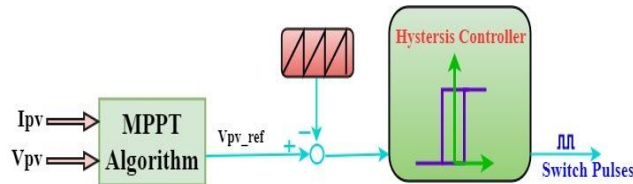


Figure 3.2. Block schematic of an MPPT controller.

3.2.1.2 The DC Link's voltage regulator

The objective of this controller is to uphold a stable voltage on the DC link at a pre-established value (v_{dc}^*), thereby ensuring optimal system operation. This is accomplished by controlling the power transfer from the photovoltaic (PV) side to the grid side through the generation of a reference root mean square (RMS) value for the grid current (I_d^*), as illustrated in Figure (3.3) To preserve system reliability, this controller operates at a narrower bandwidth compared to the inverter controller.

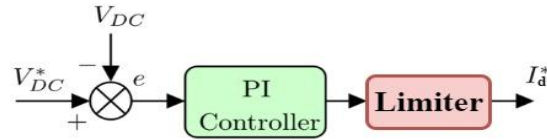


Figure 3.3. DC Link's voltage regulator.

3.3 Results and discussion

A MATLAB simulation model is developed to validate the viability of the control approach. The FCS-MPCC algorithm is encoded using the S-function to execute the control effect. The sampling interval is established as 2×10^{-5} seconds, and the simulated system's parameters are presented in Table 1.

Table 3.1. Parameters of the simulated system

Parameters of the PV module	value	Parameters of the system	value
I_{sc} [A]	9	L [H]	$10e-3$
T_r [°C]	25	f [Hz]	50
P [KW]	5.75	C [F]	0.005
N_s	300	T_s [S]	$1e-5$
R_s/Ω	0.2		

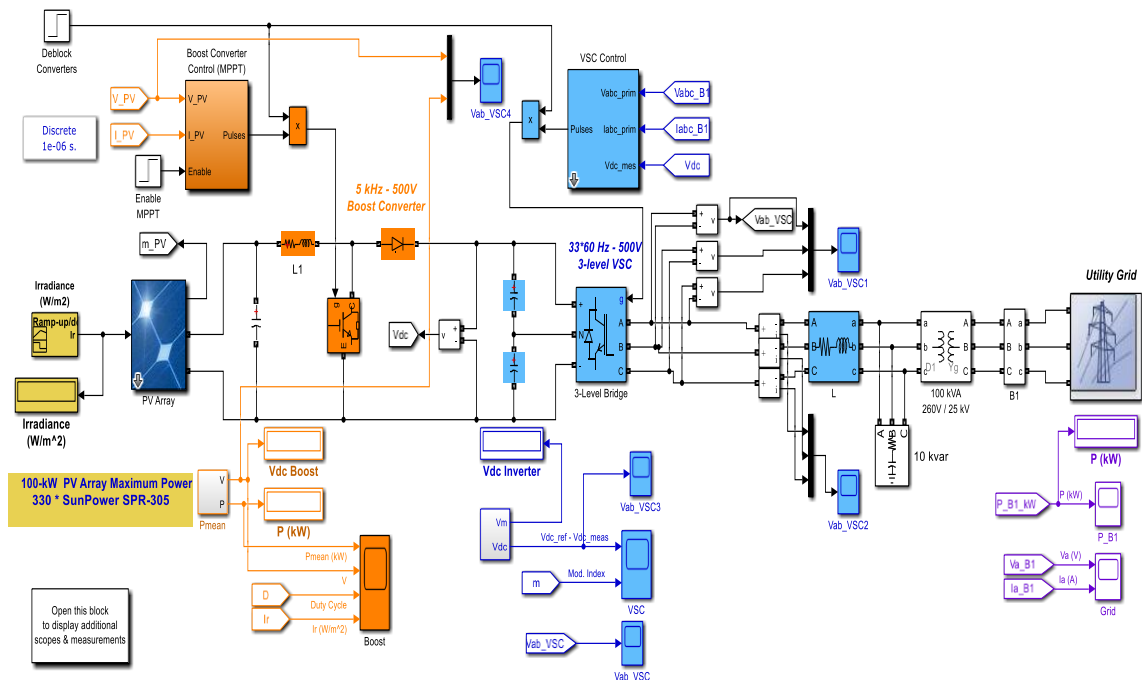


Figure 3.4. Simulation model in the MATLAB

This diagram represents a grid-connected photovoltaic (PV) power system. The solar panels generate direct current (DC) electricity from sunlight, and the MPPT controller adjusts the operation of the panels so they always produce maximum power. The DC voltage then passes through a Boost converter, which raises it to a higher level, while the DC link capacitor stabilizes this voltage.

A three-phase inverter (VSC) converts the DC voltage into alternating current (AC). The control system synchronizes the inverter with the grid and regulates the output current. The current passes through a filter to remove harmonics and obtain a clean sinusoidal waveform, then through a transformer to match the grid voltage level. Finally, active power is injected into the utility grid while voltage, current, and power are measured.

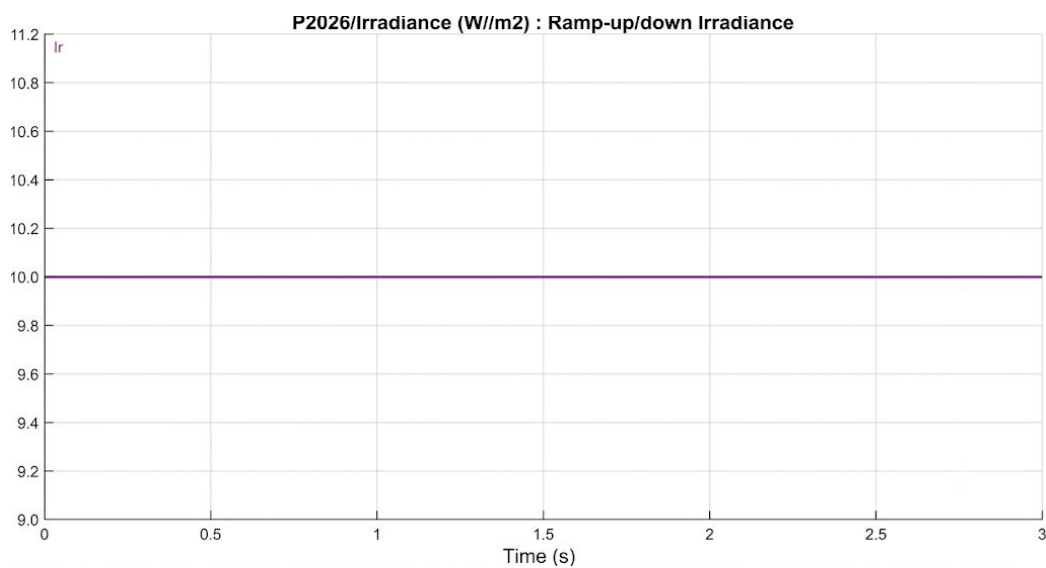


Figure 3.5. Solar rays [w/m2]

