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Improving Power Quality of Grid-Connected Solar Photovoltaic Systems Using Advanced Control Strategies

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بسم الله الرحمن الرحيم

GRATITUDE

First and foremost, I thank God Almighty for granting me the strength, patience, and perseverance to complete this journey. Without His blessings, none of this would have been possible.

I extend my deepest gratitude to my supervisor, Dr. BOUGUERNE Abla, for her unwavering support, insightful guidance, and constant encouragement, which were invaluable throughout the development of this dissertation.

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DEDICATION

To my beloved family,

To my father, BOUFEKER Omar, and my mother, GABBECH Rafika your endless love, sacrifices, and prayers have been the foundation of all my achievements. Thank you from the bottom of my heart.

To my dear sisters, Imane, Hadil, and Maram, and to my only brother, Salah thank you for your constant encouragement, kindness, and unwavering belief in me throughout this journey.

To my friends, who have stood by me through every challenge and every success your support has meant more to me than words can express.

This work is dedicated to all of you, with love and gratitude.

الملخص

تركز هذه الأطروحة على التحكم، النمذجة، والمحاكاة في أنظمة الطاقة الشمسية الكهروضوئية (PVالمربوطة بالشبكة، مع التركيز بشكل خاص على تحسين جودة الطاقة باستخدام استراتيجيات تحكم متقدمة. وتتمحور الدراسة حول مقارنة تقنيات التتبع الأقصى لنقطة القدرة ((MPPT، التي تُعد ضرورية لزيادة كفاءة الأنظمة الكهروضوئية. تم تنفيذ عدة خوارزميات MPPT وتقييم أدائها من حيث كفاءة التتبع، سرعة الاستجابة، وتعقيد الخوارزمية. وقد أُجريت محاكاة دقيقة لتقييم أداء كل تقنية في ظل ظروف بيئية مختلفة. وتُظهر النتائج مقارنة شاملة تبرز مزايا وقيود كل طريقة، مما يُساعد في اختيار استراتيجية التحكم الأنسب لتحسين جودة الطاقة وأداء التشغيل في الأنظمة الكهروضوئية المرتبطة بالشبكة.

الكلمات المفتاحية : نظام الطاقة الشمسية(PV) ، النمذجة الألواح الشمسية، التتبع الأقصى لنقطة القدرة(MPPT) ، خوارزميةP&O ، خوارزميةINC ، المنطق الضبابي، دراسة مقارنة.

Abstract

This dissertation focuses on the control, modeling, and simulation of grid-connected photovoltaic (PV) systems, with a particular emphasis on improving power quality using advanced control strategies. A key component of this study is a comparative analysis of various Maximum Power Point Tracking (MPPT) methods, which are essential for optimizing the efficiency of PV systems. Different MPPT algorithms are implemented and evaluated in terms of tracking efficiency, dynamic response, and algorithmic complexity. The performance of each technique is assessed through detailed simulations under varying environmental conditions. The results provide a comprehensive comparison that highlights the strengths and limitations of each method, thereby supporting the selection of the most suitable MPPT control strategy for enhancing the power quality and operational performance of grid-connected PV systems.

Keywords: PV system, Pv system Modeling, MPPT, P&O, INC, Fuzzy logic, Comparative study.

Résumé

Ce mémoire porte sur le contrôle, la modélisation et la simulation des systèmes photovoltaïques (PV) raccordés au réseau, avec un accent particulier sur l'amélioration de la qualité de l'énergie à l'aide de stratégies de commande avancées. L'étude repose principalement sur une analyse comparative des différentes méthodes de suivi du point de puissance maximale (MPPT), essentielles pour optimiser le rendement des systèmes PV. Plusieurs algorithmes MPPT sont implémentés et évalués selon leur efficacité de suivi, leur réponse dynamique et leur complexité algorithmique. Des simulations détaillées ont été réalisées dans diverses conditions environnementales pour analyser les performances de chaque méthode. Les résultats permettent une comparaison approfondie mettant en évidence les avantages et les limites de chaque technique, afin de choisir la stratégie de commande la plus adaptée pour améliorer la qualité de l'énergie et les performances des systèmes PV connectés au réseau.

Mots-clés : Système photovoltaïque (PV), modélisation d'un pv system, MPPT (suivi du point de puissance maximale), P&O, INC, logique floue, étude comparative.

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ABBREVIATION

Abbreviation	Full Term
PV system	Photovoltaic system
MPPT	Maximum Power Point Tracking
P&O	Perturb and Observe
INC	Incremental Conductance
FLC	Fuzzy logic controller
DC	Direct Current
AC	Alternating Current
Ipv	PV current
Vpv	PV vltage
Ppv	PV power
Vdc	DC Voltage
R	resistance
PWM	Pulse width modulation
g	Radiation
T	temperature
Rs	Series resistances
Rsh	Shunt resistances
d	duty cycle

GENERAL INTRODUCTION

Renewable energy represents a viable solution for several countries around the world that have chosen to adopt it. Renewable energy is derived from natural resources that replenish quickly enough to prevent depletion. Examples include solar photovoltaic (PV), solar thermal, wind, geothermal, and hydroelectric power. Among these, solar photovoltaic (PV) systems are currently considered the most suitable, optimal, and efficient for producing clean electricity energy [1].

Given the global energy transition and the variety of renewable resources available, energy producers are developing increasingly effective technologies to capture and convert solar energy into usable electricity. These technologies typically involve PV panels that convert solar radiation into direct current (DC), which can then be adapted and delivered to electrical loads or injected into the power grid. One of the key challenges lies in ensuring optimal energy extraction from PV systems under varying environmental conditions while maintaining cost-effectiveness for widespread adoption [1].

PV generators exhibit a non-linear Current-Voltage (I-V) characteristic, with a unique operating point where the extracted power is maximized known as the Maximum Power Point (MPP). This point varies with solar irradiance and temperature. To ensure continuous operation near the MPP, a DC-DC converter is placed between the PV generator and the load. This converter is controlled by Maximum Power Point Tracking (MPPT) algorithms, which dynamically adjust the operating point for optimal energy harvesting [2].

This study aims to evaluate and compare several MPPT control methods applied to PV systems, focusing particularly on conventional and intelligent approaches. The goal is to analyze their efficiency in tracking the MPP and maintaining system performance under real-world conditions.

This thesis is organized into four chapters:

Chapter I: presents a general overview of PV systems, including the photovoltaic effect, historical development, and the main types of systems: standalone, grid-connected, and hybrid. It also describes the modeling of core components such as the PV generator and boost converter and provides simulation results under varying conditions of irradiance and temperature. The advantages and disadvantages of PV systems are also examined.

Chapter II: explores the concept and theoretical basis of MPPT. It classifies different control techniques and focuses on conventional algorithms, namely Perturb and Observe (P&O) and Incremental Conductance (INC). Their implementation and simulation results are presented, followed by a comparative analysis.

Chapter III: introduces the theory of fuzzy logic and presents its application to MPPT in PV systems. It includes the design and simulation of a fuzzy logic controller, with performance evaluation under fluctuating weather conditions. The results are compared to those of conventional MPPT methods.

Chapter IV: investigates the operation of a grid-connected PV system controlled by a fuzzy logic-based MPPT algorithm. It presents the simulation architecture and results, demonstrating the stability, power quality, and performance of the system when integrated into the electrical grid.



CHAPTER I
OVERVIEW OF PV SYSTEMS



CHAPTER I

OVERVIEW OF PV SYSTEMS

I.1 Introduction

In recent years, renewable energies have begun to play a significant role in electrical energy. Among these emerging sources, photovoltaic (PV) solar energy stands out as a promising example of the energy of the future. It is now being widely used around the world. PV solar energy is an unlimited resource abundant, freely available, silent, and environmentally friendly. It converts solar radiation into useful electrical energy using PV solar cells [3, 4].

In this chapter, we will explain the energy conversion system process carried out by PV cells and provide general information on the history of photovoltaic technology. We will then present the different types of PV systems. Next, we will model the key components of a standalone PV system, such as the PV generator and the step-up boost converter. Simulation results of PV system in various temperature and radiation, finally, we will discuss the advantages and disadvantages of photovoltaic energy system [4].

I.2 Definition of Photovoltaic Solar

Solar energy is one of the emerging sources of renewable energy. It refers to the energy harnessed by solar panels and converted into electricity. PV electricity is generated using technology that transforms solar energy (photons) into electrical energy. This conversion is carried out through PV cells, which are most often arranged in PV panels [5]. See figure I.1.

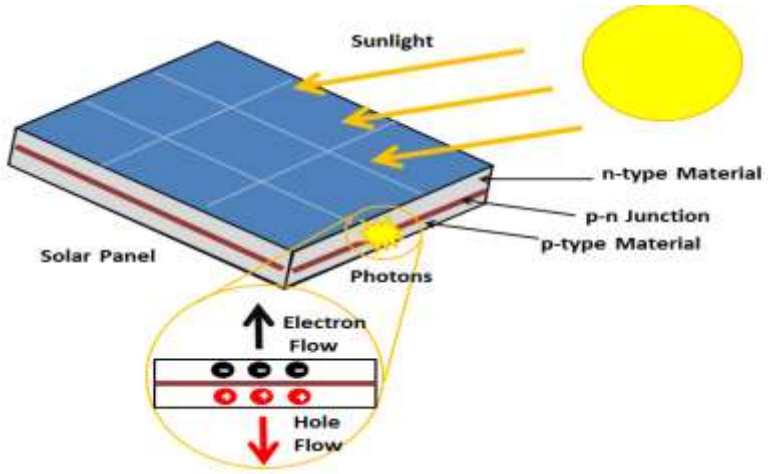


Figure I.1 Principe of photovoltaic Solar Energy

I.3 History of PV system

The history of photovoltaic (PV) technology has seen several important milestones. The key dates are highlighted below:

In 1839 *Discovery of the Photovoltaic Effect*: French physicist Alexandre-Edmond Becquerel discovered the photovoltaic effect while experimenting with an electrolytic cell.
In 1873 Photo-*conductivity of Selenium*: Willoughby Smith discovered the photo-conductive properties of selenium, a key step in PV development.
In 1883 First *Selenium Solar Cell*: Charles Fritts built the first true solar cell using a thin layer of gold on selenium, achieving an efficiency of about 1%.
In 1954*Modern Silicon Solar Cell*: Researchers Chapin, Fuller, and Pearson at Bell Labs developed the first practical silicon solar cell with an efficiency of 6%.
In 1958*First Use in Space*: The Vanguard 1 satellite became the first to use solar cells in space, proving their reliability for powering spacecraft.
In 1973 First *PV-Powered Building*: The University of Delaware built “Solar One,” one of the first buildings to be powered by solar PV.
In 1980s – *Commercialization and Grid Connection*: PV began to be used more widely in off-grid and remote applications, and early efforts toward grid-tied systems started.
In 2000s *Expansion and Cost Reduction*: Rapid advancements in manufacturing and government incentives led to increased production and significant cost reductions.
In 2010s at Present Global *Adoption and Innovation*: PV technology has become a major component of global energy strategies, with innovations like bifacial panels, perovskite cells, and floating solar farms [6].

I.4 Photovoltaic system

The term photovoltaic comes from Greek and means "light." It is composed of two parts: “photos” (meaning light) and the name of the Italian physicist Alessandro Volta, who invented the electric battery in 1800 and gave his name to the unit of electric potential—the volt.
In 1839, Edmond Becquerel discovered the phenomenon of a relationship between sunlight and certain minerals. When these metals were exposed to light, electrical energy was generated. However, this discovery did not find an immediate explanation at the time. Later, Albert Einstein demonstrated that sunlight is made up of photons, which carry electrical

energy when they interact with matter under certain conditions. The energy of a photon is given by the following equation [6]:

$$E = h \cdot f \tag{I.1}$$

Where:

E : is the energy of the photon,

h : is Planck's constant,

f : is the frequency of the photon.

The photovoltaic (PV) effect refers to the direct conversion of solar radiation energy into electrical energy using cells, typically made of silicon. To generate a sufficient amount of power, individual cells are interconnected to form a solar module.

I.5 PV Cell

The PV cell, also known as a solar cell, is the smallest functional unit in a photovoltaic system. It is made of semiconductor materials and directly converts light energy into electrical energy. PV cells are composed of the following elements:

A thin semiconductor layer (a material with a band gap that acts as an energy barrier which electrons cannot cross without external excitation, and whose electronic properties can be modified). The most commonly used material is silicon, which has relatively good electrical conductivity.

The most recent generations of PV cells include new multilayer reflective structures beneath the semiconductor. These layers allow light to bounce within the material for a longer duration, thereby increasing the efficiency of the energy conversion process.

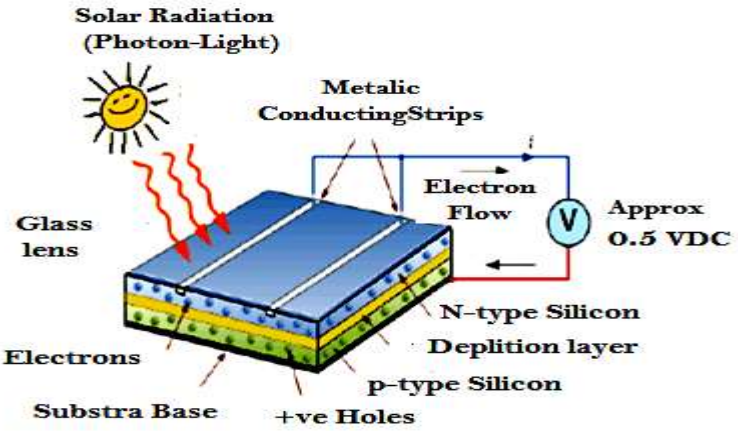


Figure I.2 Basic Structure of a Solar Cell

A PV cell is based on the physical phenomenon known as the photovoltaic effect, which generates an electromotive force (Fem) when the surface of the cell is exposed to light. The voltage generated can vary between 0.3 V and 0.7 V, depending on the material used, its arrangement, as well as factors such as temperature and the aging of the cell [7] .

I.6 Types of Photovoltaic Systems

Photovoltaic systems are classified into three types based on their requirements:

I.6.1. Standalone System

A photovoltaic system is considered autonomous or isolated when it is not connected to the grid. The standalone PV system is designed to supply electrical power to locations where there is no grid connection. The energy produced is either used immediately or stored in batteries for later use. In such applications, it is not always feasible to set up a conventional power supply network, either due to technical constraints or economic reasons. The performance of standalone systems heavily depends on the condition and quality of the batteries, as they are a fundamental component in these types of systems [8].

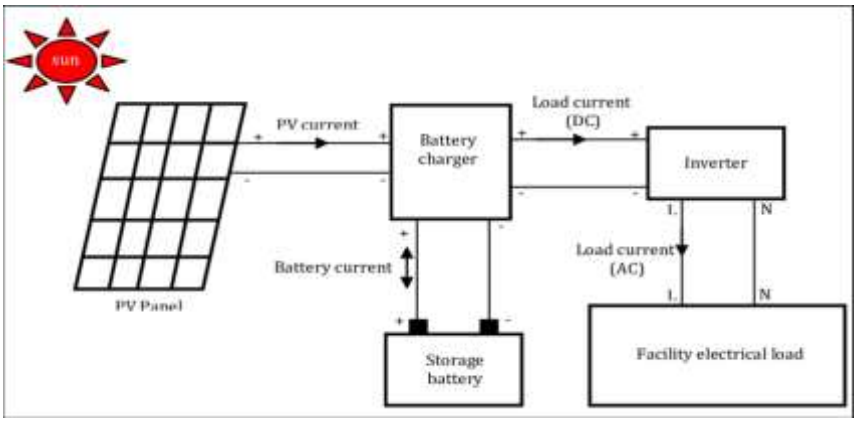


Figure I.3 Standalone PV Systems

I.6.2. Grid-connected PV System

A photovoltaic (PV) system can be connected in parallel with the electricity grid. The solar panels are connected in series to form strings, which are then linked to an inverter. The role of the inverter is to convert the direct current (DC) generated by the solar panels into alternative current (AC). Each inverter is selected based on the power rating of the panels and can accommodate one or more strings [9].

If the local consumption exceeds the PV system's production, the grid supplies the additional electricity. On the other hand, if the PV system generates more electricity than is needed locally, the excess energy is supplied to the public grid, where it can be used by other consumers connected to the network.

In grid-connected systems, the inverter takes the place of batteries. It is therefore the key component in these types of systems [10] .

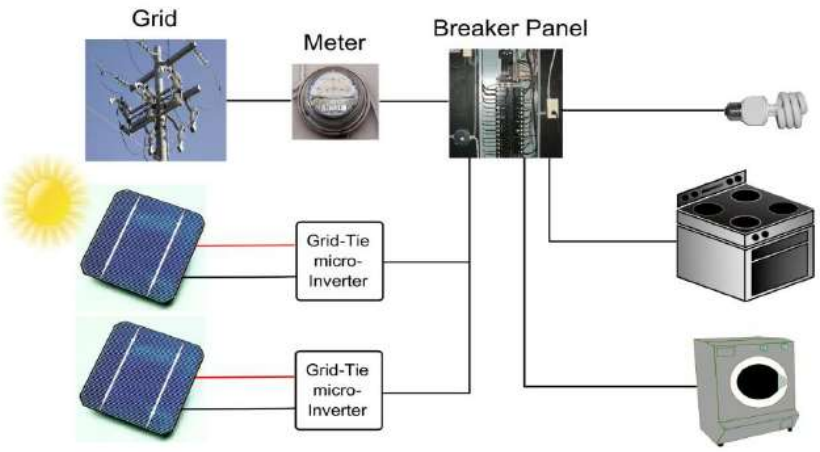


Figure I.4 Grid-connected PV System

I.6.3. Hybrid System

Hybrid systems receive part of their energy from one or more additional sources that are also independent of electricity distribution networks. In practice, the photovoltaic generator is combined with a wind turbine or a fuel-powered generator, or both, along with energy storage accumulators. Such a system is designed for applications that require continuous power supply at relatively high capacity [8,12].

A photovoltaic hybrid system optimizes the combined use of multiple renewable and/or fossil energy sources, along with associated storage solutions, to ensure reliable and efficient energy supply.

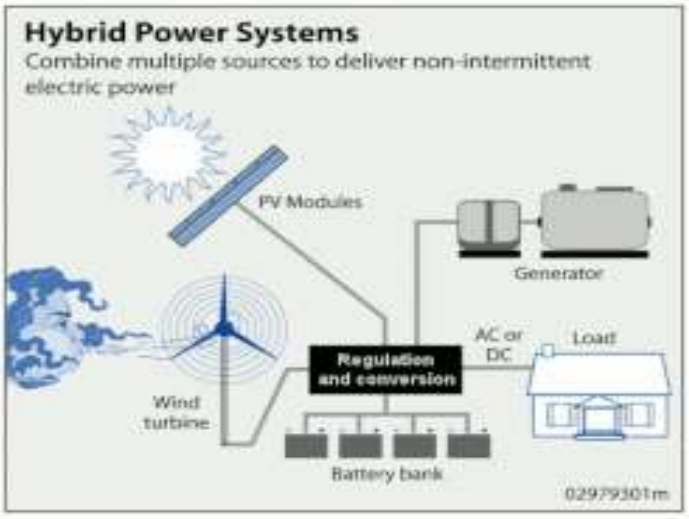


Figure I.5 Hybrid Photovoltaic System

I.7 Standalone Photovoltaic Systems

The standalone PV energy production system is an autonomous solar power generation setup. It consists of a PV generator, made up of one or more modules connected in series or parallel, and a DC-DC power converter controlled by an algorithm that enables Maximum Power Point Tracking (MPPT) [13, 14].

The system also includes a DC load that directly uses the energy generated. Figure I.6 shows the block diagram of the standalone PV system**.**

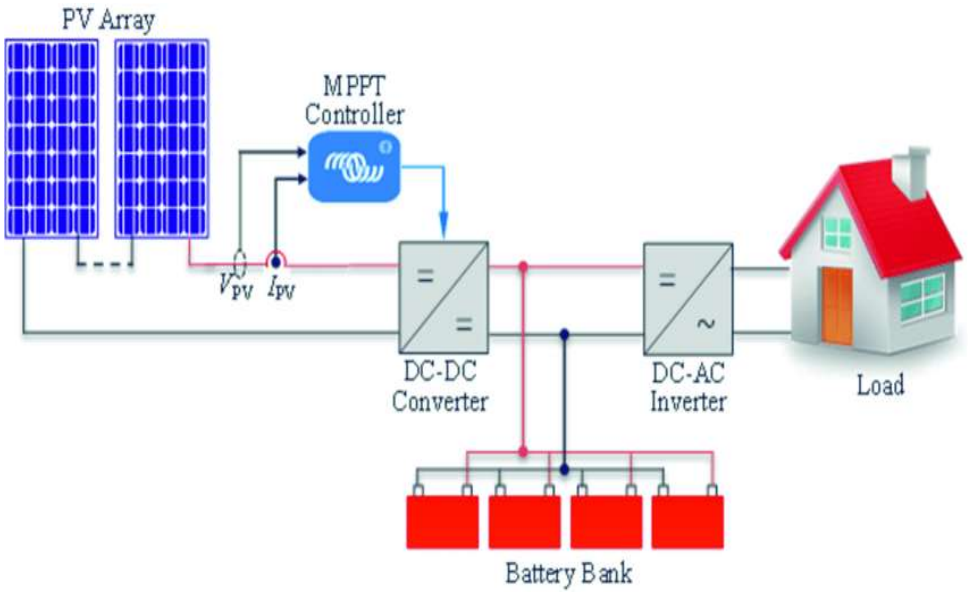


Figure I.6 Block Diagram of the Standalone PV System

In this chapter, we present the modeling of a standalone photovoltaic system, consisting of a photovoltaic generator and a boost converter. However, the MPPT control technique will be examined in detail in the following chapter

I.7.1. Photovoltaic Generator

Solar cells are typically connected in series and parallel configurations, and then encapsulated under glass to form a PV module. A photovoltaic generator composed of multiple interconnected modules that form a unit capable of producing high continuous power, suitable for standard electrical equipment [15, 16].

PV modules are usually connected in series-parallel combinations to increase both the voltage and current at the output of the PV generator. The interconnected modules are mounted on metal supports, tilted at a desired angle depending on the location. This entire setup is commonly referred to as a PV module array or PV field. Figure I.7 illustrates the equivalent circuit of a PV cell. This model includes a current source and a diode in parallel, as well as a series resistance (R_s) and a parallel (shunt) resistance (R_{sH}) to account for energy losses and dissipative effects within the cell.

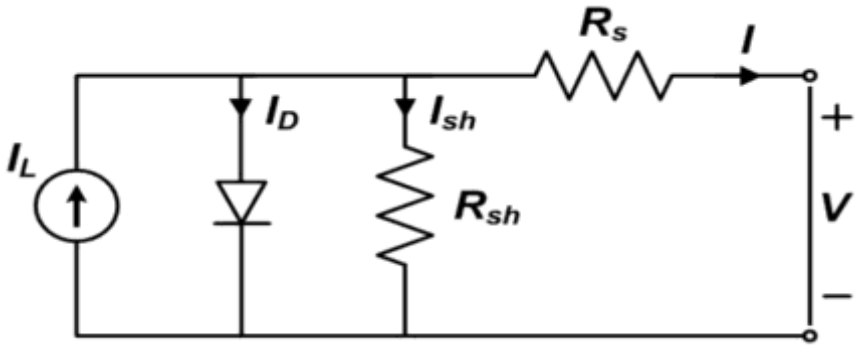


Figure I.7 Equivalent Circuit of a Photovoltaic Cell

The **series** resistance (R_s) represents the internal resistance of the PV cell. It primarily depends on the resistance of the semiconductor material, the contact resistance of the collector grid, and the resistivity of the metallic grid lines.

The shunt resistance (R_{sh}) accounts for effects such as leakage currents around the edges of the cell. This resistance is typically reduced due to the penetration of metallic impurities into the PN junction, especially when this penetration is deep. Low shunt resistance leads to higher losses and reduced efficiency of the PV cell.

This circuit model of cell PV system can be used not only for a single PV cell, but also for a module or a panel composed of multiple interconnected modules.

The equation that relates the output current of a PV module composed of Ns cells connected in series to the voltage at its terminals is given by:

$$I = I_{ph} - I_0 \left(e^{\frac{q(V+I_{Rs})}{nKT}} - 1 \right) - \frac{V+I_{Rs}}{R_{sh}} \quad \text{(I.2)}$$

Where:

I: Output current of the module

V: Output voltage across the module

I_{ph}: Photocurrent (depends on irradiance and temperature)

I_0: Diode reverse saturation current

q: Electron charge (1.602×10^{-19} C)

n: Diode ideality factor

k: Boltzmann constant (1.381×10^{-23} J/K)

T: Temperature in Kelvin

R_s: Series resistance

R_{sh}: Shunt resistance

N_s: Number of series-connected cells in the module

I.7.2. Boost Converter

Choppers, or DC-DC converters, are devices that allow control of electrical power in DC circuits with high flexibility and excellent efficiency. A chopper typically consists of capacitors, inductors, and switching devices. In the ideal case, these components do not consume active power, which is why boost converters generally achieve high efficiency [17, 17].

The boost converter is a parallel DC-DC converter inserted between the PV generator and the rest of the power conversion chain. Its basic electrical circuit is shown in Figure I.8. A typical application of the boost converter is to increase the input voltage to a higher output voltage.

It is characterized by its duty cycle d, where is limited between, 0<d<1, which defines the relationship between the average output and input values. In steady-state analysis of a boost converter, the system of equations is given by :

$$V_{out} = \frac{V_{in}}{1-d} \quad \text{(I.3)}$$

Where:

V_{in}: Input voltage (from the PV generator)

V_{out}: Output voltage (to the load or inverter)

d: Duty cycle of the switching signal

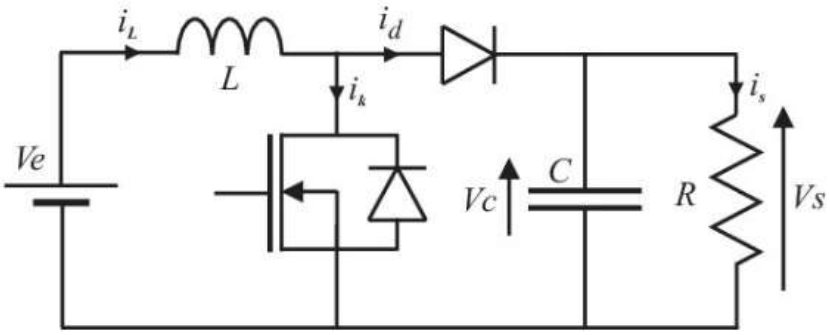


Figure I.8 Electrical Diagram of the Boost Converter

This boost converter is essential in MPPT (Maximum Power Point Tracking) applications, as it enables the system to adjust the operating point of the PV generator to extract maximum power under varying irradiance and temperature conditions.

I.8 Advantages and Disadvantages of a PV sytem

I.8.1. Advantages

One of the key strengths of photovoltaic (PV) systems is their high reliability. These systems have no moving parts, which minimizes mechanical failure and reduces maintenance needs. This reliability makes them ideal for use in remote or isolated areas where regular servicing may not be practical. Their proven dependability is also a primary reason for their use in space missions and satellites [19,20].

Another significant advantage of PV systems is their modularity. Photovoltaic panels can be installed individually or in groups, allowing systems to be tailored to meet specific energy requirements from small-scale household needs to large industrial applications. This scalability supports both incremental deployment and large centralized installations.

PV systems also benefit from very low operating costs. Since they do not rely on fuel, there is no need for fuel procurement, transportation, or storage. Furthermore, they require minimal technical intervention, reducing the need for highly specialized personnel or ongoing maintenance.

In terms of environmental impact, solar energy is one of the cleanest sources available. PV systems generate electricity without producing noise, greenhouse gases, or harmful emissions. The only environmental consideration is land use, which becomes more significant in large-scale ground-mounted installations.

Photovoltaic technology is also well-suited for urban settings. Due to their compact size and quiet operation, solar panels can be installed on rooftops, building facades, or small open areas without disrupting the surrounding environment or creating noise pollution. This makes them an attractive option for densely populated regions.

Furthermore, solar energy is available almost everywhere on Earth, making PV systems accessible on a global scale. This widespread availability supports the use of solar power in both developed and developing regions, regardless of existing infrastructure.

Lastly, PV systems offer the advantage of localized energy production. Since the energy can be generated near the point of consumption, transmission losses that are common in centralized power grids can be significantly reduced or avoided altogether. This improves overall system efficiency and reduces dependency on extensive power distribution networks.

I.8.2. Disadvantages

One of the primary limitations of photovoltaic (PV) systems is the high manufacturing cost. The production process for solar modules relies on sophisticated technologies and materials, which require substantial financial investment. As a result, the initial cost of deploying a PV system can be significantly higher than conventional alternatives [19, 20].

Another major challenge lies in the area of energy storage. When solar-generated electricity must be stored for later use commonly in chemical batteries the overall cost of the system increases considerably. This is further complicated by ongoing issues in battery technology, particularly concerning their high prices, limited lifespans, and maintenance requirements.

In terms of energy efficiency, PV modules generally operate at relatively modest conversion rates. Under real-world conditions, most commercial modules convert only 10% to 15% of the incoming solar energy into usable electricity. Although the theoretical maximum efficiency for a single junction cell is approximately 28%, current technologies fall short, resulting in constrained energy output per surface area.

When compared to conventional diesel generators, photovoltaic systems may struggle to compete, particularly in scenarios that demand large and consistent power supply. While PV

systems are ideal for small-scale or off-grid applications, they are often less cost-effective than diesel solutions in larger installations, especially in the absence of subsidies or energy storage.

Furthermore, the capital investment required for PV system installation remains a significant barrier. Despite long-term savings on operational costs, the upfront expense associated with equipment, installation, and infrastructure is still considerably higher than that of traditional energy systems.

Lastly, for standalone photovoltaic systems that operate independently from the grid, energy storage becomes indispensable. These systems rely heavily on batteries to ensure a continuous power supply, particularly during periods without sunlight. However, the high cost of battery storage components continues to pose a financial challenge for widespread adoption of autonomous solar solutions.

I.9 Simulation of PV panel

Based on the equations and the model of the photovoltaic system, a simulation of the photovoltaic module was carried out in MATLAB under standard test conditions, with an irradiance of 1,000 W/m² and a cell temperature of 25 °C. The table below presents the specifications of the photovoltaic module used in the simulation.

System parameters	
Rated power (Vmp)	200
Voltage at maximum power (Vmp)	26.4
Current at maximum power (Imp)	7.58
Open circuit voltage (Voc)	32.9
Short circuit current (Isc)	8.21
Total number of cells in Series (Ns)	54
Total number of cells in parallel (Np)	1

Tables 1.1: System parameters

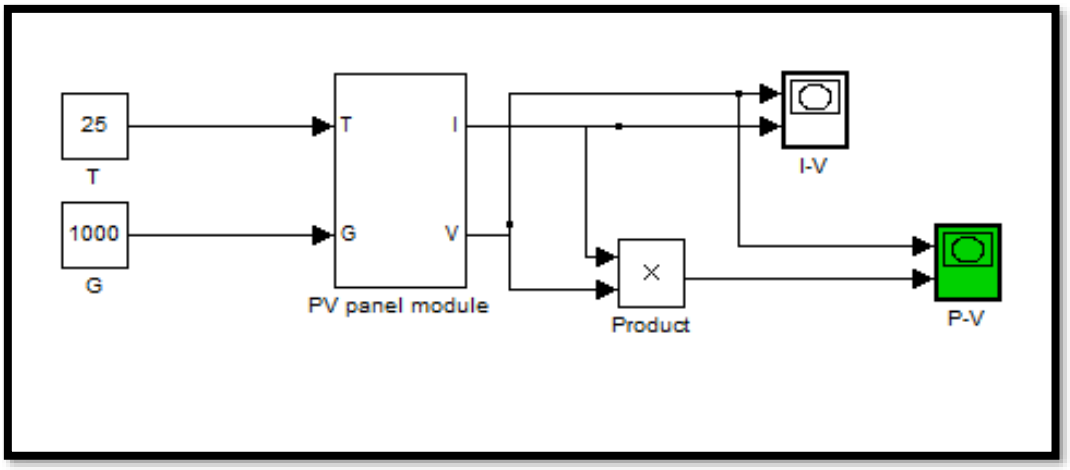


Figure I.9 Model bloc of PV panel

When simulating this photovoltaic panel model under standard test conditions with T = 25°C and G = 1000 W/m², the following results are obtained

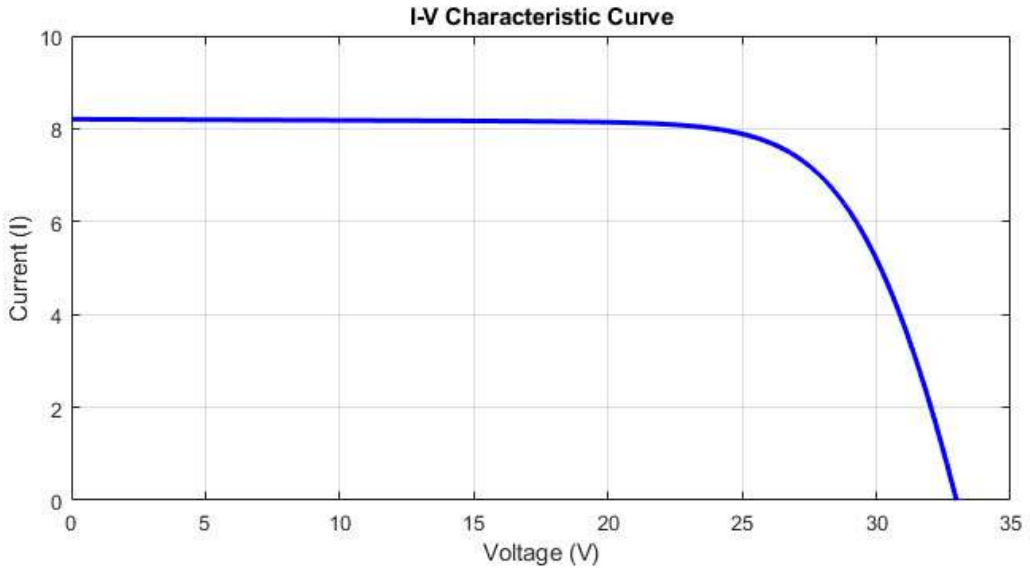


Figure I.10 The I-V (current-voltage) characteristic of the PV panel

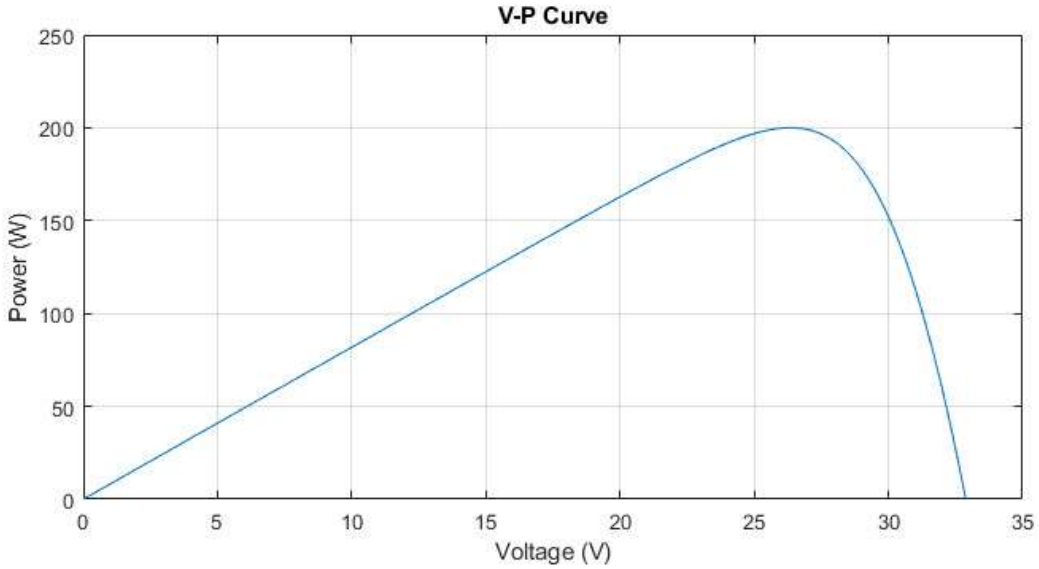


Figure I.11 The P-V (power-voltage) characteristic of the PV panel

The I-V characteristic shows that the PV panel is considered as a constant current source for low voltage values with a current approximately equal to the short-circuit current (ISC). As the voltage increases, the current begins to decrease exponentially until it reaches zero at the voltage equal to the open-circuit voltage (VOC). Across the entire voltage range, there is only one point where the panel operates at the Maximum Power Point (MPP).

I.9.1 The influence of different parameters

1.9.1.1 The influence of temperature

To observe the influence of temperature, the irradiance is fixed at 1000 W/m² while the temperature is varied across three values: 25°C, 45°C, and 55°C.