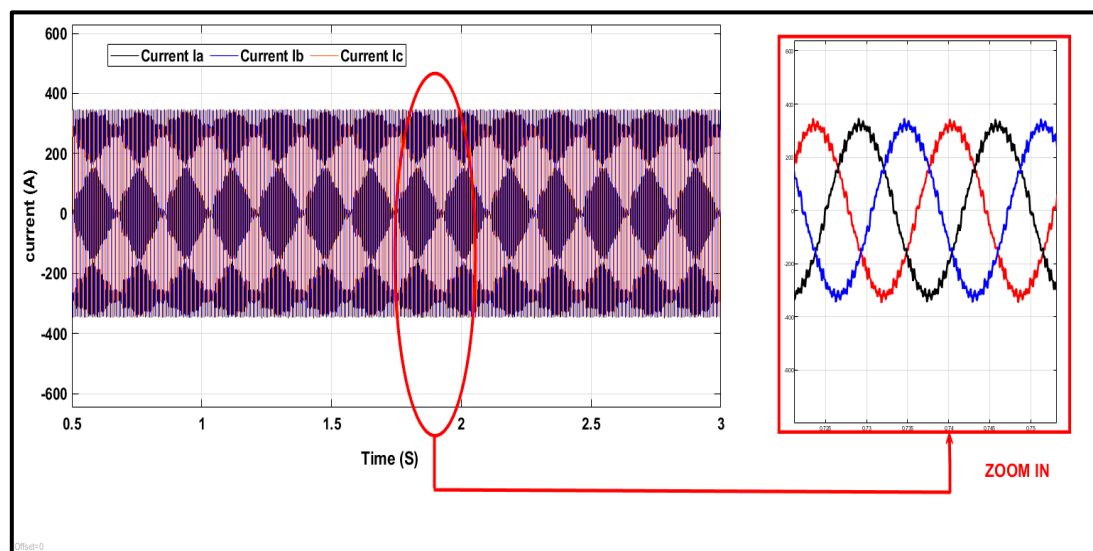


Figure 3.6. Converter current

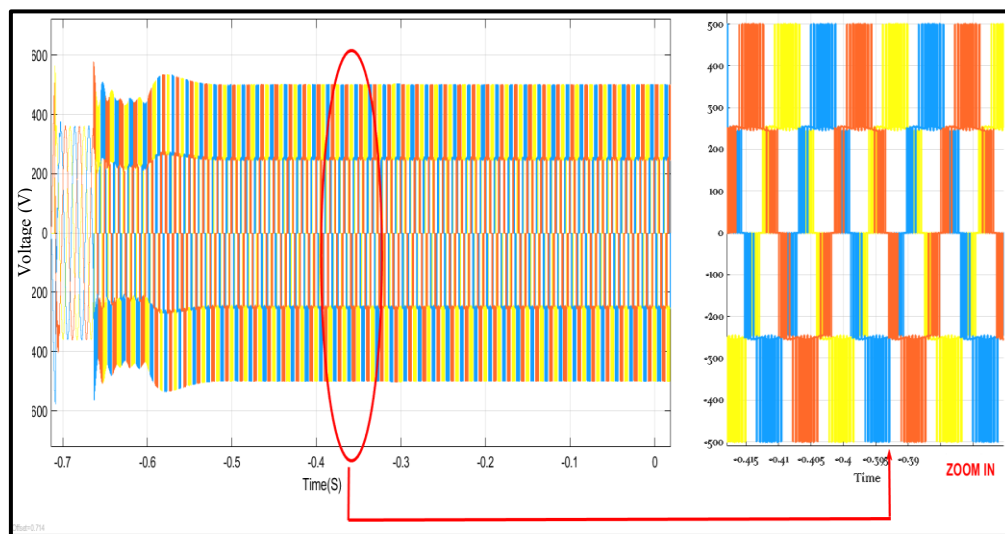


Figure 3.7. voltage Results

The results obtained are as follows, Figure 3.5: The initial solar intensity at 0 seconds is 600 W/m^2 , which decreases to 500 W/m^2 after 1.5 seconds. Figure 3.7 Displays The grid current, which aligns with the generated reference currents from the current controllers, exhibits a decrease in peak value proportional to the reduction in irradiation level.

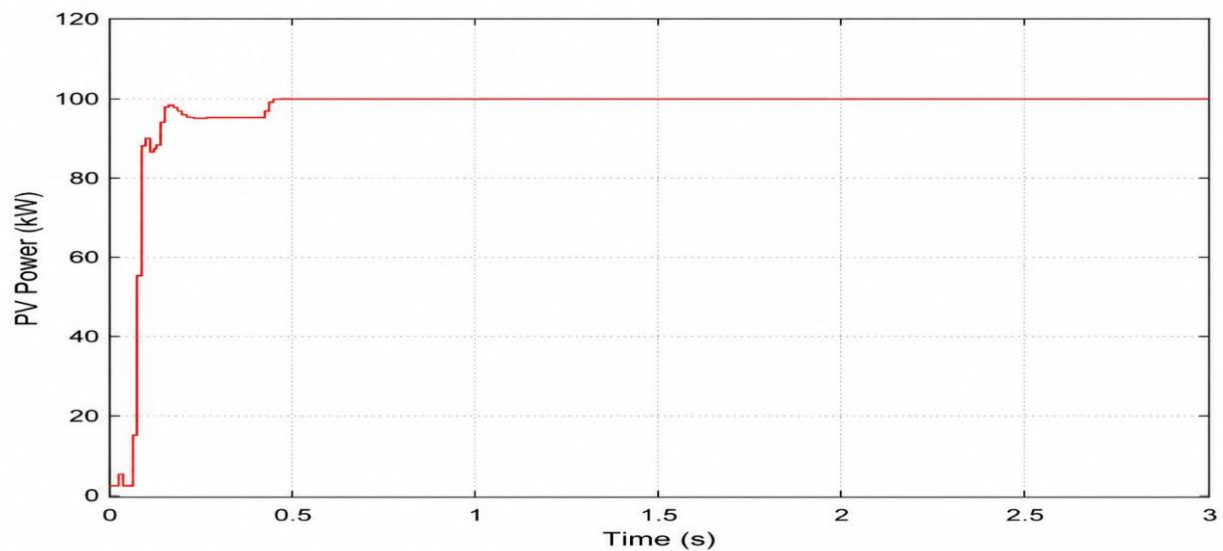


Figure 3.8. PV panel power extraction profile

the power values of the solar panel and the elevator's converter can be compared. It is evident that the boost converter possesses a higher power value. The power fluctuations observed in the upconverter can be attributed to the dynamic processes of charging and discharging the inductor

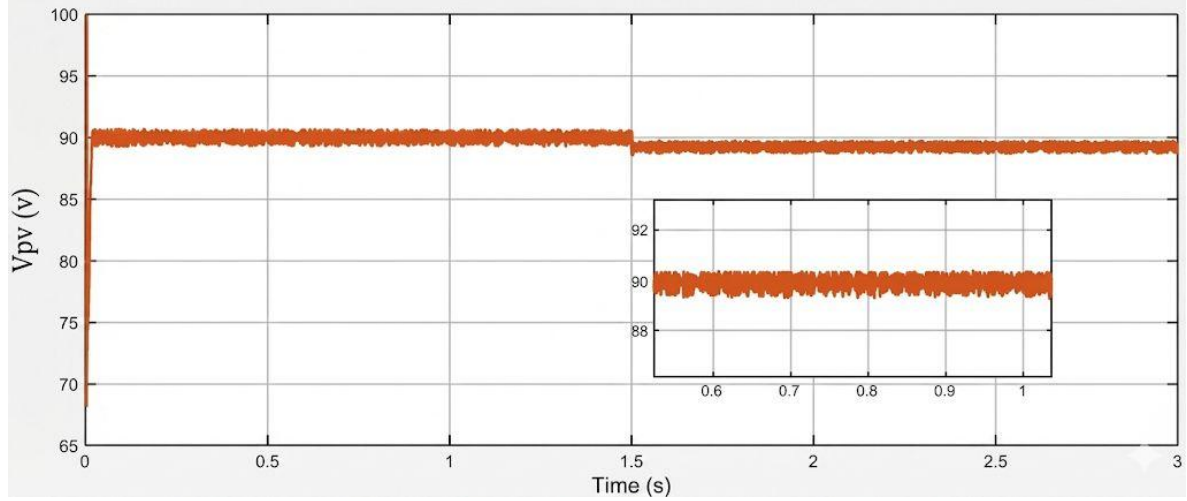


Figure 3.9. PV voltage corresponding MPPT controller

the voltage at the solar panel and the boost converter can be described as follows:

the power generated by the boost converter is higher due to its boosting capability. The fluctuations observed in the power are attributed to the charging and discharging of the inductance within the system. Additionally, there is a decrease in power from the boost converter after 1.5 seconds, caused by a non-linear drop in solar radiation intensity, despite an increase in the voltage at the solar panel.

To compensate for insufficient power, the MPPT system strives to maximize capacity by increasing the input voltage (V_{in}). This adjustment necessitates a modification in the expulsion mechanism, resulting in a lower output voltage (V_{out}) for the boost converter.

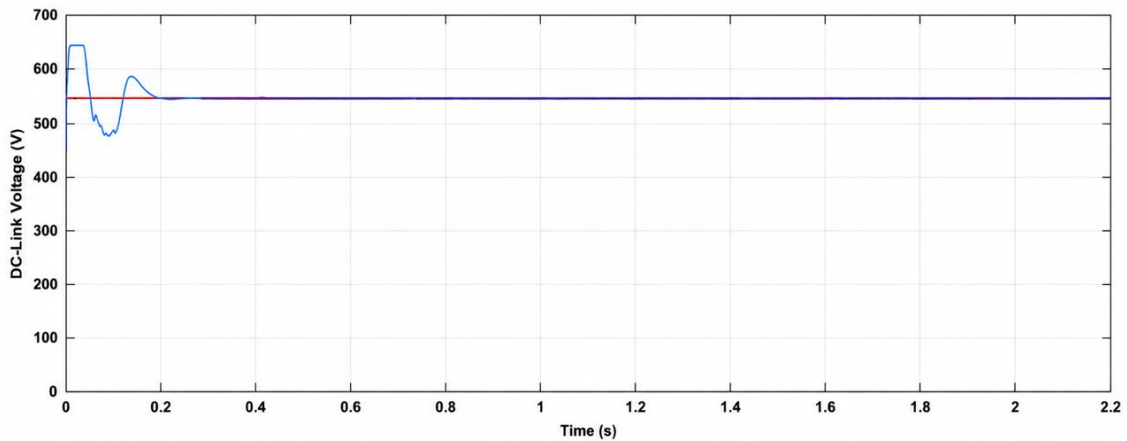


Figure 3.10. Dynamic response off DC-link voltage for proposed system

Observations from the dc-link voltage tracking reveal that the conventional PI control method is significantly influenced or impacted As shown in the Figure 3.9.