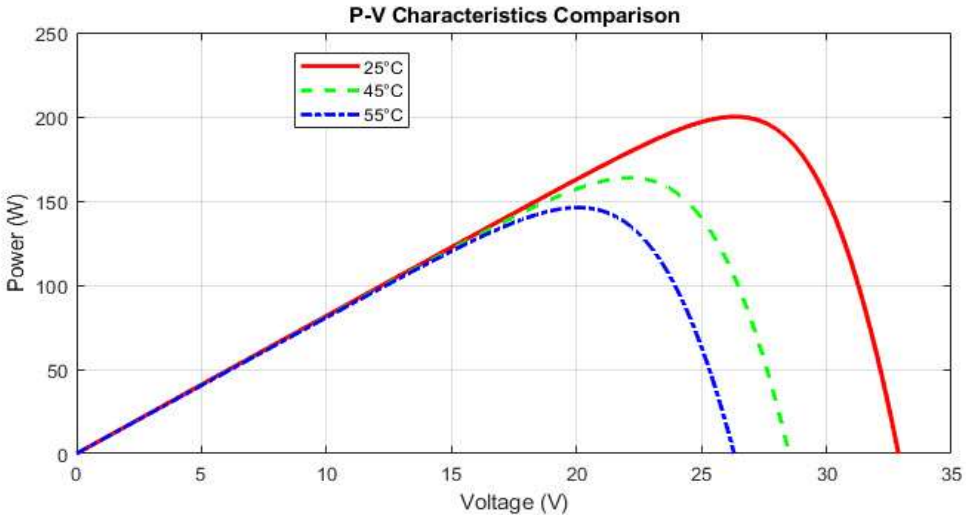


Figure I.12 the influence of temperature

The increase in voltage as temperature decreases and the slight gain in current as temperature increases are noticeable. This can be explained by improved light absorption, as the energy band gap decreases with increasing temperature. The increase in current can be neglected at the maximum power point and even in the overall behavior of the cell.

I.9.1.2 The influence of irradiance

We set the temperature to 25°C while varying the irradiance (1000, 700, and 400 [W/m²]), then simulated the model and plotted the curve for each value.

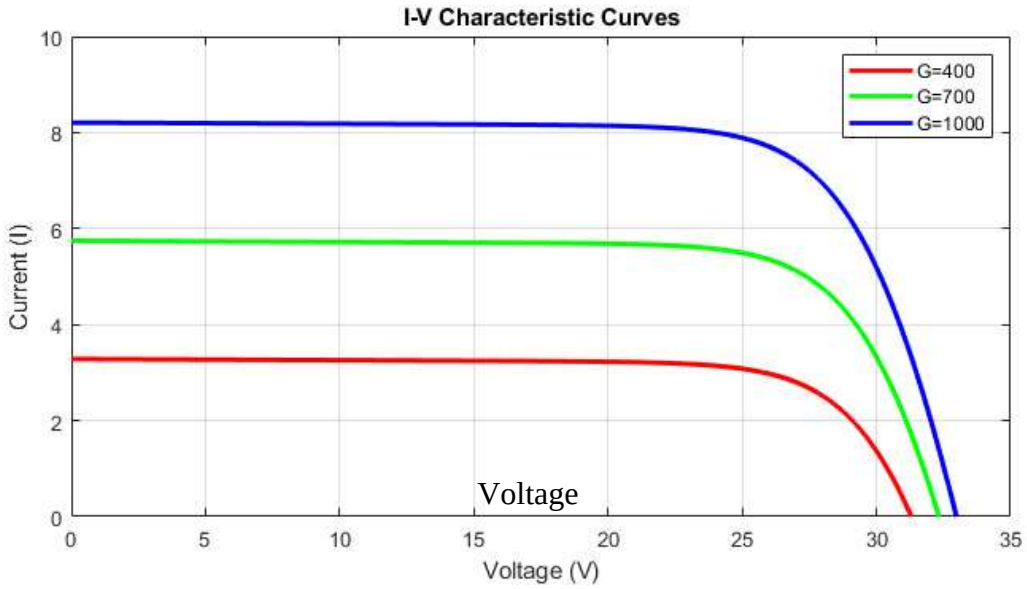


Figure I.13 the influence of irradiance

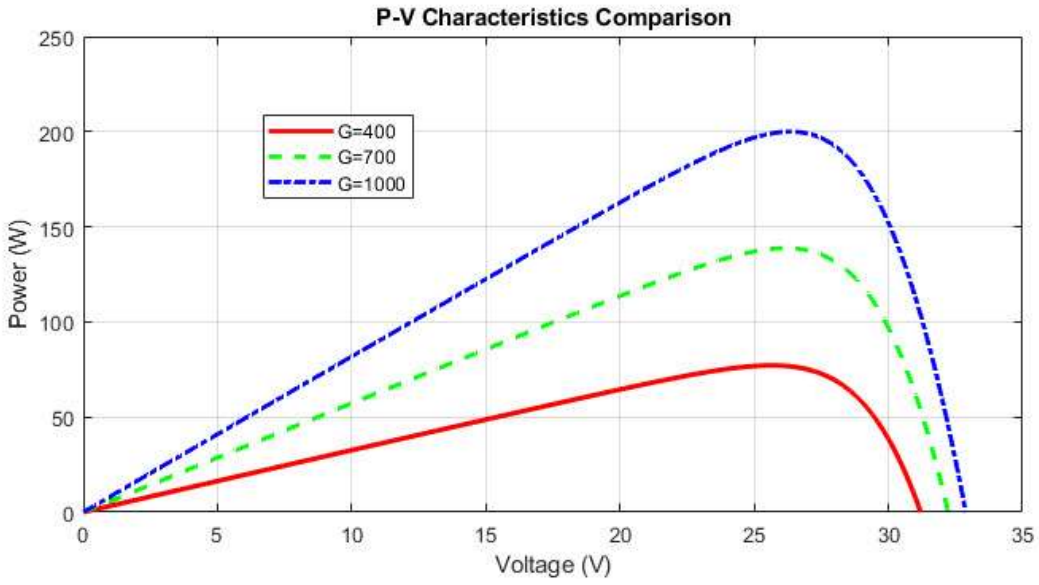


Figure I.13 Influence of lighting on the PV panel

We can observe that the current is directly proportional to the irradiance at these levels. However, the voltage does not degrade significantly as the irradiance decreases. The characteristic of I-V curves shift towards higher values, enabling the module to produce greater electrical power.

I.10 Conclusion

In this chapter, we explained the principle of the photovoltaic (PV) **e**ffect and introduced the fundamental component of photovoltaic technology: the solar cell. We reviewed the historical development of PV and presented the different types of PV systems, with a particular focus on autonomous systems. We also modeled and simulated the PV generator and the boost converter. Finally, we concluded with a summary of the advantages and disadvantages of photovoltaic energy. In the next chapter, we will explore the various Maximum Power Point Tracking (MPPT) algorithms used to optimize the performance of photovoltaic systems.



CHAPTER II

CONVENTIONAL MAXIMUM POWER POINT TRACKING (MPPT) TECHNIQUES



CHAPTER II
MAXIMUM POWER POINT TRACKING (MPPT) TECHNIQUES

II.1 Introduction

In PV photovoltaic systems, the output characteristics between current and voltage are inherently nonlinear. Under steady conditions of irradiance and temperature, the current-voltage (I-V) characteristic curve of a PV module exhibits a distinct point at which the system delivers its maximum electrical power commonly referred to as the Maximum Power Point (MPP). To operate the system at this point and ensure maximum energy extraction, a control strategy known as Maximum Power Point Tracking (MPPT) is typically employed.

MPPT techniques are designed to continuously adjust the operating parameters of the PV system to align with the MPP, thereby optimizing the power transferred from the PV generator to the load. This chapter begins by outlining the basic principles underpinning MPPT control. It then presents a classification of the main MPPT algorithms discussed in academic and technical literature. Subsequently, two conventional tracking methods the Perturb and Observe (P&O) and Incremental Conductance (INC) are examined in detail. Finally, the chapter concludes with a comparative analysis of these two algorithms, emphasizing their operational behavior, efficiency, and implementation complexity [21, 22].

II.2 Principle of Maximum Power Point (MPP) Tracking

Direct coupling between a photovoltaic (PV) generator and a resistive load is a commonly used configuration in solar energy systems. This approach is widely favored for its simplicity, reliability, and minimal installation cost. In such systems, the operating point of the PV generator is determined by the electrical impedance of the connected load, which may not always coincide with the Maximum Power Point (MPP). As a result, the system may operate inefficiently under certain conditions, highlighting the importance of implementing MPPT techniques to optimize power extraction [23, 24].

Concept is illustrated in Figure II.1, which shows a PV generator directly supplying a DC load without any intermediate control circuitry. The figure highlights the direct transfer of current (I_{PV}) and voltage (V_{PV}) from the generator to the load, where the operating point is solely influenced by the load characteristics.

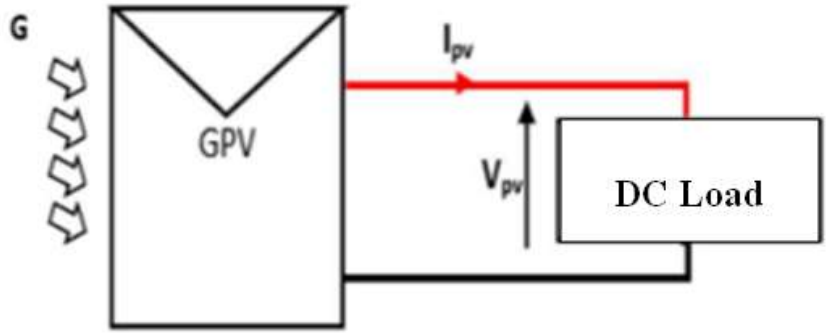


Figure II.1 Direct coupling between a PV generator and a resistive load

As illustrated in Figure II.2, a PV generator can be directly connected to three types of loads: a DC voltage source, a DC current source, and a purely resistive load. The three corresponding operating points A, B, and C can deliver powers PA, PB, and PC respectively.

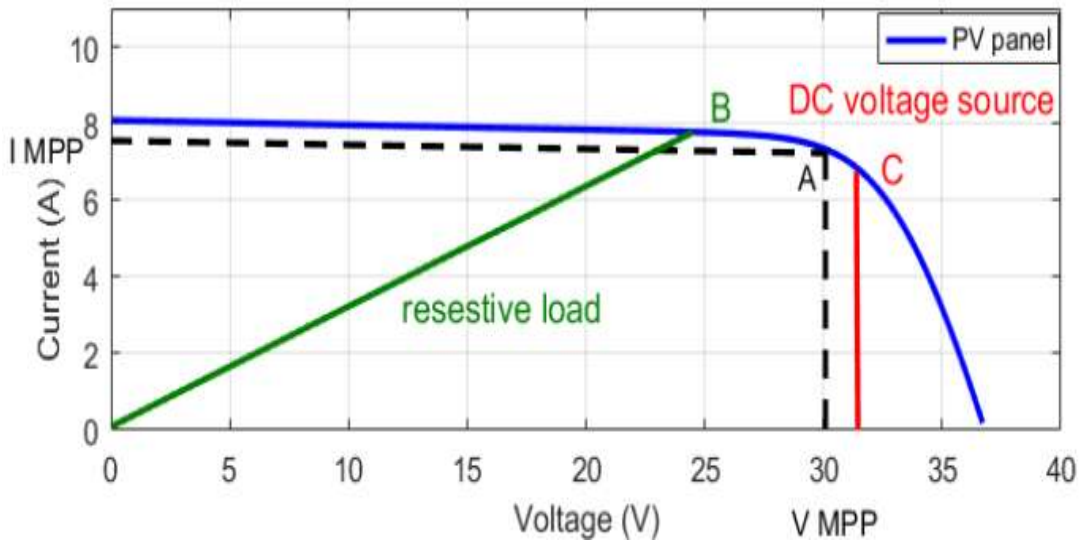


Figure II.2 Operating points of a PV generator in direct connection, depending on the load

Thus, the main drawback of this setup is that it does not provide any form of operational control. There is also no guarantee that the maximum available power from the PV generator will be delivered to the load. Furthermore, some types of loads require alternating voltage and current. To address this issue and to extract, at every moment, the maximum available power from the PV generator and transfer it to the load, a power adaptation stage is used. This stage acts as an interface between the two components and, through a control action, ensures the transfer of the maximum power delivered by the generator.

In general, the adaptation stage used in PV systems is a DC-DC power converter controlled by an MPPT algorithm, which enables tracking of the Maximum Power Point (MPP) [4], as

illustrated in Figure II.3. Thus, regardless of weather conditions (temperature and irradiance), the control of the converter ensures that the system operates at the maximum power point.

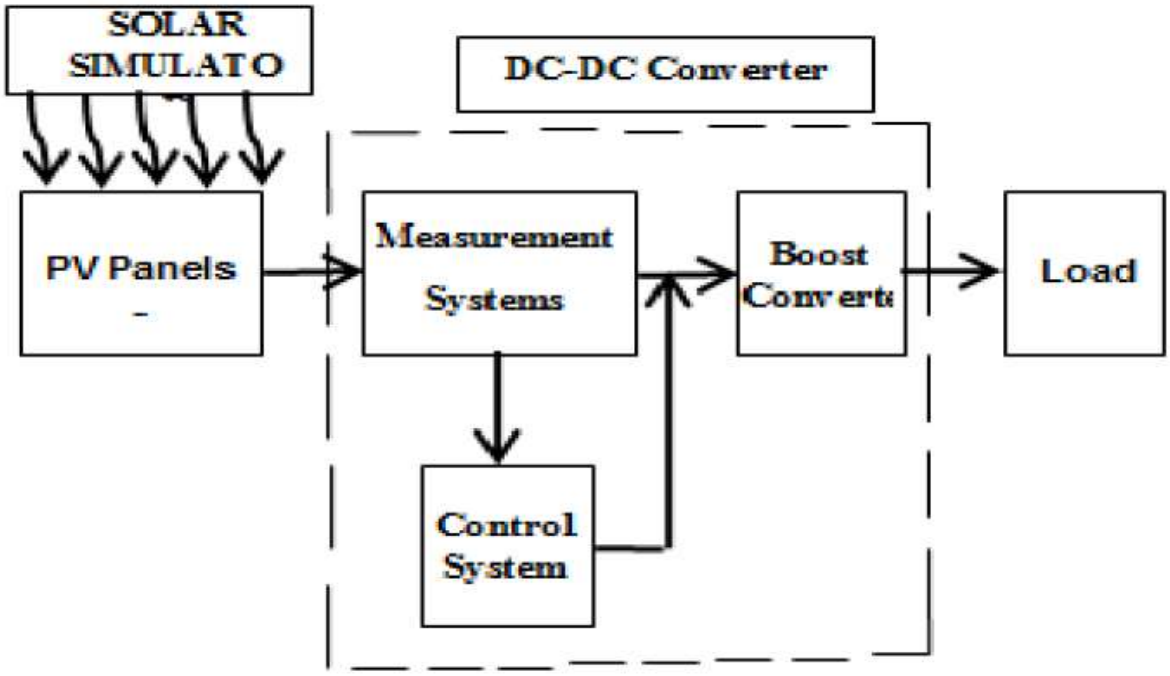


Figure II.3 Block diagram of the PV system adapted by a DC-DC converter

The MPPT controller varies the duty cycle of the static converter using an appropriate electrical signal to extract the maximum power that the PV generator can provide. The MPPT algorithm can be more or less complex depending on how it searches for the Maximum Power Point (MPP). In general, it operates by adjusting the duty cycle of the DC-DC converter based on the variation of its input parameters current, voltage, and consequently the power of the PV generator until it reaches the MPP.

II.3 Classification of MPPT Control Techniques

MPPT control techniques can generally be classified based on the type of electronic implementation: analog, digital, or hybrid. However, it is more useful to classify them according to the type of tracking method they employ and the input parameters used by the MPPT controller. These techniques can be classified as follows [25,26]:

II.3.1 Conventional Techniques

There are standard conventional MPPT techniques, such as Perturb and Observe (P&O) and Incremental Conductance, which have been widely used since the earliest PV installations. These techniques are relatively low-cost and rely on very simple algorithms. They can be considered among the best solutions for tracking the maximum power point under constant and uniform irradiance conditions. However, these techniques no longer ensure good

performance during sudden atmospheric changes, which has led researchers to propose improvements over the past decades, such as adaptive P&O and modified Incremental Conductance.

II..3.2 Advanced Techniques

The performance of standard conventional techniques has evolved through various improvements; however, their use in applications requiring high precision and fast response remains limited. Recently, advanced MPPT techniques have become the focus of significant research efforts aimed at considerably enhancing the performance of maximum power point tracking. These advanced techniques can be classified into three subcategories:

- Artificial Intelligence-based techniques, such as artificial neural networks and fuzzy logic control.
- Metaheuristic approaches, such as genetic algorithms, particle swarm optimization, random search methods, and ant colony optimization;
- Nonlinear control methods, such as sliding mode control, predictive control, the direct Lapugnoy method, and discrete nonlinear PID control.

II.3.3. Hybrid Techniques

Hybrid MPPT techniques have been recently proposed in the literature to improve tracking accuracy and achieve even higher efficiencies under varying atmospheric conditions. These techniques have demonstrated better performance compared to other methods. Hybrid MPPT techniques can be classified into three main categories: a combination of two conventional techniques, a combination of two advanced techniques, and a combination of one conventional and one advanced technique.

II.4. MPPT Control Methods

Several algorithms for Maximum Power Point Tracking (MPPT) can be found in the literature. In this section, we examine a few methods such as the Perturb and Observe (P&O) algorithm and the Incremental Conductance algorithm.

II.4.1 Perturb and Observe Algorithm

The Perturb and Observe (P&O) algorithm is one of the most widely used methods for Maximum Power Point Tracking (MPPT) in photovoltaic (PV) systems. It is a simple, efficient, and cost-effective technique that enables PV modules to operate at or near their

maximum power point under varying environmental conditions. The P&O algorithm is especially attractive for its ease of implementation, as it requires only voltage and current measurements from the PV array.

The core mechanism of the P&O method relies on introducing perturbations in the operating voltage or current of the PV module and then observing the resulting change in output power. By evaluating whether the power has increased or decreased following the perturbation, the algorithm determines whether to continue in the same direction or reverse it. This trial-and-error approach allows the system to "climb" the power–voltage curve of the PV array and settle near the point of maximum power [24].