The Figure 3.10 shows The solar panels exhibit initial current values, which subsequently decrease after 1.5 seconds due to an increase in temperature. The temperature-induced power loss prompts the MPPT controller to determine the maximum power capacity based on the solar panels' characteristics. As a result, the current value is lower than its previous level.

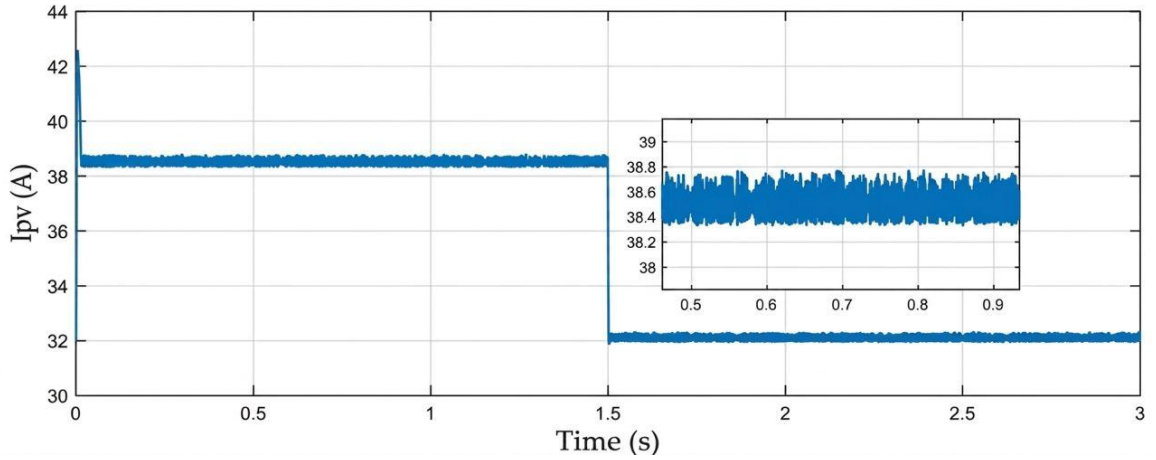


Figure 3.11. PV current corresponding MPPT controller

3.4 Model predictive control (MPC)

Recent progress in digital signal processors (DSPs) has played a crucial role in the rise of Model Predictive Control (MPC) as an effective and promising digital control strategy. MPC has found wide application in power electronics, variable-speed motor drives, and energy conversion systems, gaining significant popularity in diverse industrial sectors due to its adaptability and high efficiency [17].

Model Predictive Control (MPC), in contrast to traditional control methods, is a nonlinear control strategy that provides enhanced performance, particularly in power converter applications [18, 19]. This approach overcomes various technical and operational challenges associated with conventional control methods, particularly in systems operating at low switching frequencies, which are crucial for energy conversion systems at the megawatt scale.

Model Predictive Control (MPC) offers significant advantages for systems with rapidly changing electrical variables, positioning it as an optimal solution for high-performance power conversion applications. Notable benefits of MPC include:

The system features an easy-to-implement design that is compatible with digital controllers. It eliminates the need for proportional-integral (PI) controllers and avoids the use of pulse-width modulation (PWM). The system ensures fast dynamic response and steady-state performance under various operating conditions. It offers robust compensation for disturbances and delays, integrates nonlinearities and system constraints smoothly, and enables effective multivariable control with decoupling [20].

MPC functions by employing a system model to forecast the future behavior of a specified control variable, subsequently determining the optimal control action according to a predefined optimization criterion. In the context of power electronics, MPC methods are typically classified into four primary categories, as shown in Figure III.1: deadbeat control, hysteresis-based control, trajectory-based control, and model predictive control (MPC) [19, 21].

These classifications emphasize the various approaches in predictive control, each offering unique benefits suited to particular applications in power electronics and energy conversion systems.

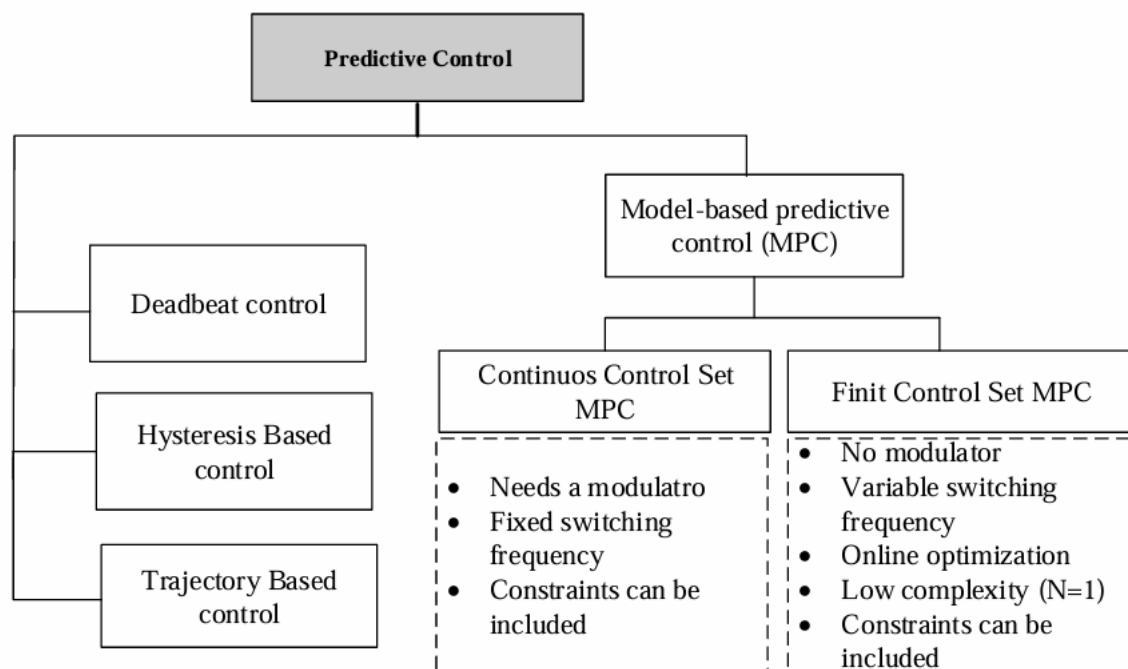


Figure 3.12. Classifications of predictive control methods.

Hysteresis-based predictive control aims to maintain the controlled variable within a hysteresis band, while trajectory-based control follows a specific reference trajectory. Deadbeat control ensures error reduction to zero at the next sampling instant. Model Predictive Control (MPC) minimizes a cost function for optimization, making it an effective strategy for power converters and electrical drives. MPC is valued for its flexibility in handling multivariable systems, nonlinearities, constraints, and faster dynamic responses. It relies on mathematical models to predict behavior and optimize control objectives.

MPC techniques applied to power electronics are generally classified into two main categories [22, 23]:

- **Continuous Control Set MPC (CCS-MPC):** This method considers control variables as continuous and utilizes an average converter model for optimization, aiming to minimize the error between the references and predicted future states. As depicted in Figure 3.12 (a), the controller generates a reference duty cycle, which is subsequently processed by a modulator to determine the required switch positions. The modulator's role guarantees that the converter operates at a constant switching frequency.
- **Finite Control Set MPC (FCS-MPC):** Contrary to CCS-MPC, the approach illustrated in Figure 3.12 (b) takes advantage of the discrete characteristics of power converters by directly selecting the optimal switching states. It systematically evaluates all potential switching combinations and identifies the one that minimizes the predefined cost function, thereby removing the requirement for a modulator.

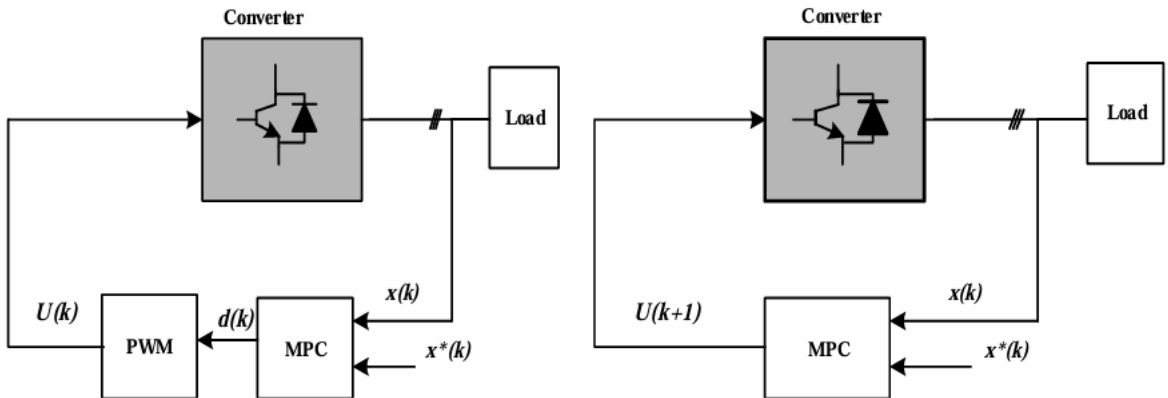


Figure 3.13. (a) Continuous Control Set MPC (CCS-MPC). (b) Finite Control Set MPC (FCS-MPC).

3.5 Principle and basic structure of MPC

Model Predictive Control (MPC) is an effective control strategy for Two-Level inverters and other multilevel inverters, offering high precision, fast transient response, and discrete characteristics. It operates on a discrete-time model to predict future control variable behavior using current switching states [19, 20, 24].

The MPC framework (Figure 3.13) predicts future system states over a defined horizon using the system model and real-time measurements. It optimizes control actions by minimizing a cost function, applying the first action while continuously updating predictions and adjustments at each sampling step.

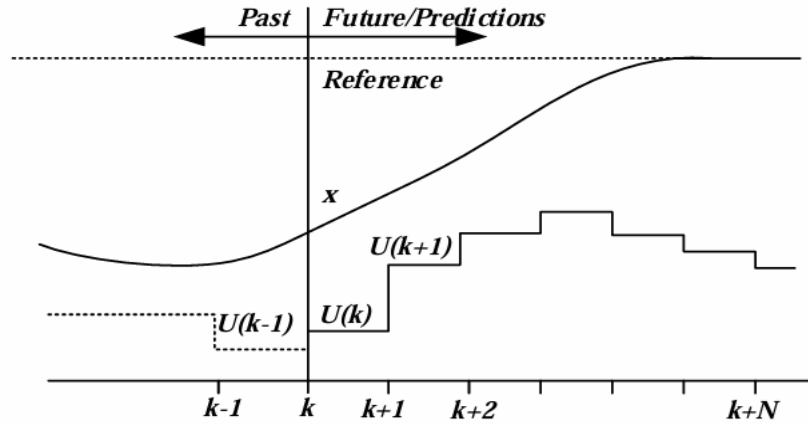


Figure 3.14. Working principle of MPC.

The general structure of a Model Predictive Control (MPC) scheme is depicted in Figure 3.14. The MPC design process involves a systematic series of steps aimed at achieving optimal control performance:

- **Acquisition of Feedback Signals:** The necessary feedback signals are obtained for use in the predictive model or for reference calculation.
- **Reference Calculation and Prediction:** The reference control variable is determined based on the specific application requirements. Future reference values are then estimated using extrapolation techniques.
- **System Modeling:** The mathematical representation of the system is established by deriving equations that describe the dynamic behavior of the controlled variables. In general, a linear model is employed, expressed as:

$$\frac{dX}{dT} = AX + BU \quad \text{III.1}$$

Where X represents the state variables to be controlled (such as voltage, current, flux, or power), and U denotes the control input (such as grid voltage, switching state, or DC voltage).

- **Discretization of the System Model:** A discrete-time formulation is essential for forecasting the progression of control variables, which are assessed according to the cost function. To achieve discretization, the first-order forward Euler method is employed due to its computational simplicity and sufficient precision in ensuring dependable performance. The system's discrete-time representation is expressed as follows:

$$\frac{dx}{dt} \simeq \frac{x(k+1) - x(k)}{T_s} \quad \text{III.2}$$

Where T_s is the sampling time, $x(k+1)$ and $x(k)$ is the value of the controlled variable in the next sampling time and at the current state, respectively.

- **Cost Function Minimization:** The predicted values of the control variables $x_i^P(k+1)$ are compared with their reference values $x^*(k+1)$ using a predefined cost function g formulated as::

$$g = |x^*(k+1) - x_i^P(k+1)|, i = 1, \dots, n \quad \text{III.3}$$

The optimization process minimizes g by selecting the optimal switching state that aligns predicted values with the reference trajectory, eliminating the need for a separate modulation block and simplifying system design.

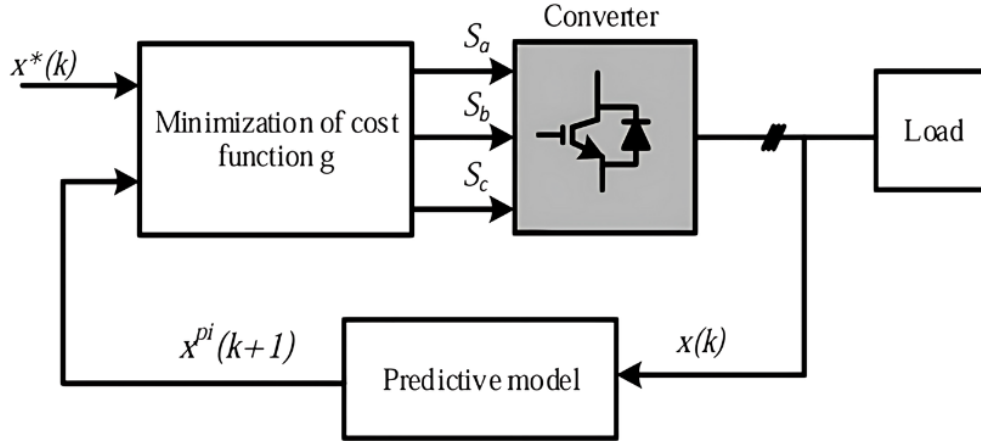


Figure 3.15. Model predictive control scheme for power converters.

3.6 Setup and Adaptive Modeling of the Suggested Energy Framework

Figure 3.15 illustrates a system incorporating a DC-AC inverter [8]. The system employs an RL circuit for the grid-side load, with the inverter facilitating DC-AC conversion and transmitting power to the grid through a filter. It follows a standard configuration, highlighting the inverter's key role in integrating renewable energy into the grid.

The investigated system facilitates the conversion of DC power, derived from sources such as photovoltaic (PV) arrays, battery storage units, or other DC-based energy systems, into AC power through a DC-AC inverter. The inverter's functionality is governed by Finite Control Set Model Predictive Control (FCS-MPC), optimizing power conversion efficiency and ensuring seamless grid integration.

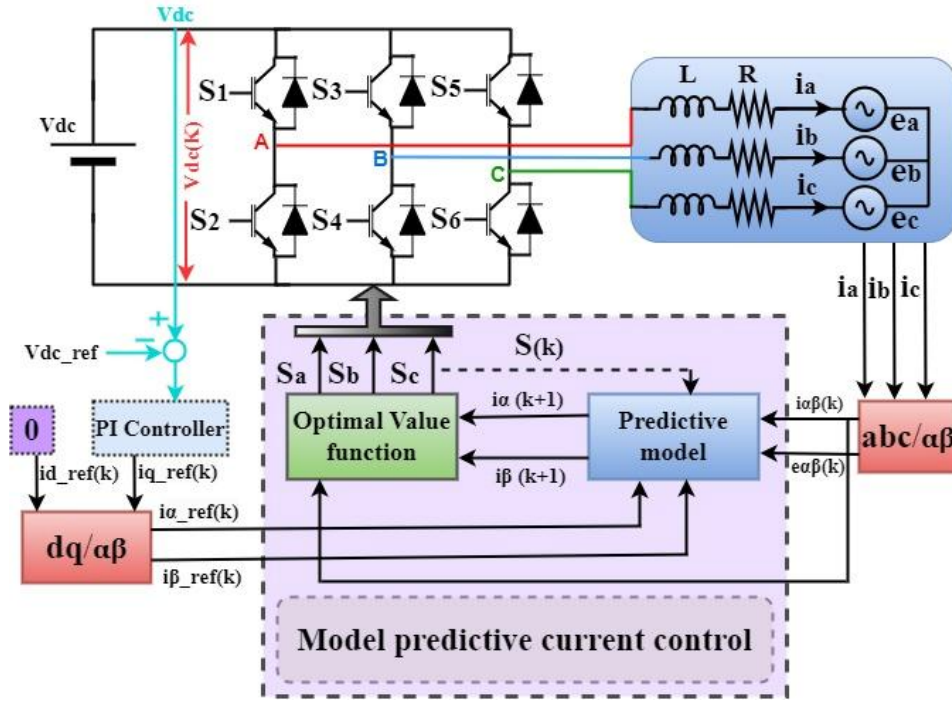


Figure 3.16. The topological structure of the FCS-MPC Grid-connected PV power generating system.