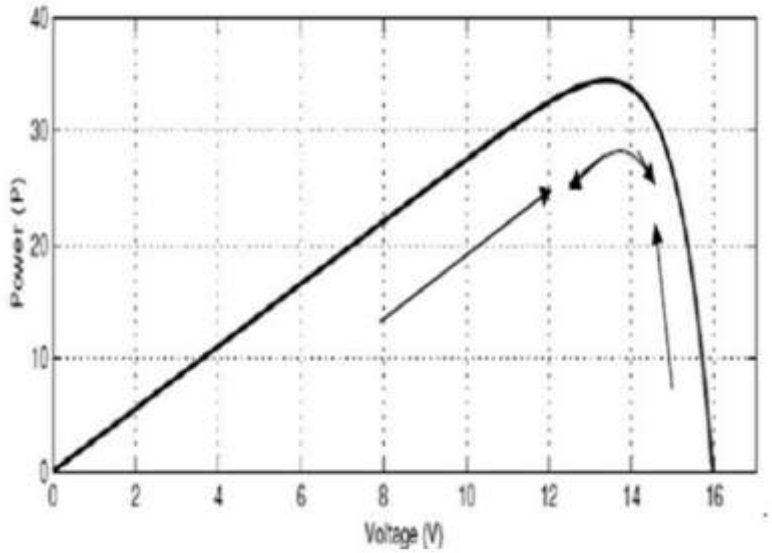


Figure II.4 MPP tracking using the Perturb and Observe algorithm

In practical PV systems, the P&O algorithm is typically embedded in the control unit of a DC-DC converter, such as a boost converter. The converter adjusts its duty cycle based on the MPPT algorithm's decisions to modify the input voltage of the PV module. The process begins by measuring the initial voltage and current of the array to calculate power. A small change is then applied to the operating voltage, and the new power is calculated. If the new power is greater than the previous one, the perturbation continues in the same direction; if not, the direction is reversed. This cycle repeats continuously, causing the system to oscillate around the maximum power point and respond to changes in irradiance and temperature [27, 28, 29].

As shown in the flowchart below, the algorithm starts by acquiring the current and previous values of voltage and power. It then determines the change in power (ΔP) and change in

voltage (ΔV). Based on the signs of these changes, the algorithm decides whether to increase or decrease the voltage in the next iteration. This process continues to track the maximum power point dynamically, even as external conditions vary.

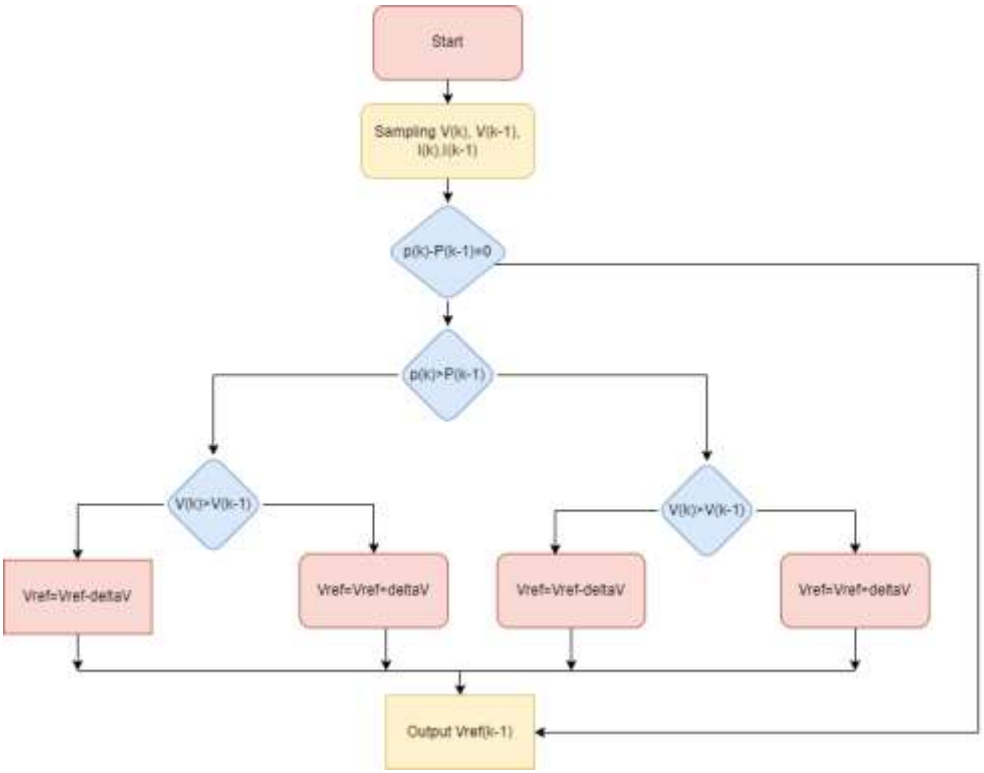


Figure II.5 Flowchart of P&O approach

This method offers a reliable and straightforward solution for MPPT, especially in applications where hardware simplicity and low computational demands are critical. However, it is important to note that the P&O method may cause small oscillations around the MPP during steady-state operation and may be less responsive under rapidly changing environmental conditions. Despite these limitations, it remains a preferred choice for many practical PV systems due to its balance of performance and simplicity.

II.4.1.1 Simulation of MPPT using P&O algorithm

The diagram in Figure (II.6) illustrates a simulated model of a photovoltaic (PV) system equipped with a Maximum Power Point Tracking (MPPT) mechanism based on the Perturb and Observe (P&O) algorithm. This simulation, developed using MATLAB/Simulink, aims to replicate how a PV system dynamically adjusts its operating point to extract the maximum available power under changing environmental conditions.

At the core of the model is a solar panel connected to a boost converter, which serves to regulate the voltage output. The panel's voltage and current are continuously monitored to

calculate the instantaneous power being produced. These power readings are then processed by the P&O algorithm, which functions by slightly adjusting the converter's duty cycle and observing the resulting change in power [29, 30].

Depending on whether the power increases or decreases, the algorithm determine the next adjustment to move the operating point closer to the maximum power point (MPP). Through this iterative process, the system effectively "tracks" the MPP in real-time.

The simulation also incorporates varying irradiance levels, allowing the model to demonstrate how the P&O algorithm responds to changing sunlight conditions. This makes the simulation a valuable tool for analyzing the efficiency and behavior of MPPT strategies in solar energy systems.in this study we have used China Sunergy (Nanjing) SST235-60P panel with the characteristic bellow:

- **Pv panel characteristic**

Parameter	Value
Module Name	China Sunergy (Nanjing) SST235-60P
Maximum Power (Pmax)	235.024 W
Open Circuit Voltage (Voc)	36.8 V
Voltage at Maximum Power Point (Vmp)	29.6 V
Short-Circuit Current (Isc)	8.54 A
Current at Maximum Power Point (Imp)	7.94 A
Cells per Module (Ncell)	60
Temperature Coefficient of Voc (%/°C)	-0.37
Temperature Coefficient of Isc (%/°C)	0.06
Series-Connected Modules per String	8
Parallel Strings	1

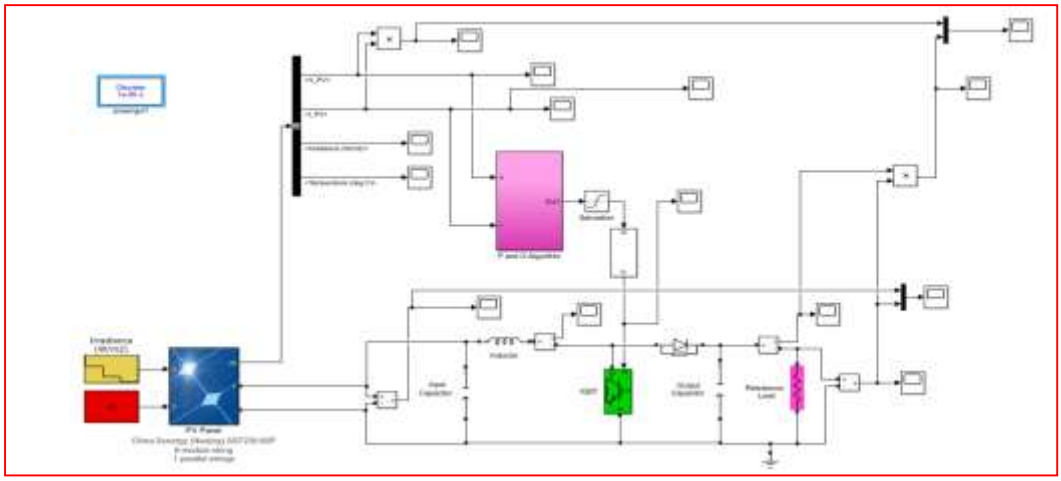


Figure II.6 Bloc de simulation of PV system using P&O

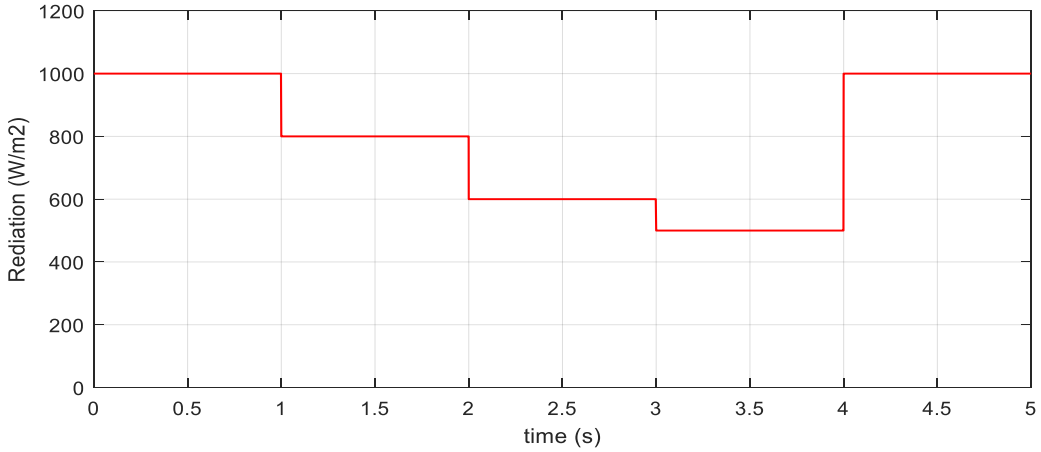


Figure II. 7 Radiation varies

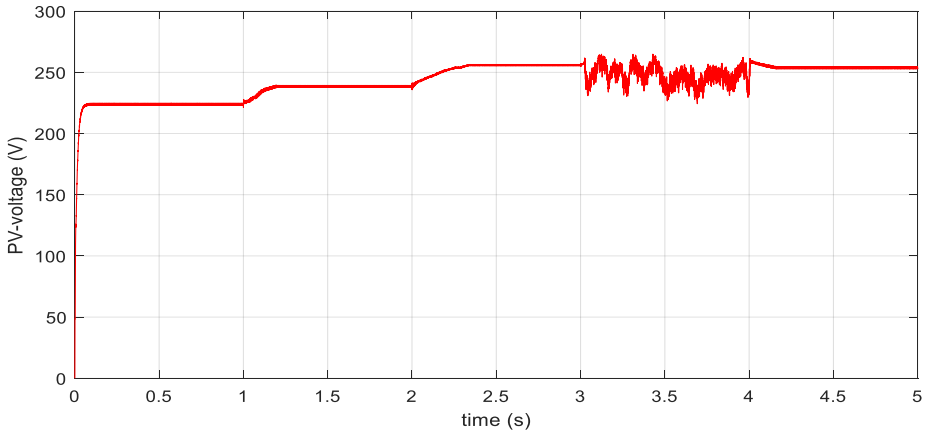


Figure II.8 PV Voltage using P&O Algorithm

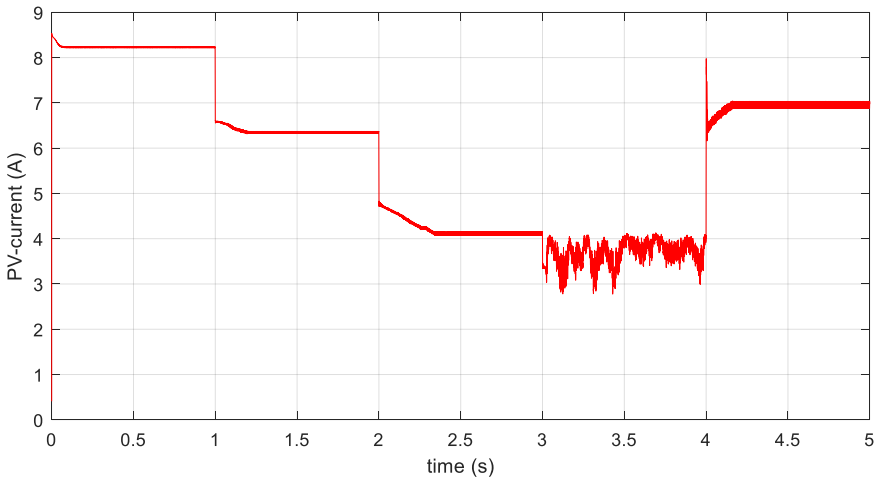


Figure II.9 PV Current using P&O Algorithm

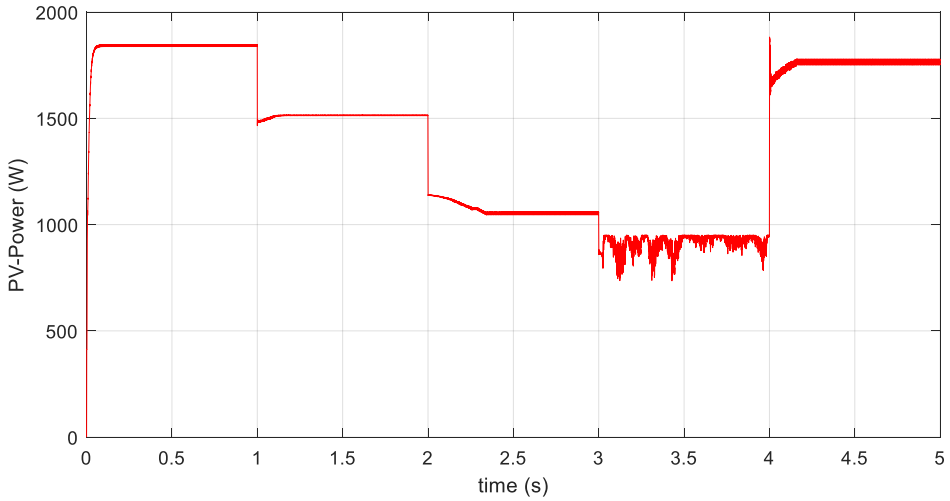


Figure II.10 PV Power using P&O Algorithm

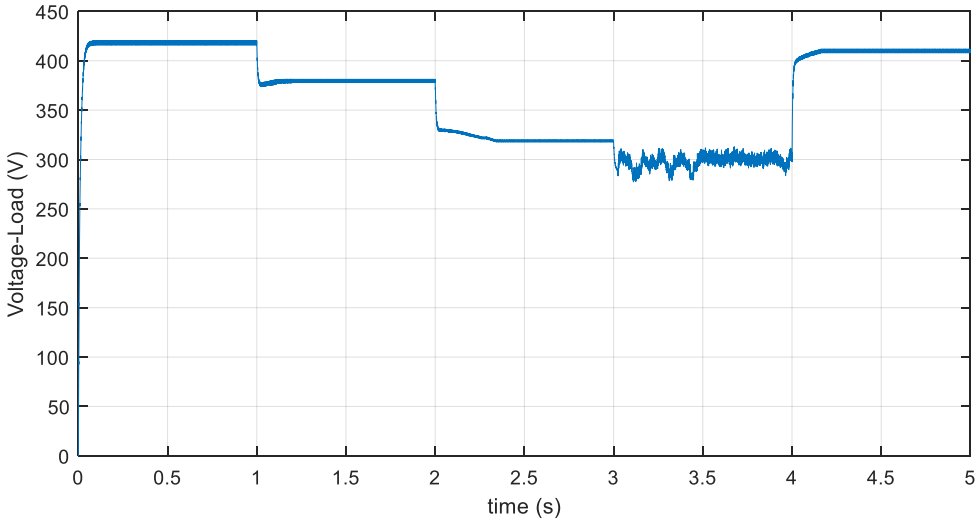


Figure II.11 Voltage Load using P&O Algorithm

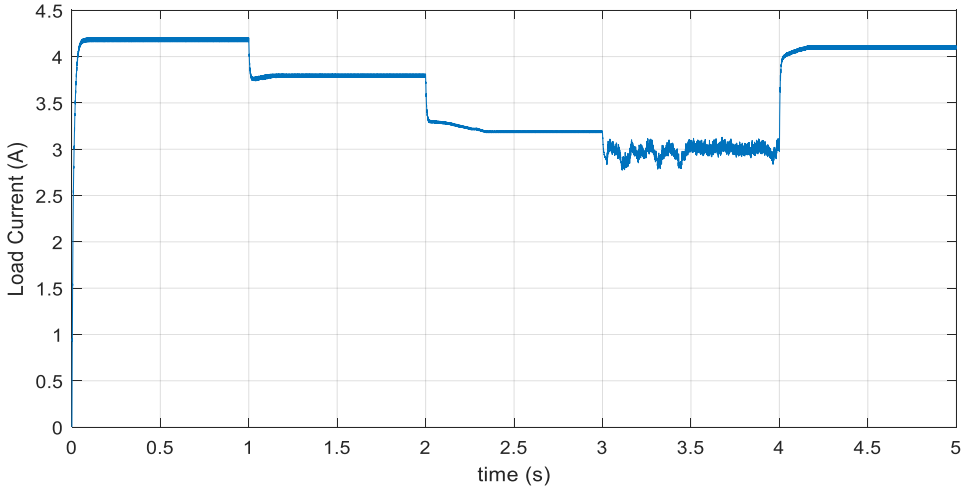


Figure II.12 Load Current using P&O Algorithm

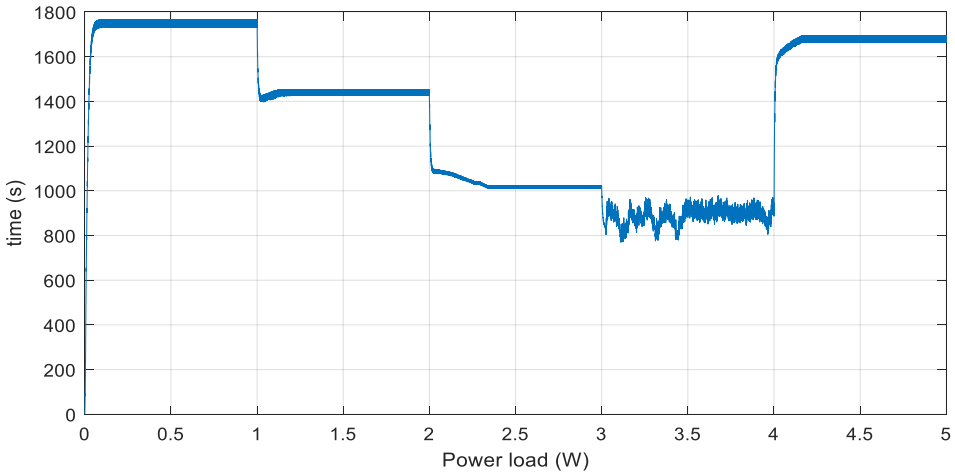


Figure II.13 Power load Current using P&O Algorithm

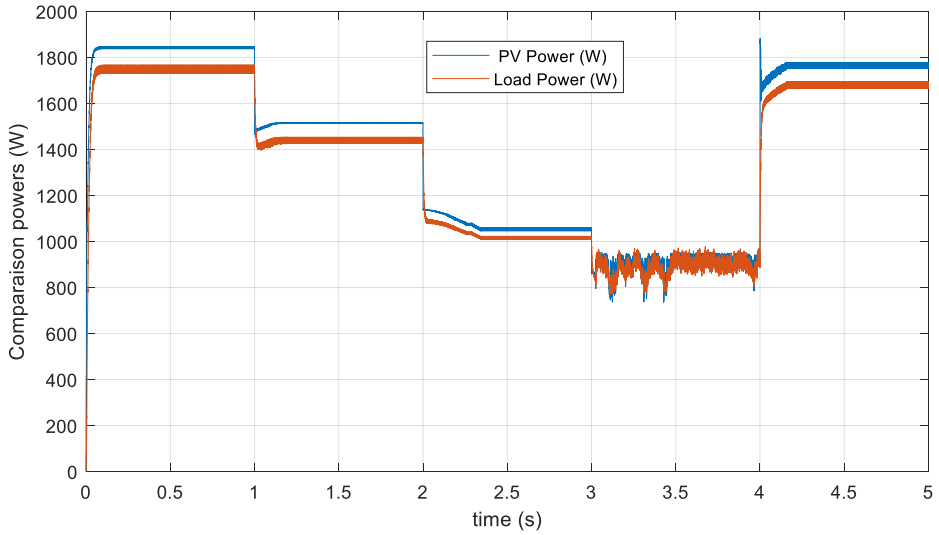


Figure II.14 Comparison of powers using P&O Algorithm

During the simulation, solar irradiance was varied in a stepwise manner to evaluate the dynamic response of the P&O algorithm. The irradiance levels changed from an initial value of 1000 W/m², down to 800 W/m², then to 600 W/m², and further to 500 W/m², before returning to 1000 W/m² in the final stage. The ambient temperature was kept constant at 25°C throughout the simulation to isolate the effect of irradiance on PV performance.