3.7 Regulation of the DC Link Voltage

This controller stabilizes the DC-link voltage at a predefined reference (v_{dc}^*), optimizing system performance by regulating the reference RMS grid current (I_d^*). This ensures efficient power transfer from the PV system to the grid (Figure 3.16). Operating within a narrower bandwidth than the inverter controller, it enhances system stability and reliability.

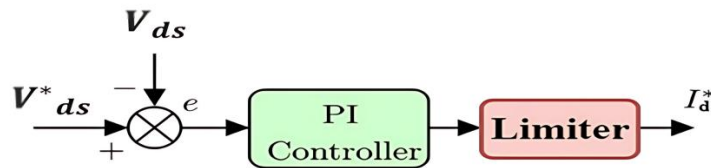


Figure 3.17. DC Link's voltage regulator.

3.8 Predictive Model Control Approach for Three-Phase Inverters

3.8.1 Converter model

The transformation of electrical energy from direct current (DC) to alternating current (AC) is executed via the power circuit of a three-phase inverter, as depicted in Figure 3.17. To mitigate the risk of short circuits, each phase of the inverter employs two switches

functioning in a complementary manner, thereby guaranteeing the system's operational safety and reliability [25].

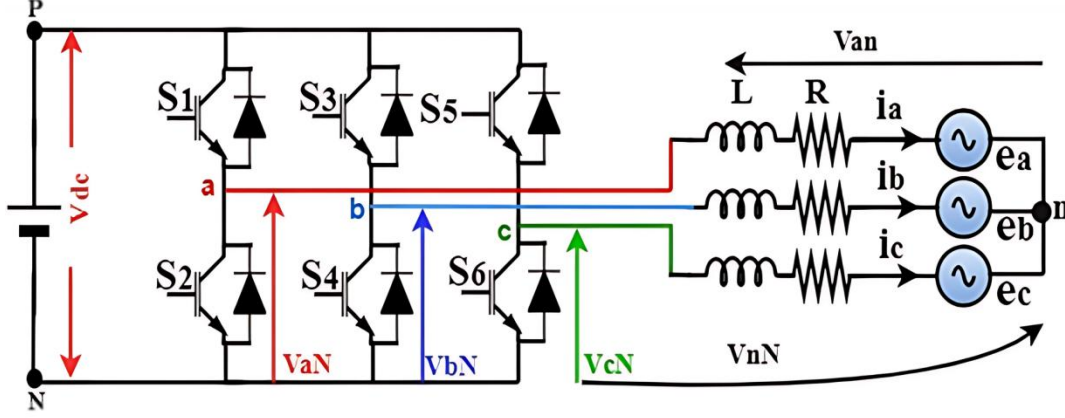


Figure 3.18. Voltage Source Inverter Power Circuit.

The DC power source and the operational states of switches S_1 through S_6 can be effectively characterized through the switching signals S_a , S_b , and S_c , as delineated in the subsequent formulation:

$$S_a = \begin{cases} 1 & \text{if } S_1 \text{ on and } S_2 \text{ off} \\ 0 & \text{if } S_1 \text{ off and } S_2 \text{ on} \end{cases} \quad \text{III.4}$$

$$S_b = \begin{cases} 1 & \text{if } S_3 \text{ on and } S_4 \text{ off} \\ 0 & \text{if } S_3 \text{ off and } S_4 \text{ on} \end{cases} \quad \text{III.5}$$

$$S_c = \begin{cases} 1 & \text{if } S_5 \text{ on and } S_6 \text{ off} \\ 0 & \text{if } S_5 \text{ off and } S_6 \text{ on} \end{cases} \quad \text{III.6}$$

The dynamic behavior of the load current for each phase can be described based on the defined variables illustrated in Figure 3.17. The corresponding formulation for each phase is expressed as follows.

$$U_{an} = L \frac{di_a}{dt} + Ri_a + e_a + U_{nN} \quad \text{III.7}$$

$$U_{bn} = L \frac{di_b}{dt} + Ri_b + e_b + U_{nN} \quad \text{III.8}$$

$$U_{cn} = L \frac{di_c}{dt} + Ri_c + e_c + U_{nN} \quad \text{III.9}$$

The system representation fundamentally relies on three essential parameters: the load inductance L , load resistance R , and the electromotive force e of the grid, as they collectively influence its overall performance and behavior.

3.8.2 Model Predictive Current Control (MPC) for a Three-Phase Inverter

Model Predictive Control (MPC) for three-phase inverters utilizes historical and current system states to predict future inverter current values over the next switching cycle. This is achieved through a complex mathematical model implemented in the sampling period T_s of the predictive control technique. By employing an optimal value function, the controller determines the most suitable switching combination to ensure accurate current tracking [26]. The value function for system optimization and the predictive model are formulated according to the following specifications [27]. The algorithmic flowchart outlining the predictive current control process is presented in Figure 3.18.

The Model Predictive Current Control with Constraints (MPCC) framework fundamentally relies on the predictive model as its core computational structure. The prediction of future current values at the subsequent time step $(k + 1)$ is derived through this approach.

3.9 Application of the Forward-Euler Method in Discretization

The Forward-Euler technique is a prevalent numerical method for estimating a function's derivative within discrete-time frameworks. Due to its simplicity in arithmetic operations, it remains an effective and computationally efficient option for modeling applications.

The discretization process employing the Forward-Euler method estimates the derivative as follows:

$$\frac{di}{dt} \approx \frac{i(k + 1) - i(k)}{T_s} \quad \text{III.10}$$

Using the Forward-Euler method, discretized into the following form.

$$\begin{cases} i_\alpha(k + 1) = \left(1 - \frac{RT_s}{L}\right) i_\alpha(k) + \frac{T_s}{L} (v_\alpha(k) - \hat{e}_\alpha(k)) \\ i_\beta(k + 1) = \left(1 - \frac{RT_s}{L}\right) i_\beta(k) + \frac{T_s}{L} (v_\beta(k) - \hat{e}_\beta(k)) \end{cases} \quad \text{III.11}$$

To enhance the predictive control model, an alternative mathematical formulation is utilized, where $\hat{e}(k)$ represents the estimated back EMF, and the superscript "p" denotes predicted variables. The predicted current at time step K+1 is given by:

$$i^p(k+1) = \left(1 - \frac{RT_s}{L}\right) i(k) + \frac{T_s}{L} (V(k) - \hat{e}(k)) \quad \text{III.12}$$

$$\hat{e}(k-1)$$

The estimated back EMF at the previous step ($k-1$) is determined using:

$$\hat{e}(k-1) = V(k-1) - \frac{L}{T_s} i(k) - \left(R - \frac{L}{T_s}\right) i(k-1) \quad \text{III.13}$$

Assuming that the variation of back EMF over a sampling interval is negligible due to its relatively low frequency compared to the sampling rate, it can be approximated as:

$$\hat{e}(k) = \hat{e}(k-1) \quad \text{III.14}$$

The performance index of prediction error is formulated to minimize the deviation between the predicted and reference currents at time step k+1. The optimal switching action is determined by selecting the switching state that minimizes this difference. The value function is defined as:

$$g = |i_\alpha^*(k+1) - i_\alpha^p(k+1)| + |i_\beta^*(k+1) - i_\beta^p(k+1)| \quad \text{III.15}$$

This function ensures that the system tracks the reference current accurately by selecting the most appropriate switching combination from the set of predicted values.