As shown in the graph, each drop in irradiance results in a corresponding decrease in both PV power and load power. These changes are clearly visible at approximately 1 s, 2 s, and 3 s on the time axis. The P&O algorithm responds to each change by adjusting the operating point of

the PV system, ensuring that it continues to track the new maximum power point (MPP) under the updated conditions.

Between 3 and 4 seconds, where irradiance reaches its lowest point (500 W/m²), a noticeable oscillation in power is observed. This behavior is typical for the P&O algorithm under rapidly changing or low-irradiance conditions and results from the algorithm's periodic perturbations. Despite this temporary instability, the system maintains operation near the MPP, demonstrating the algorithm's ability to adapt to changing conditions.

In the final stage, after 4 seconds, the irradiance returns to 1000 W/m², and both the PV power and the load power rise sharply and stabilize at around 1850 W. The graph shows a very close alignment between the generated PV power and the load power, indicating that the energy extracted from the PV system is being efficiently delivered to the load with minimal losses. This close matching of power confirms the effectiveness of the P&O MPPT in dynamically optimizing the system's output.

Overall, the simulation verifies that the P&O algorithm performs well under both steady-state and varying irradiance conditions. It successfully tracks the MPP across all scenarios, with only brief oscillations during low-irradiance transitions, and ultimately ensures that power generation closely follows load demand.

II.4.2 Incremental Conductance Algorithm

The Incremental Conductance (INC) algorithm is another commonly used method for Maximum Power Point Tracking (MPPT) in photovoltaic (PV) systems. Unlike the Perturb and Observe (P&O) method, which relies on tracking the power change directly, the INC algorithm is based on a more analytical approach that uses the relationship between the derivative of power with respect to voltage and the instantaneous conductance of the PV module. This method allows for more accurate and stable tracking, particularly under rapidly changing environmental conditions.

The mechanism behind the INC algorithm is founded on the principle that the slope of the power–voltage (P–V) curve of a PV module is zero at the maximum power point, positive to the left of the MPP, and negative to the right. Mathematically, this condition is expressed as:

$$\frac{dP}{dV} = \frac{d(VI)}{dV} = I + V\frac{dI}{dV} \tag{2.1}$$

At the maximum power point, this derivative is zero, so the condition becomes:

$$\frac{dI}{dV} = -\frac{I}{V} \tag{2.2}$$

The INC algorithm continuously calculates both the incremental conductance $\frac{dI}{dV}$and the instantaneous conductance $-\frac{I}{V}$, and compares them to determine the direction in which to adjust the operating voltage.

In a PV system, the INC algorithm is implemented within the control logic of a power converter. The system begins by sampling the voltage and current of the PV array. It then calculates the changes in both parameters (ΔV and ΔI) compared to the previous sample. If the condition $\frac{dI}{dV} = -\frac{I}{V}$ satisfied, the system is at the maximum power point, and no adjustment is made. If the result indicates that the operating point is to the left of the MPP $\frac{dI}{dV} > -\frac{I}{V}$, the voltage is increased. Conversely, if it is to the right $\frac{dI}{dV} < -\frac{I}{V}$ the voltage is decreased. This logical process continues in real time, allowing the algorithm to track the MPP accurately, even when solar irradiance or temperature changes suddenly.

As shown in the flowchart below, the algorithm starts by acquiring the previous and current values of voltage and current. It then computes the incremental and instantaneous conductance values and applies the corresponding decision rules. Based on these comparisons, the algorithm adjusts the reference voltage of the PV array and updates the values for the next iteration.

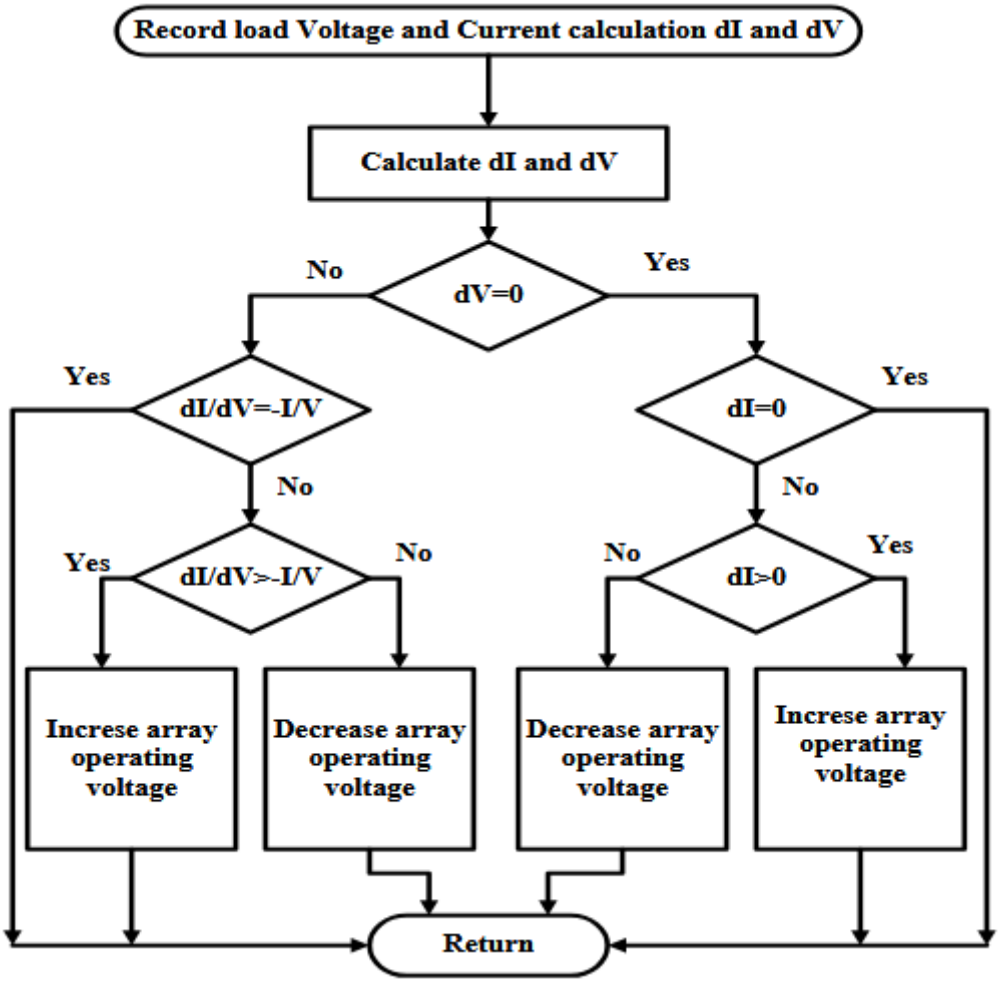


Figure II.15 Flowchart of the Incremental Conductance algorithm

The INC method offers improved performance over the P&O method in terms of stability and responsiveness, especially under dynamic conditions. It reduces the steady-state oscillations around the MPP and is less likely to be misled by temporary fluctuations in power due to rapid environmental changes. However, it does require slightly more complex control logic and additional calculations per iteration, which may increase implementation complexity compared to P&O [31].

Nonetheless, the Incremental Conductance algorithm remains a reliable and effective MPPT strategy for modern PV systems, particularly in applications where precise tracking and high power quality are essential.

II.4.2.1 Simulation of MPPT using incremental conduction algorithm

Figure (II.07) presents the block diagram of the Incremental Conductance (INC) technique implemented in MATLAB/Simulink as part of a photovoltaic (PV) energy system. This

diagram illustrates the integration of a solar panel, a boost converter, and the MPPT control algorithm based on the INC method. The system continuously measures the voltage and current supplied by the PV panel to compute the instantaneous power. The INC algorithm then compares this power with its previous value to determine the appropriate adjustment to the duty cycle of the boost converter. This process guides the operating point of the PV system toward the Maximum Power Point (MPP), thereby ensuring efficient energy extraction under changing solar irradiance conditions.

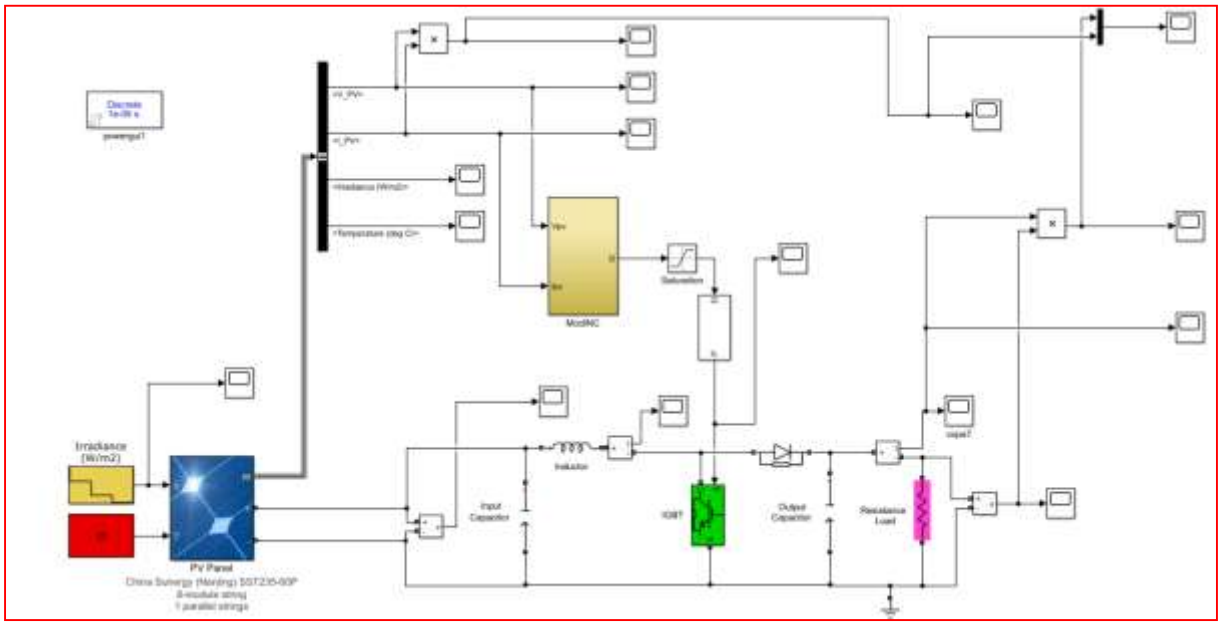


Figure II.16 Bloc de simulation of PV system using INC

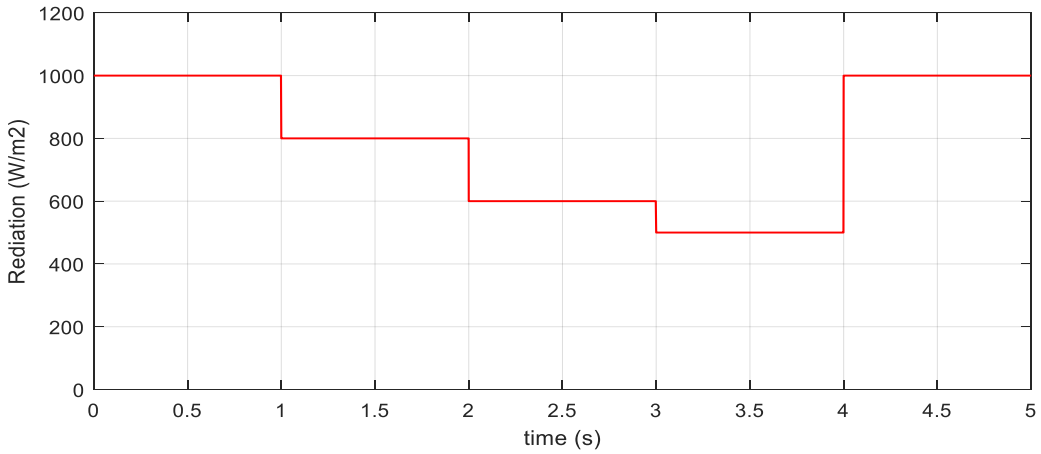


Figure II.17 Radiation varies

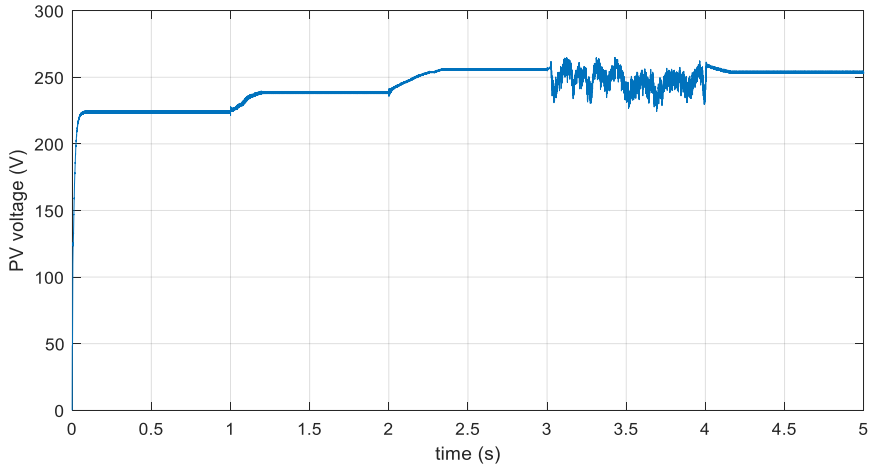


Figure II.18 PV Voltage using INC Algorithm

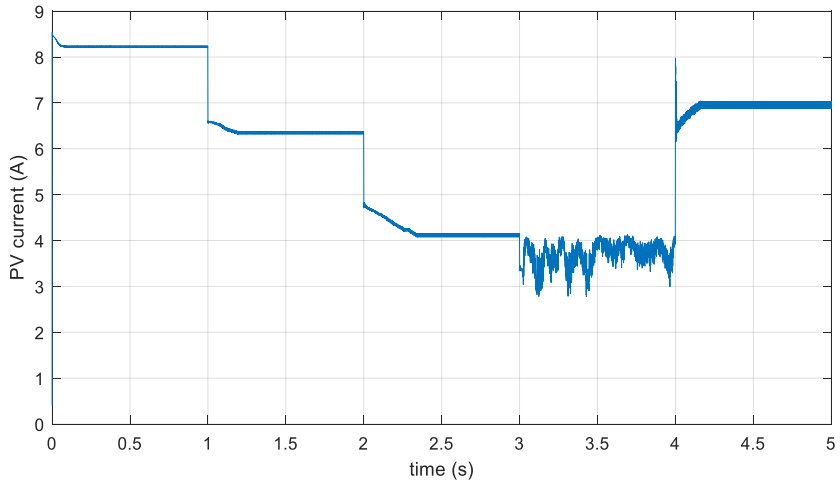


Figure II.19 PV Current using INC Algorithm

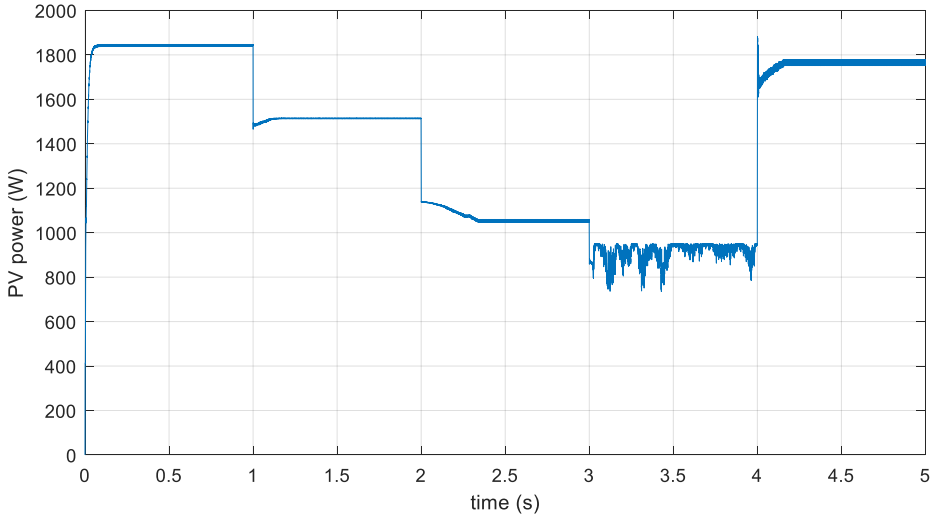


Figure II.20 PV Power using INC Algorithm

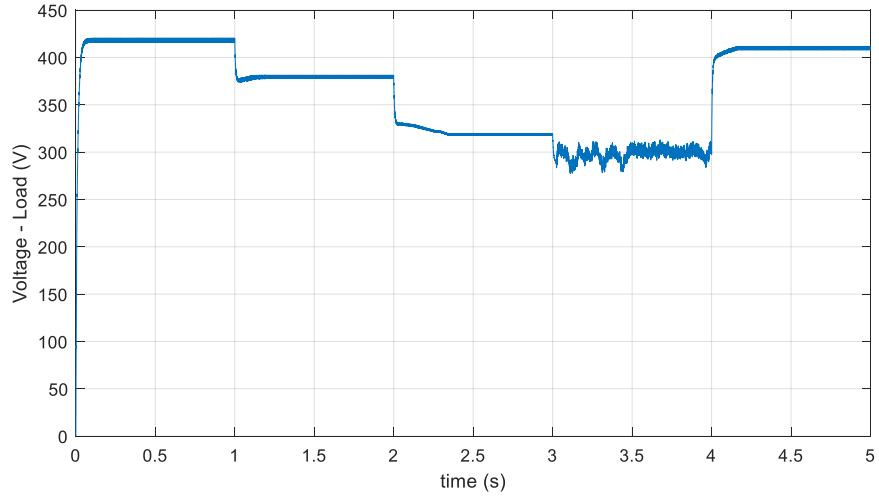


Figure II.21 Voltage Load using INC Algorithm

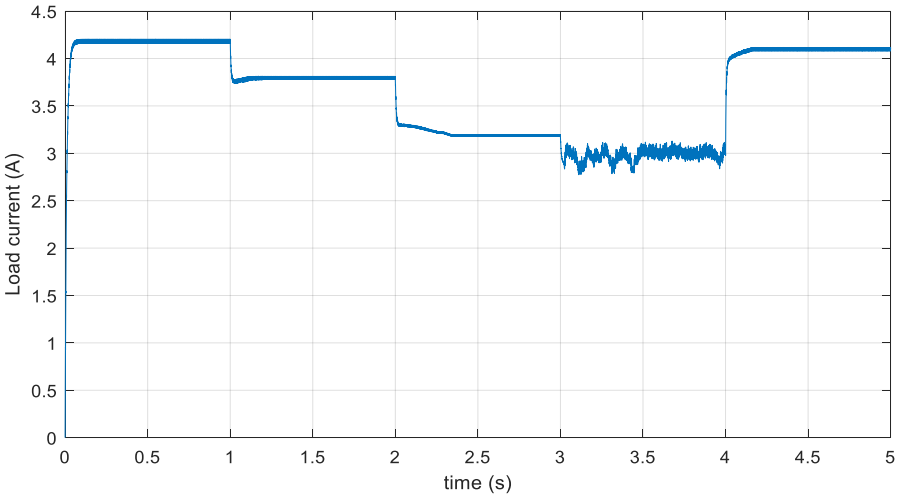


Figure II.22Load Current using INC Algorithm

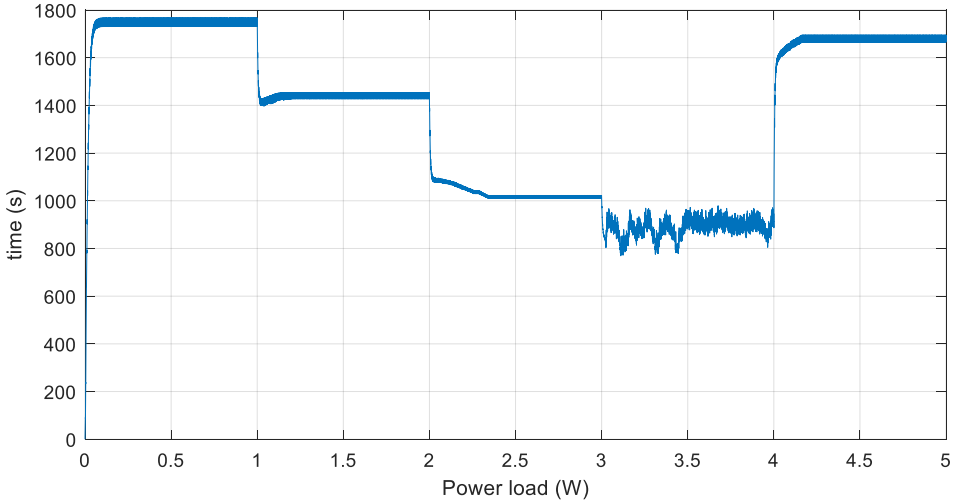


Figure II.23 Power load Current using INC Algorithm

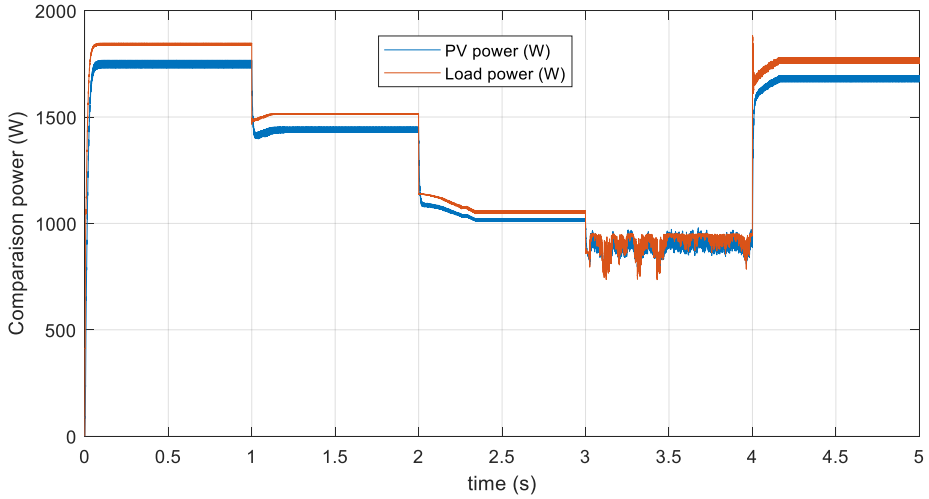


Figure II.24 Comparison of powers using INC Algorithm

During the simulation using the Incremental Conductance (INC) algorithm, the irradiance was gradually varied to test how well the system could adapt. Starting from 1000 W/m², the irradiance dropped step by stepto 800, then 600, then 500 W/m²before finally returning to 1000 W/m². Throughout this process, the ambient temperature remained steady at 25°C.

As expected, the power output from the PV panel changed each time the irradiance level shifted. When irradiance decreased, the maximum power point (MPP) naturally dropped as well, and the INC algorithm had to adjust the system's operating point to track this new optimum.

Looking at the graph, we can see that the blue curve shows the actual power generated by the PV array, while the orange curve reflects the power delivered to the load. For most of the simulation, both curves follow each other very closely. This means the algorithm was doing a good job of matching the available power with what the load needed especially during stable irradiance levels.

However, between 2.5 and 3.5 seconds when the irradiance was at its lowest we can spot a bit of instability in the load power. It starts to fluctuate more noticeably, which indicates that the INC algorithm was having a harder time maintaining a steady operating point in those lower-light conditions. This is a known behavior with INC, as it relies on calculating changes in voltage and current, which can become noisy or less accurate when power levels are lower.

Despite that brief period of fluctuation, the system quickly regains stability once the irradiance goes back up. Toward the end of the simulation, when conditions return to 1000 W/m², the PV and load power curves once again align almost perfectly. This shows that the

INC algorithm is still effective overall it just needs a bit of tuning or filtering to perform better under low-irradiance conditions.

II.5. Comparison between INC and P&O MPPT Algorithms

Figure (II.25) presents a comparative analysis of the output power from a photovoltaic (PV) array when regulated by two different MPPT algorithms: Perturb and Observe (P&O) and Incremental Conductance (INC). The graph plots the instantaneous power supplied by the PV system alongside the power delivered to the load using each algorithm, all under the same irradiance and temperature conditions.

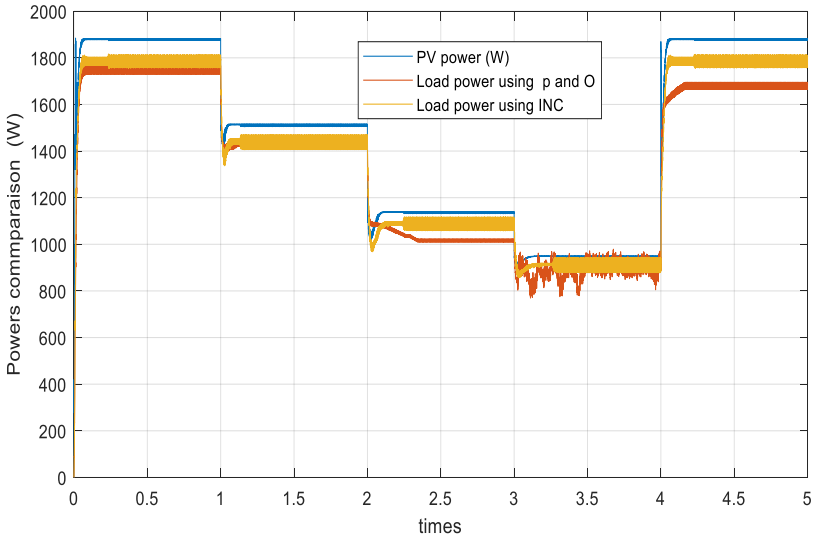


Figure II.25 Comparison of powers using INC and P&O Algorithm

- **From the simulation results we can observe that:**

The PV array power (blue curve) represents the maximum available power under the current environmental conditions.

The P&O algorithm (orange curve) closely follows the PV power curve, with only minor deviations during transient phases when conditions change. This indicates a good tracking performance and relatively fast response to variations in irradiance.

The INC algorithm (yellow curve) also tracks the MPP effectively, but there are more noticeable fluctuations and instability, particularly during the period between 2.5 and 3.5 seconds. These oscillations suggest that the INC method may be more sensitive to rapid changes or noise in the signal, affecting its ability to consistently maintain optimal power output.

Overall, the comparison highlights that while both MPPT methods can follow the maximum power point trajectory, the P&O algorithm provides smoother and more stable tracking under

the simulated conditions. The INC algorithm, though theoretically more accurate due to its use of derivative information, appears to suffer from greater fluctuations and momentary mismatches with the PV array's available power, especially during dynamic transitions.

This simulation thus demonstrates the robustness and simplicity of the P&O algorithm, making it a reliable choice for many PV systems, particularly when computational simplicity and real-time stability are prioritized.

II.6 Conclusion

In this chapter, we presented the principle of Maximum Power Point Tracking (MPPT). We classified the various MPPT algorithms found in the literature. Then, we studied several MPPT control strategies, such as the Perturb and Observe algorithm with fixed and variable step sizes, and the Incremental Conductance algorithm. Extensive results represented for comparisons of MPPT operation. The simulation of a PV module under changing of irradiance is performed to obtain maximum power. Various results are shown that the tracking behavior of maximum power by its actual power (P) using INC and P&O algorithms. There is some more power extracted by using P&O as compared with INC method which is observed from various graphs under various operating conditions. Both methods are suitable to extract maximum power, but the P&O is more superior than INC since it is working based on voltage perturbs of PV system. However, for large value of current of PV system, then INC method will be more suitable.

CHAPTER III

MPPT ALGORITHMS BASED ON FUZZY LOGIC CONTROLLER FOR PV SYSTEM

CHAPTRE III
MPPT ALGORITHMS BASED ON FUZZY LOGIC CONTROLLER FOR PV SYSTEM

III.1 Introduction

The growing global concern over environmental pollution and the depletion of fossil fuel resources has significantly increased interest in renewable energy sources. Among these, solar photovoltaic (PV) systems have become one of the most widely adopted solutions due to their sustainability, low environmental impact, and decreasing installation costs. However, the efficiency of PV systems is heavily influenced by external factors such as solar irradiance and temperature, which causes continuous variation in their operating point.

To ensure that a PV system operates at its Maximum Power Point (MPP)—the point at which it delivers the highest possible power various Maximum Power Point Tracking (MPPT) techniques have been developed. These algorithms dynamically adjust the system's operating voltage or current to extract the maximum power from the solar panels under all environmental conditions [32].

Traditional MPPT methods like Perturb and Observe (P&O) and Incremental Conductance (INC) are widely used due to their simplicity and ease of implementation. However, they often suffer from limitations such as steady-state oscillations, reduced tracking efficiency under rapidly changing conditions, and difficulty in handling the nonlinear characteristics of PV systems [33].

To address these limitations, Fuzzy Logic Control (FLC) has emerged as a powerful alternative. FLC-based MPPT algorithms do not require an accurate mathematical model of the PV system and are capable of dealing with uncertainties and nonlinearities more effectively. By mimicking human decision-making through the use of linguistic rules and fuzzy sets, fuzzy logic offers a flexible and adaptive control strategy for maximizing energy extraction from PV systems. This chapter focuses on the development and analysis of MPPT algorithms based on fuzzy logic controller for PV systems. The goal is to design a fuzzy logic controller that can accurately and efficiently track the MPP under varying environmental conditions, thereby enhancing the overall performance and reliability of PV power generation [34, 35, 36].

III.2 Objective of an MPPT based on Fuzzy Logic Controller

Fuzzy Logic Controller (FLC) is an intelligent control technique that mimics human reasoning and decision-making. In the context of Maximum Power Point Tracking (MPPT) for photovoltaic (PV) systems, fuzzy logic offers a robust and adaptive way to handle the nonlinear and time-varying characteristics of solar panels.

The primary objective of an MPPT controller is to adjust the operating point of the PV system so that it extracts the maximum possible **power** from the solar panels under varying irradiance and temperature conditions. A fuzzy logic-based MPPT controller achieves this without needing an exact mathematical model of the PV array, making it highly suitable for complex and variable systems [37, 38].

III.3 Fuzzy Logic-Based Algorithm

The Fuzzy Logic Controller (FLC) is widely used in Maximum Power Point Tracking (MPPT) systems for photovoltaic installations. Unlike traditional methods such as Perturb and Observe (P&O) or Incremental Conductance (INC)**,** fuzzy logic does not require an accurate mathematical model of the system. It relies on a linguistic and intuitive approach, making it particularly well-suited for nonlinear systems and those subject to disturbances such as rapid changes in irradiance or temperature.

The FLC algorithm operates using two main inputs: the error (E)**,** representing the change in power relative to voltage, and the change in error (ΔE)**.** These two variables are converted into linguistic values using membership functions. Then, a set of logical rules of the "IF... THEN..." type is applied to determine the appropriate corrective action, usually expressed as an adjustment of the reference voltage or the duty cycle of the DC/DC boost converter. Finally, the fuzzy output is defuzzified to generate a numerical control signal usable by the power electronics.

One of the main advantages of the fuzzy logic controller is its robustness against uncertainties and disturbances, as well as its fast response to sudden environmental changes. Additionally, fuzzy logic helps to reduce oscillations around the maximum power point, thereby improving the overall energy efficiency of the system [39]..

III.4 Structure of a Fuzzy Logic Controller for MPPT in PV Systems

A Fuzzy Logic Controller (FLC) for Maximum Power Point Tracking (MPPT) in a photovoltaic (PV) system consists of several interconnected components that work together to

continuously adjust the operating point of the PV system to ensure maximum power extraction. The structure of the controller can be divided into five main stages [36,42]:

1. Measurement Unit

- Measures the PV voltage (V) and current (I) in real-time.
- Calculates the power (P = V × I) at each time step.

$$P(k) = V(k).I(K) \tag{3.1}$$

- Computes the error (E) and the change in error (ΔE) based on power and voltage changes:

$$E(k) = \frac{P(K)-P(K-1)}{V(K)-V(k-1)} \tag{3.2}$$

$$\Delta E(k) = E(K) - E(K-1) \tag{3.3}$$

These values serve as the inputs to the fuzzy controller.

2. Inference

In the inference stage, decisions are made based on the input variables **E** and **ΔE** to determine the output variable **Δα**, using a **rule table** (Table 3.1).

E \ ΔE	NB	NS	ZE	PS	PB
NB	ZE	ZE	NB	NB	NB
NS	ZE	ZE	NS	NS	NS
NE	NS	ZE	ZE	ZE	PS
PS	PS	PS	PS	ZE	ZE
PB	PB	PB	PB	ZE	ZE

Table 3.1 Inference Rule Table

Logical relationships are established between the inputs and the output by defining membership rules. These rules are then organized into a comprehensive inference rule table. For example, according to Table 3.1, if the input variables **E** and **ΔE** have values **PB** (Positive Big) and **ZE** (Zero), this indicates that the operating point is far from the Maximum Power Point (MPP)**.** Based on the rule table, the corresponding value assigned to the output variable **Δu** is **PB**, which means a large positive change in the duty cycle is needed to move the system toward the MPP [42, 43].

3. Defuzzification

This step applies only to the output variable **Δu**. During this stage, **Δu** is converted from a linguistic variable into a numerical value in order to control the power converter and reach the Maximum Power Point (MPP).

This control method offers excellent performance in terms of accuracy and speed in tracking the MPP. However, its main drawback is that its precision depends on the complexity of the rule table used. As a result, it requires a microcontroller with high computational capacity, which inevitably leads to increased energy consumption by the microprocessor and an additional cost [42-43].

- **Fuzzy logic controller (FLC)**

FLC approach often divides challenging systems into many subsystems based on the system's understanding by human experts. In the meantime, a series of basic and easy-to-control principles have been used to mimic the methods of human management in each local working zone. Afterwards, the global control rules are constructed by integrating all local control actions with the fuzzy membership function.

Visually, the conditional statement of "IF-THEN" in the quality language components of human experts associated with the basic models is applied to analysis and synthesis. In recent years, many systems of stability analysis and control synthesis approaches have emerged in fuzzy control theory, in which the Mamdani fuzzy model is commonly used [44].

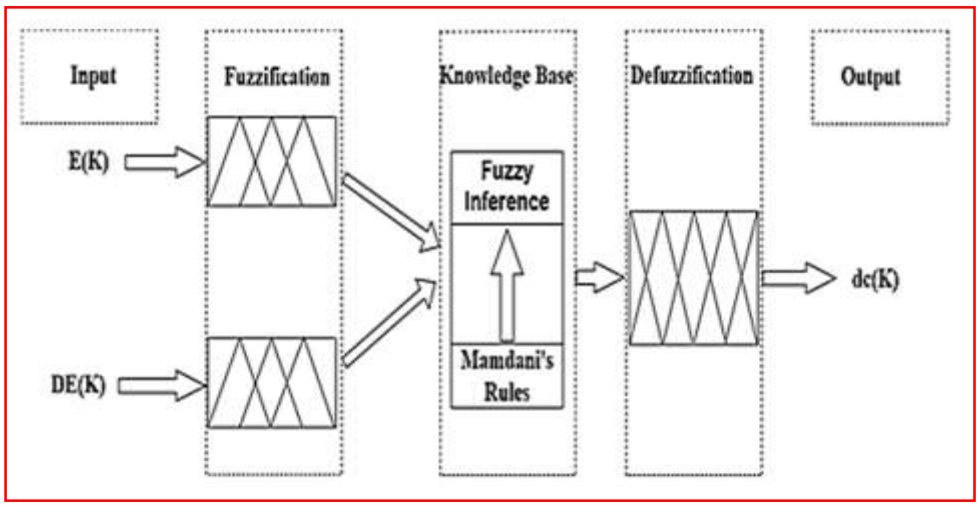


Figure III.1 FLC generality

In renewable energy systems in particular, FLC has become a popular artificial intelligent method for system control. The fact that mathematical modeling is not always necessary to apply FLC to systems is one of its advantages [42].