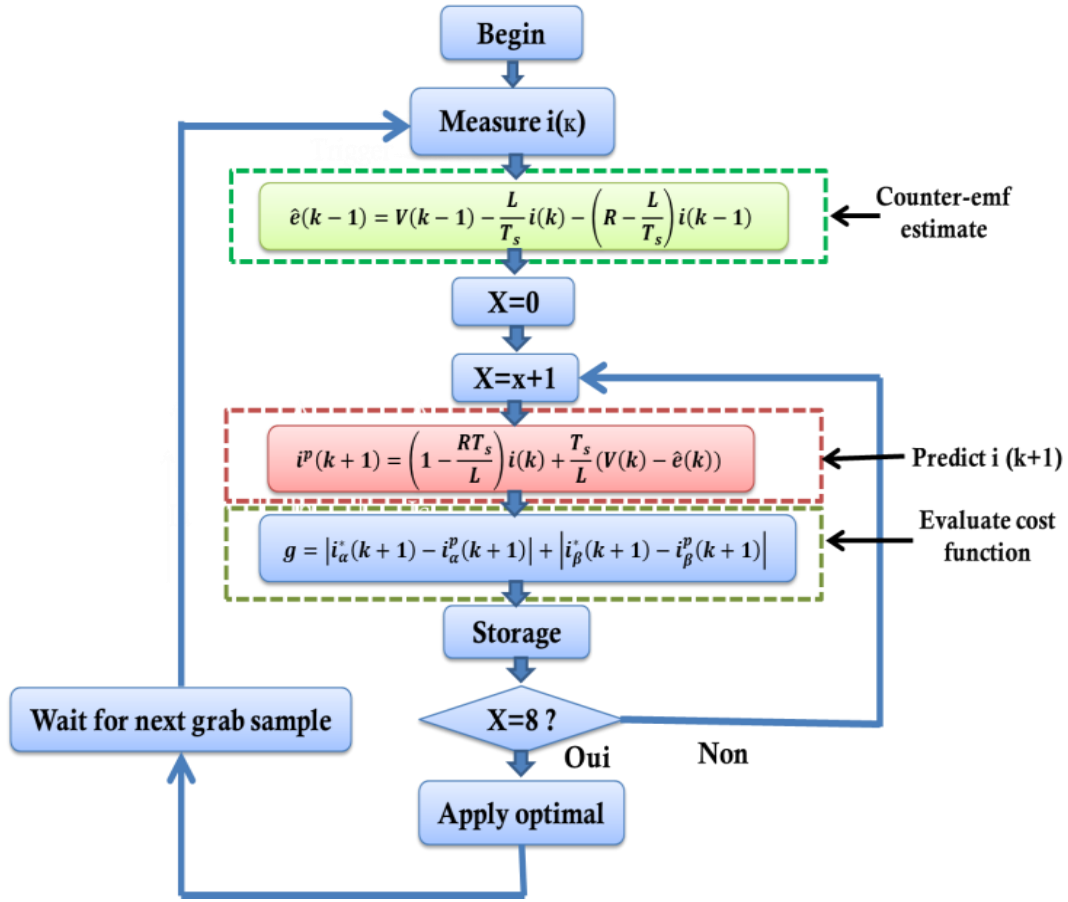


Figure 3.19. The algorithm flowchart of predictive current control.

3.10 Voltage-Adaptive MPC for Common-Mode Voltage Reduction

When a balanced three-phase power supply is connected to a load with a specific impedance, the Common Mode Voltage (CMV) is defined as the potential difference between the load's neutral point and either the electrical ground or the DC link midpoint [28]. To minimize Total Harmonic Distortion (THD), mathematical analysis determined the optimal duration and sequencing of voltage vectors [29]. The inverter's output voltage equations are as follows:

$$\begin{cases} v_{AN} = v_{AO} + v_{ON} \\ v_{BN} = v_{BO} + v_{ON} \\ v_{CN} = v_{CO} + v_{ON} \end{cases} \quad \text{III.16}$$

By addition we have:

$$\begin{aligned} v_{AN} + v_{BN} + v_{CN} \\ = v_{AO} + v_{BO} + v_{CO} + 3v_{ON} \end{aligned} \quad \text{III.17}$$

Considering the symmetrical nature of the satirical three-phase voltage system:

$$v_{AO} + v_{BO} + v_{CO} + 3v_{ON} = 0 \quad \text{III.18}$$

From equations 16 and 17, we can deduce the following results.

$$v_{ON} = -\frac{1}{3}(v_{AO} + v_{BO} + v_{CO}) \quad \text{III.19}$$

Where v_{AO} , v_{BO} and v_{CO} the voltages of the three phases collectively contribute to an average voltage, which signifies the shared component among all phase voltages. This shared component serves as a measure of the Common Mode Voltage (CMV).

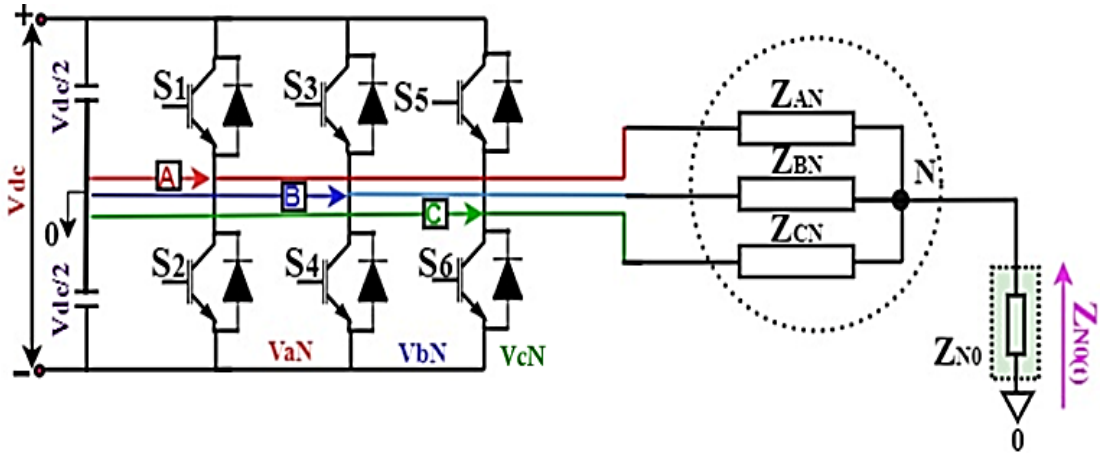


Figure 3.20. Three-Phase Two-Level VSI Supplying a Star-Connected Load.

A two-level, three-phase voltage source inverter (VSI) constitutes a key element in power converter systems and is extensively utilized in variable speed drives. As depicted in Figure 3.19, this topology functions with a DC-link voltage maintained at $V_{dc}/2$, facilitating power transfer to a star-connected grid.

The grid is characterized by phase impedances Z_{AN} , Z_{BN} , and Z_{CN} which define the electrical characteristics of each phase. Additionally, a parasitic impedance (Z_{N0}), exists between the grid's neutral point and ground, representing the capacitive coupling effect [30].

Based on the given parameters, the offset vector is determined as the nearest switching state to the zero Common Mode Voltage (CMV) plane of the reference vector. Three possible selected vectors correspond to distinct CMV values:

1. The first vector has a CMV of $-V_{dc}/6$.
2. The second vector has a CMV of $+V_{dc}/6$.

3. The third vector has a CMV of zero.

The reference vector defines a two-level subcube, with its vertices corresponding to these vectors. The remaining coordinates are derived using additional vectors, forming a total of seven vectors arranged within a hexagonal structure [31]. The CMV transitions by either $V_{dc}/6$ or $-V_{dc}/6$ during voltage changes in each phase. To ensure CMV remains within the designated range of $\pm V_{dc}/6$, specific vectors must be excluded from the switching process [32].

CMV mitigation in power electronic systems is achieved by excluding zero voltage vectors (V_0, V_7) from the switching sequence, preventing simultaneous high-side switch transitions and reducing input terminal potential differences [33], using only non-zero voltage vectors (V_1 – V_6) minimizes CMV, but additional techniques like differential amplification, shielding, and grounding may be required for effective attenuation [34].

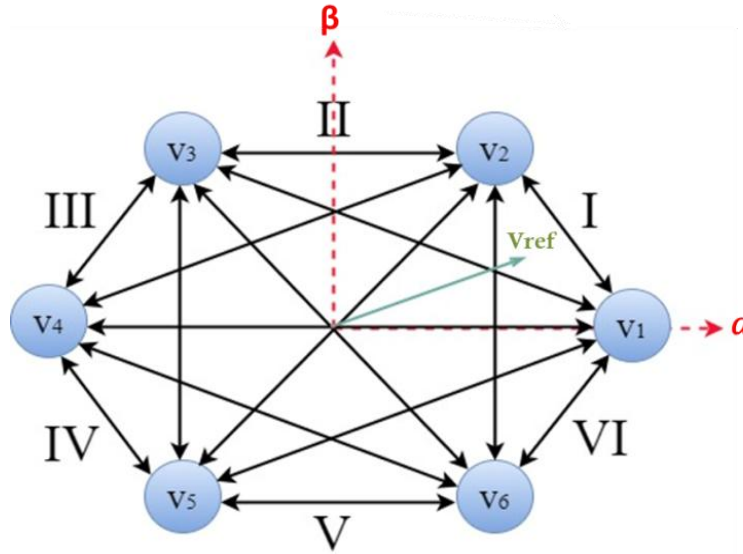


Figure 3.21. Space voltage vector distribution of a two-level inverter.