For PV system MPP monitoring, FLC is a preferred option because to its stability and endurance (Figure III.2).

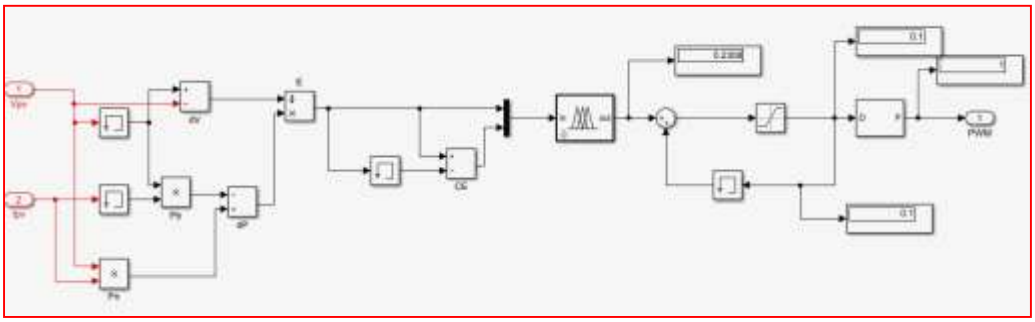
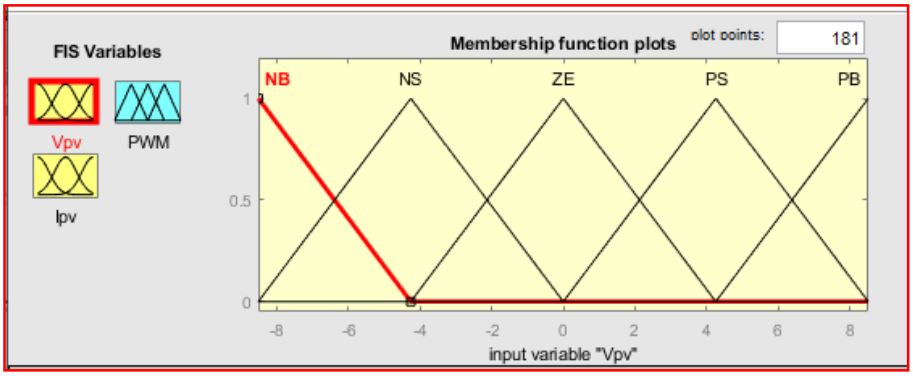


Figure. III.2 bloc of fuzzy logic controller

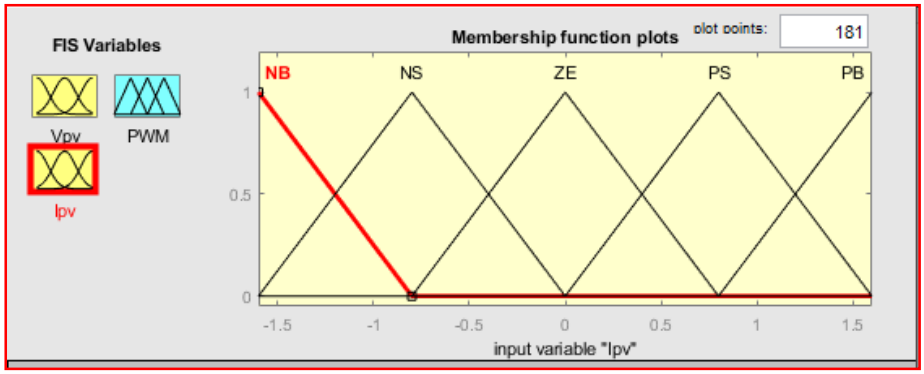
4. Fuzzification

In this context, "fuzzification" refers to the process of giving each variable a degree of uncertainty. Determining the quantity of these fuzzy sets follows an evaluation of the system's behavior. In order to keep select the required dc for the tracking of the MPP when solar irradiance fluctuates rapidly and significantly. For that, this work splits the domain of existence into seven periods for each of the three variables [41-42]:

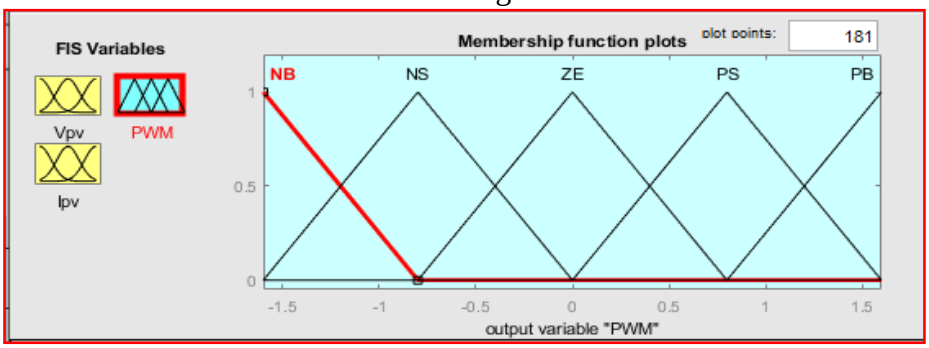
- error (E),
- change in error (ΔE), and
- the output Δu.



a. Error



b. Change error



C. Output control

Figure III.3 Membership function

5. <u>Defuzzification</u>

Defuzzification involves converting linguistic variables into numbers. The fuzzy output of the previous rule is combined with the Max function to form a single fuzzy set. This set is defuzzified and multiplied by the scale factor to obtain a single sequence value. The methodology used for the final stage of the design of the fuzzy controller is the gravity center method. It calculates the growth of the duty cycle [42,44].

III.5. MPPT based Fuzzy logic controller

Using two inputs and one output, the steps involved in applying the MPPT technique based on a Fuzzy Logic Controller (FLC) are outlined as follows [42-44]. Figure III.4 shows the block diagram of the fuzzy logic controller used for MPPT in a photovoltaic (PV) system.

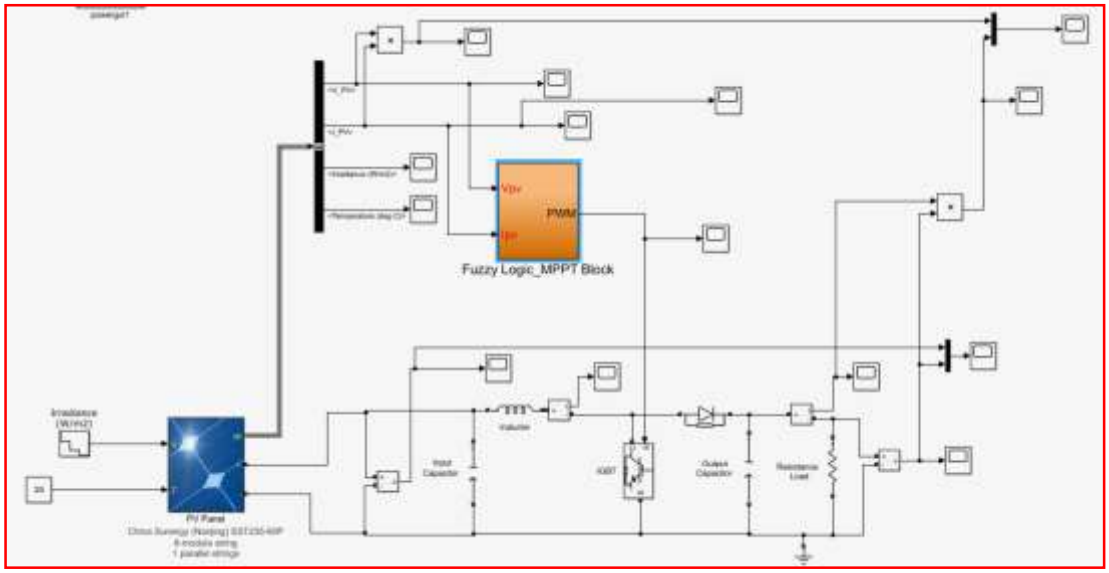


Figure III.4 Simulation bloc of PV system using FLC

III.5.1 Simulation of MPPT using FLC

The figures below show the simulation results of a stand-alone photovoltaic (PV) system, illustrating the PV voltage, PV current, and PV power, as well as the output voltage, output current, and output power, under varying irradiance conditions between 1000 W/m² and 800 W/m².

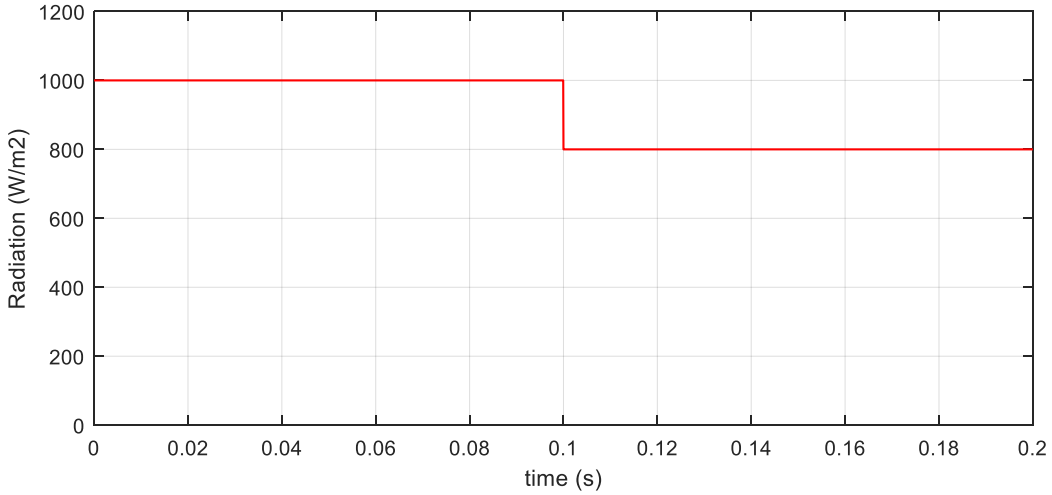


Figure III.5 Radiation varient

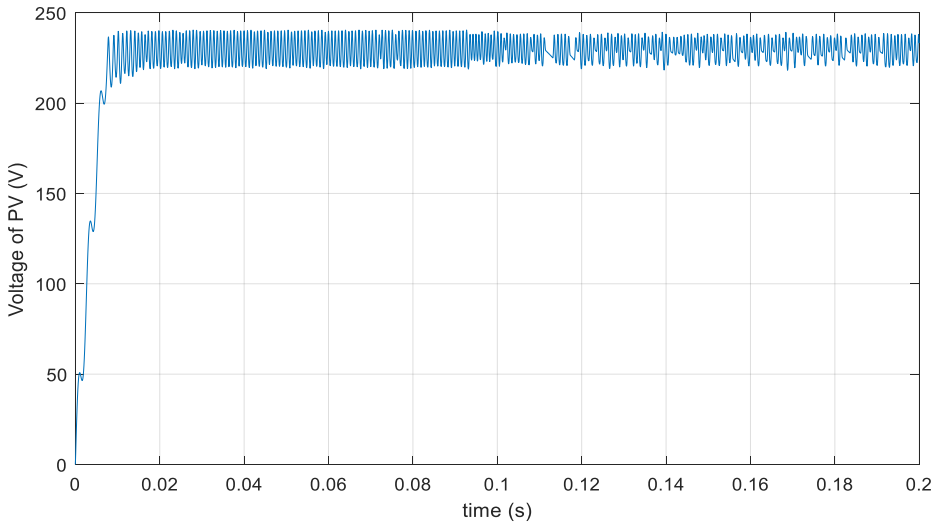


Figure III.6 PV Voltage using FLC

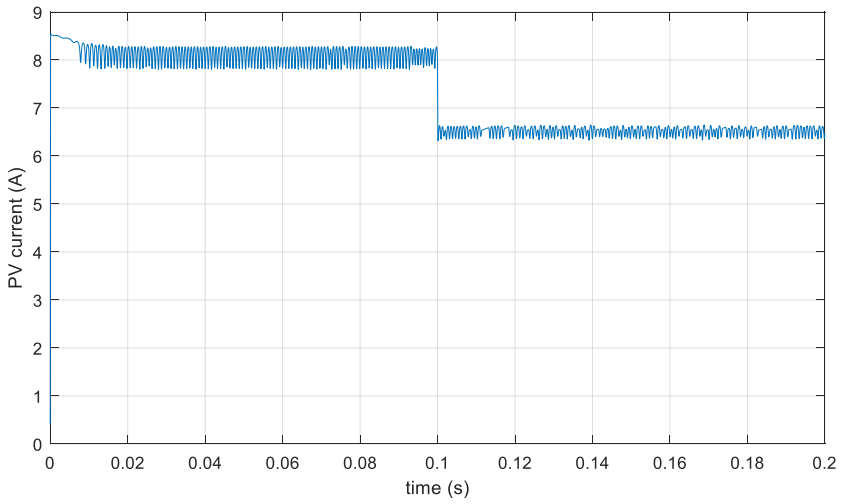


Figure III.7 PV Current using FLC

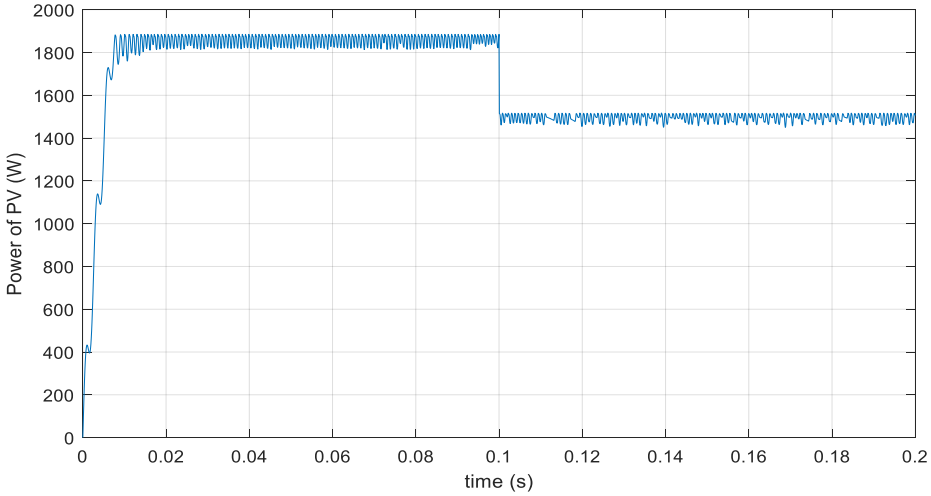


Figure III.8 Power of PV using FLC

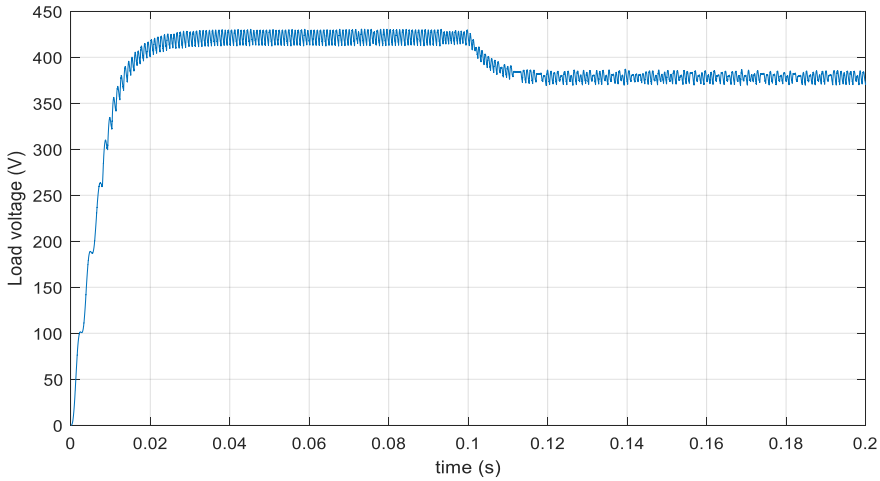


Figure III.9 Voltage Load using FLC

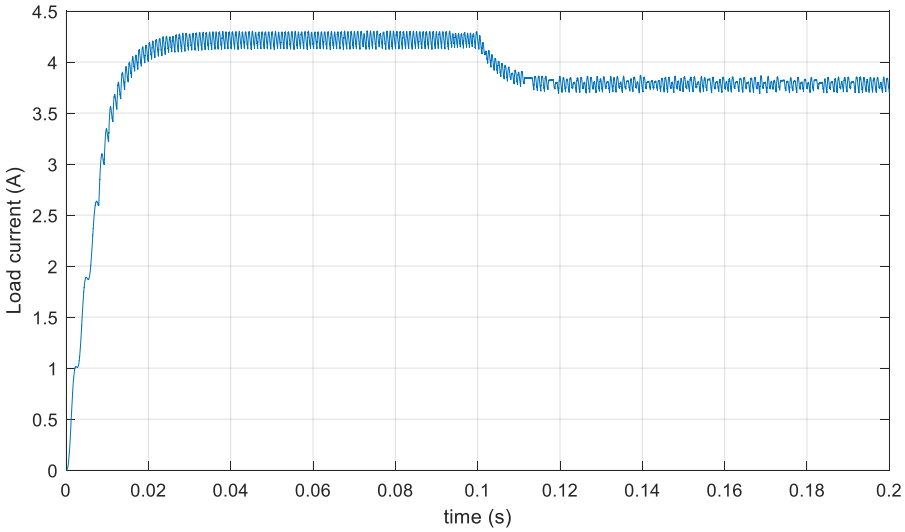


Figure III.10 Load Current using FLC

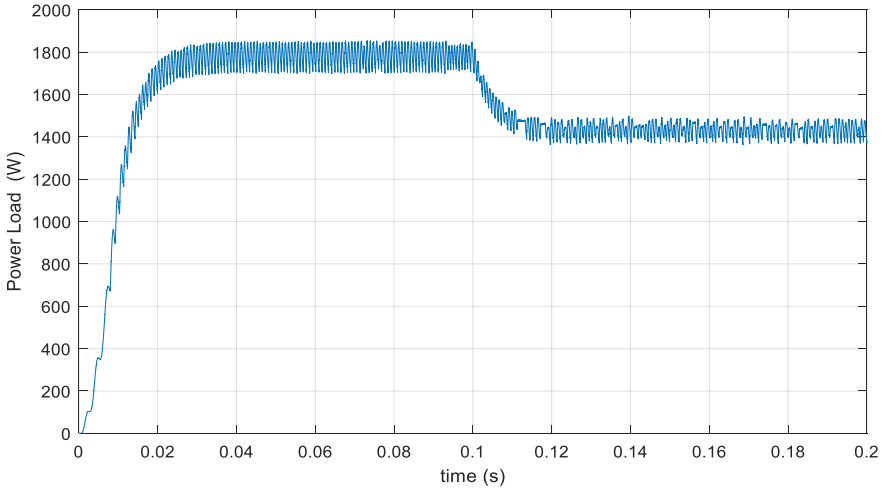


Figure III.11 Power load using FLC

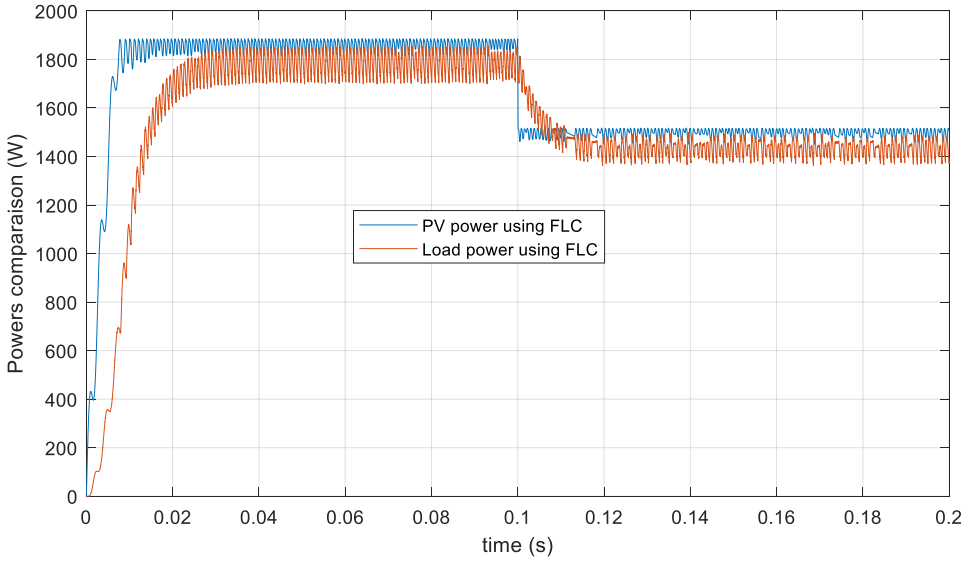


Figure III.12 Comparison of powers using FLC Algorithm

During the simulation, solar irradiance varied between 1000 W/m² and 800 W/m², while the ambient temperature was maintained at a constant 25 °C. As expected, the maximum power output of the photovoltaic (PV) system changed in response to the fluctuations in irradiance. In the final figure, it can be observed that the power generated by the PV system closely matches the load demand, indicating a near-perfect balance between energy production and consumption.