The algorithmic pre-selection of non-zero voltage vectors (V_1 – V_6) requires evaluating switching frequency and load characteristics. Despite its complexity, this approach enhances performance and efficiency in advanced power electronic systems.

Model Predictive Control (MPC) optimizes Common Mode Voltage (CMV) minimization in power converters while ensuring adaptive and precise regulation. By dynamically computing optimal control actions, MPC enhances efficiency, reliability, and overall system performance amid varying conditions and disturbances.

3.11 Simulation result

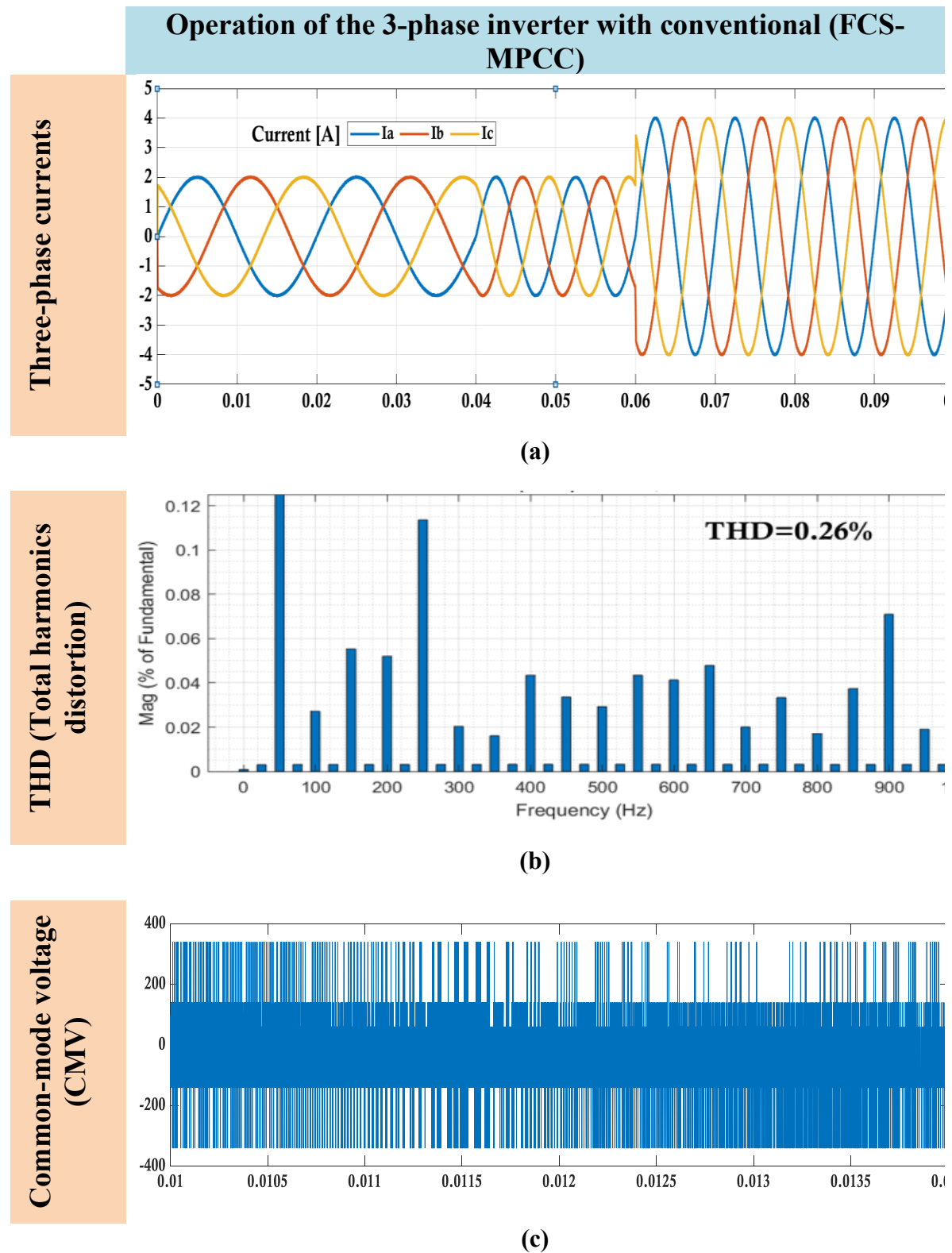


Figure 3.22. Operation of the 3-phase inverter with conventional (FCS-MPCC). (a) Three-phase currents. (b) THD. (c) CMV.

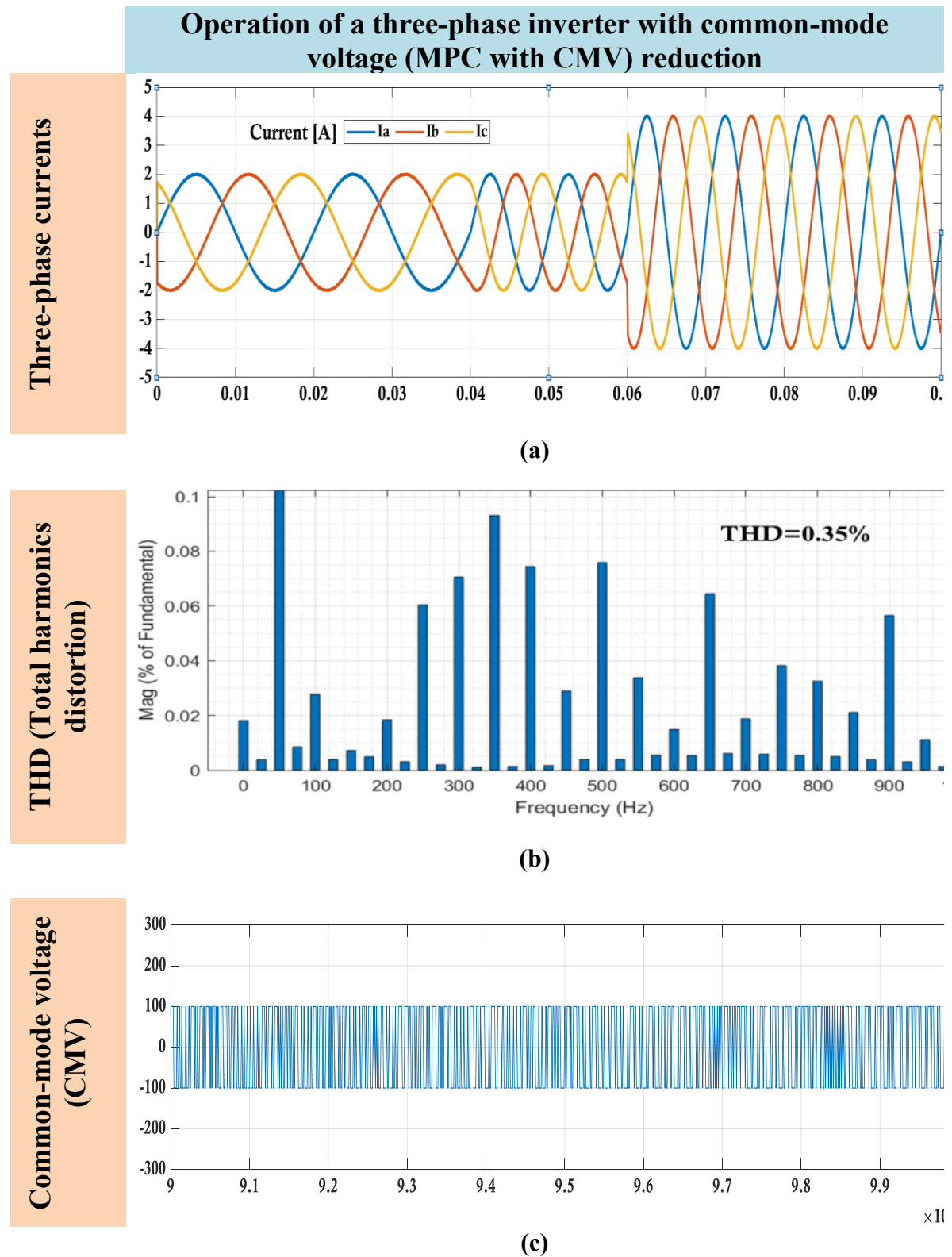


Figure 3.23. Operation of a three-phase inverter with (CMV) reduction. (a) Three-phase currents.(b) THD. (c) CMV.

Figure 3.21 evaluates the performance of a three-phase inverter controlled by the conventional FCS-MPCC method. Figure 3.21 (a) confirms the sinusoidal nature of the currents and the control strategy's robustness across a frequency range of 50 Hz to 100 Hz. These findings highlight its adaptability to varying operating conditions. Figure 3.21 (b) presents the Total Harmonic Distortion (THD) of the currents (0.26% and 0.35%), while Figure 3.21 (c) illustrates the Common Mode Voltage (CMV) of the inverter.

Figure 3.22 presents the performance analysis of a three-phase inverter utilizing the Common Mode Voltage (CMV) technique. In Figure 3.22 (a), the plotted three-phase currents exhibit sinusoidal characteristics, reflecting their expected behavior. Figure 3.22 (b) displays the Total Harmonic Distortion (THD) measurement of the currents, with a recorded value of approximately 0.35%. Additionally, Figure 3.22 (c) illustrates the CMV of the three-phase inverter.

The comparison of CMV values obtained using various strategies, as illustrated in Figures 3.21 (c) and 3.22 (c), underscores the effectiveness of the proposed approaches. In Figure 3.21 (c), the CMV simulation based on the FCS-MPCC method, which includes zero vectors, results in an inverter CMV reaching a maximum of $V_{dc}/2$. This higher CMV level leads to increased power losses and may compromise the stability and safety of the network. In contrast,

Figure 3.22 (c) illustrates the CMV results achieved through the proposed MPC integrated with CMV reduction strategies. The findings indicate a substantial reduction in CMV to $V_{dc}/6$, the theoretical minimum, underscoring the efficacy of the proposed method in mitigating CMV effects. This reduction contributes to enhanced system stability and overall performance, surpassing conventional approaches.

When comparing the performance analysis of the three-phase inverter using the conventional MPC technique (Figure 3.21) with the one employing the CMV-based technique (Figure 3.22), several distinctions can be observed.

Regarding the three-phase currents shown in Figures 3.21 (a) and 3.22 (a), both waveforms exhibit a sinusoidal profile, confirming that the current behavior aligns with theoretical expectations in both cases. However, in terms of total harmonic distortion (THD), Figure 3.21 (b) reports a THD of approximately 0.26% for the MPC-based inverter, whereas Figure 3.22(b) indicates a THD of about 0.35% for the CMV-based inverter. This

suggests that the CMV technique achieves a lower THD, implying a reduction in harmonic content compared to the conventional MPC approach.

The proposed MPC with CMV strategy enhances three-phase inverter performance, ensuring sinusoidal currents and robustness across 50–100 Hz. Experimental results show comparable THD levels (0.26% for FCS-MPC, 0.35% for MPC with CMV), confirming effective harmonic mitigation and improved power quality, validating its real-world applicability.

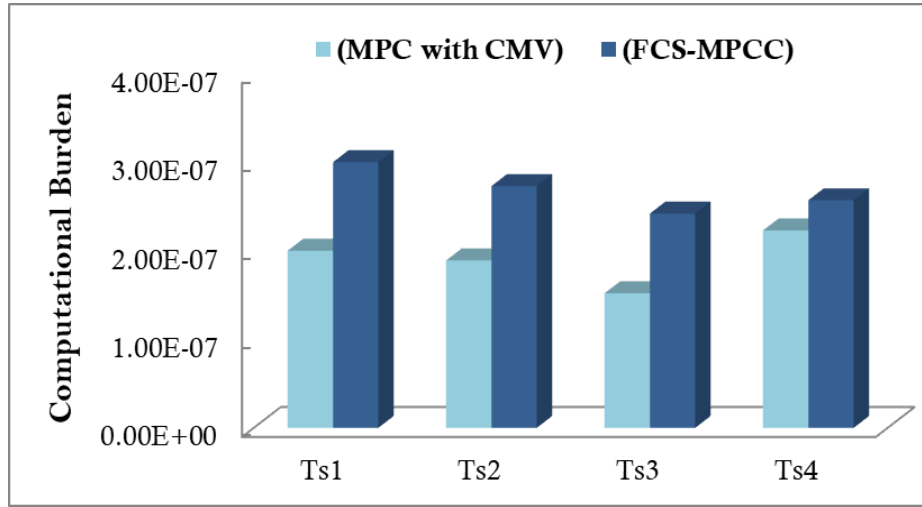


Figure 3.24. Comparison of Computational Burden for MPC with CMV and FCS-MPCC Methods across Different Sampling Times (Ts) in Predictive Algorithms.

Figure 3.23 presents a comparative analysis of the computational burden of MPC with CMV and FCS-MPCC across four sampling times (T_{s1} – T_{s4}) in predictive control. The results indicate that MPC with CMV consistently requires fewer computational resources than FCS-MPCC. At T_{s2} , for example, MPC with CMV has a computational burden of approximately $2e^{-7}$, compared to $3e^{-7}$ for FCS-MPCC, reflecting a reduction of $1e^{-7}$. Similar efficiency gains are observed at T_{s3} and T_{s4} , highlighting MPC with CMV as a more computationally efficient choice for resource-constrained predictive control applications.

3.12 Conclusion

The study introduced an integrated methodology that amalgamates finite control set and model predictive current control (FCS-MPCC) techniques to govern Vdc link in grid-connected systems featuring renewable energy sources. The articulated approach, coupled with Maximum Power Point Tracking (MPPT) for photovoltaic solar and Common Mode Voltage (CMV) suppression, exhibited noteworthy efficacy in elevating system stability

and reliability. Through extensive simulation-driven inquiries, the methodology adeptly forecasted inverter currents, opted for optimal voltage vectors, and proficiently curbed CMV. The outcomes substantiated the efficacy of the proposed methodology in augmenting the dependability and stability of grid-connected inverters, providing insightful perspectives for the optimization of grid-linked renewable energy systems and streamlining the integration of renewable energy into the grid. Rigorous simulation results and experimental validations were conducted, demonstrating impeccable concurrence and affirming the efficacy and advantages of our devised strategy.

General Conclusion

General Conclusion

In conclusion, examined in depth the integration of photovoltaic (PV) systems into electrical power grids, with a particular focus on the role of advanced control strategies in enhancing system performance, stability, and energy efficiency. In the context of the global energy transition and the increasing reliance on renewable energy sources, solar energy represents one of the most promising and widely available solutions for sustainable electricity generation.

However, despite its advantages, the integration of photovoltaic systems into electrical grids presents several technical challenges mainly related to the intermittent and variable nature of solar radiation. These fluctuations directly affect the stability of power generation and the quality of energy injected into the grid. For this reason, the present study has focused on improving PV system behavior through the use of advanced power electronics and intelligent control strategies.

The research has particularly investigated the role of power electronic converters, Maximum Power Point Tracking (MPPT) techniques, and Model Predictive Control (MPC) methods. The results highlight that these approaches significantly improve the dynamic performance of grid-connected photovoltaic systems, ensuring better adaptability to environmental variations and more stable operation under changing weather conditions.

- **Main Findings**

The study led to several important findings:

- ✓ The application of advanced control strategies, especially Model Predictive Control (MPC), greatly enhances the stability and dynamic response of grid-connected PV systems by anticipating system behavior and optimizing control actions in real time.
- ✓ Improved MPPT algorithms contribute significantly to maximizing energy extraction from photovoltaic panels, ensuring operation closer to the optimal power point even under rapidly changing solar irradiance.

- ✓ The integration of advanced inverter control techniques helps reduce Common-Mode Voltage (CMV) and significantly improves Power Quality by minimizing Total Harmonic Distortion (THD).
- ✓ The combination of predictive control and optimized power conversion systems leads to a more reliable, efficient, and grid-compliant photovoltaic energy system.
- ✓ Overall, the system becomes more resilient to environmental variations and better suited for large-scale renewable energy integration.

- **Recommendations**

Based on the results obtained, several recommendations can be proposed for future research and practical implementation:

- ✓ Further development of intelligent and adaptive control algorithms based on artificial intelligence and machine learning could significantly improve the real-time performance of PV systems.
- ✓ The integration of hybrid energy storage systems (such as batteries or supercapacitors) is recommended to compensate for the intermittency of solar energy and enhance grid stability.
- ✓ Future research should focus on reducing the computational complexity of Model Predictive Control (MPC) to make it more suitable for real-time industrial applications.
- ✓ More experimental validation and hardware implementation studies are needed to confirm the simulation results under real operating conditions.
- ✓ It is also recommended to explore multi-source renewable energy systems (solar-wind hybrid systems) to improve energy reliability and continuity.

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Chapter 3

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