III.6 Comparison between INC, P&O and fuzzy logic MPPT Algorithms

In order to optimize the energy output of photovoltaic systems, we developed three Maximum Power Point Tracking (MPPT) algorithms: the Incremental Conductance (INC) algorithm, the Perturb and Observe (P&O) algorithm, and a method based on fuzzy logic. This comparative study aims to evaluate their respective performance in terms of convergence speed, stability around the maximum power point, implementation complexity, and adaptability to changes in solar irradiance and temperature. The ultimate goal is to determine which algorithm delivers the highest energy efficiency under various operating conditions. Figure III.13 illustrates this comparison.

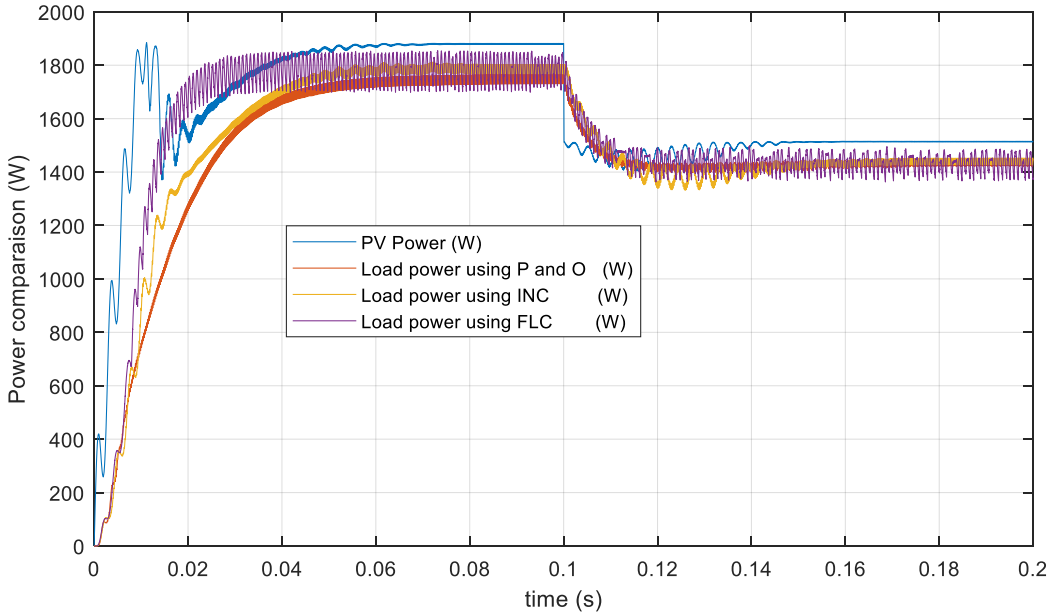


Figure III.12 Comparison of powers using INC - P&O and FLC Algorithm

To analyze the comparison between the Perturb and Observe (P&O), Incremental Conductance (INC), and Fuzzy Logic Controller (FLC) MPPT algorithms based on the curves we can summarize typical key differences observed in such comparisons under identical irradiance and temperature conditions |42-48].

- Tracking Speed (Dynamic Response)
  - **P&O:**

    Moderate tracking speed. Responds by perturbing voltage/current and observing power change. May take longer to reach MPP under fast-changing conditions.
  - **INC:**

    Faster tracking compared to P&O, especially under rapidly changing irradiance. It calculates the derivative of the power w.r.t voltage to make more accurate decisions.
  - **Fuzzy Logic:**

    Often the fastest among the three. Uses rule-based decision-making which can adapt quickly to changes in irradiance and temperature.

- **Steady-State Oscillations**
  - **P&O:**

    Suffers from steady-state oscillations around MPP due to continuous perturbation. This can lead to power loss.

- **INC:**

  Less oscillatory than P&O, especially when finely tuned, since it stops perturbing once the MPP is reached.

- **FLC:**

  Can be designed to have minimal or no oscillations due to adaptive rules and fuzzy decision-making.

Accuracy in Reaching True MPP

- **P&O:**

  May not always reach the exact MPP, especially under variable conditions. Can get stuck if perturbation size is not optimized.

- **INC:**

  More accurate than P&O in reaching the true MPP since it relies on instantaneous conductance slope.

- **FLC:**

  High accuracy depending on the quality of the rule base and membership functions. Can outperform both P&O and INC in complex scenarios.

Performance under Rapidly Changing Conditions

- **P&O:**

  Performs poorly; it can misinterpret power changes due to irradiance variation as a response to its own perturbation.

- **INC:**

  Performs better; can distinguish between power changes due to irradiance vs. voltage changes.

- **FLC:**

  Generally performs best under rapidly changing conditions if well-trained, as it adapts to nonlinearities and external variations.

Implementation Complexity

- **P&O:**

  Simple to implement with low computational requirement.

- **INC:**

  Moderate complexity due to derivative calculation.

- **FLC:**

  Highest complexity among the three due to fuzzy logic rule base, but modern microcontrollers can handle it efficiently.

III.7 Conclusion

In this chapter, we first presented the principle of Maximum Power Point Tracking (MPPT) using a Fuzzy Logic Controller (FLC). A simulation of a photovoltaic (PV) module under varying irradiance conditions was carried out to evaluate its ability to extract maximum power. The results demonstrate the effectiveness of the FLC in tracking the actual maximum power output (P) in real time.

Next, a comparison of simulation results between the Perturb and Observe (P&O), Incremental Conductance (INC), and FLC methods was presented. The advantages of each approach were discussed based on their performance under different operating conditions.

The simulation results show that the P&O algorithm extracts slightly more power than the INC method in various scenarios, mainly due to its voltage-based perturbation approach. While both methods are effective for MPPT, P&O tends to perform better under dynamic conditions. However, when dealing with higher PV system currents, the FLC method proves to be more suitable due to its intelligent control strategy, which provides better adaptability and stability.



CHAPTER IV

PV SYSTEM CONNECTED TO THE GRID BASED ON FUZZY LOGIC CONTROLLER



CHAPTER IV

PV SYSTEM CONNECTED TO THE GRID BASED ON FUZZY LOGIC CONTROLLER

IV. 1 Introduction

The connection of a photovoltaic (PV) system to the electrical grid is made possible through power electronics. In this chapter, we present a study on the integration of a PV system with the electrical grid. Simulation results are presented and discussed.

IV.2 General Structure of a Grid-Connected to PV System

There are two main configurations for grid-connected to the PV system:

IV.2.1 PV System directly connected to the Grid

This type of installation consists of a photovoltaic generator directly connected to the electrical grid via an inverter [47].

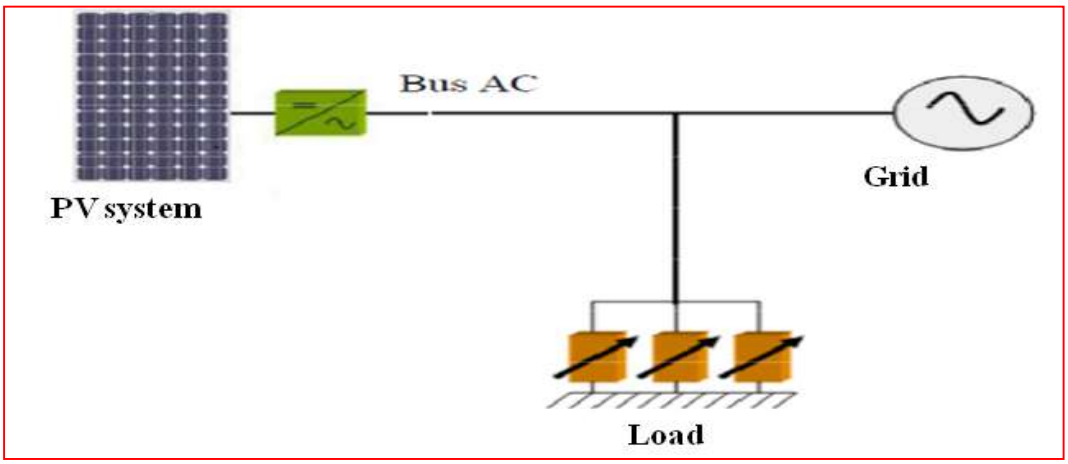


Figure IV.1 Directly Grid-Connected Photovoltaic Systems [49]

IV.2.2 Using a DC/AC Converter

The PV system is connected to a DC/DC power converter, which adjusts the voltage to meet the system's requirements. This voltage is then fed into an inverter that produces a modulated AC voltage. A filter is subsequently used to reduce the harmonic content, resulting in an output voltage that meets the standards of the electrical grid and can therefore be injected into it.

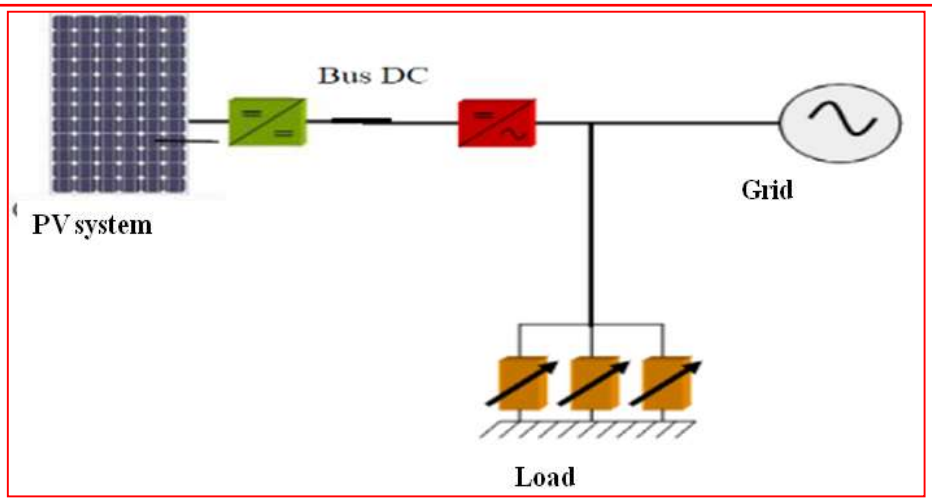


Figure IV.2 Grid-Connected PV System Using a DC/AC Converter [49]

IV.3 DC/AC Inverter for Photovoltaic System

The three phase inverter is a static converter that transforms direct DC voltage to AC voltage. The output voltage of the inverter should be as close as possible to a sine wave, meaning that the harmonic distortion must be very low. The quality of this waveform mainly depends on the control technique used.

IV.3.1 Inverter Structure

Figure 4.3 shows a three-phase voltage source inverter. It consists of three legs, each made up of bidirectional current switches that are controlled for both turn-on and turn-off operations. These switches are typically implemented using IGBT transistors paired with anti-parallel diodes. On the DC side, energy is stored using a voltage capacitor. At the output, a passive filter is used to connect the voltage-source inverter to the electrical grid [50].

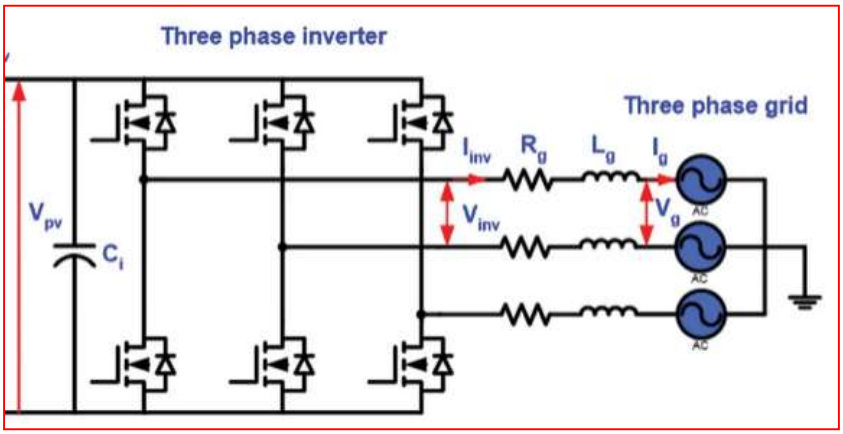


Figure IV.3 Three-phase voltage inverter connected to grid

In practice, the two semiconductors in the same inverter leg are controlled in a complementary manner: when one conducts, the other is turned off. In reality, the state where both switches are simultaneously on only occurs briefly during switching transitions. To prevent a short circuit caused by the switching delay, a dead time is inserted between the turn-off command of one switch and the turn-on command of the other. However, under the assumption of instantaneous switching, this mode of operation is not considered, and therefore, there is no risk of short-circuiting the capacitor.

IV.3.2 PWM control

The use of Pulse Width Modulation (PWM) helps reduce the lower-order current harmonics, thereby improving the power factor. However, this technique does not completely eliminate harmonic distortion. PWM control is largely inspired by techniques used in information transmission. It involves modulating a high-frequency triangular carrier wave with a much lower-frequency sinusoidal reference wave. This modulation process is used to control the switching of the inverter and shape the output voltage waveform accordingly [51, 52].

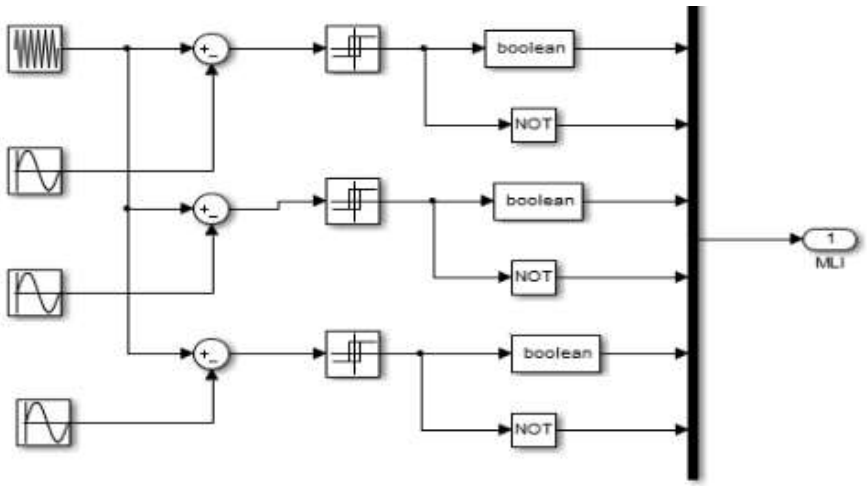


Figure IV.4 Principe of PWM Control

V.4 Simulation of a Grid-Connected PV System

Figure IV.5 presents the simulation block diagram of a PV system with MPPT based on fuzzy logic controller, connected to the electrical grid via an AC/DC inverter. A passive filter RLC is used to facilitate the connection to the grid and to suppressing harmonics pollution. Simulation results are presented in figures bellows:

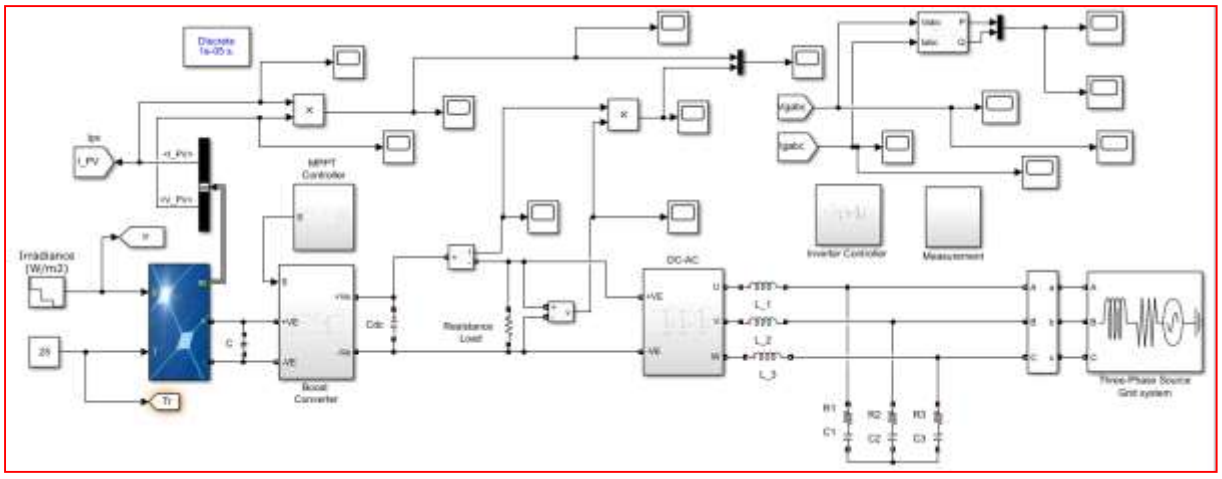


Figure IV.5 Simulation bloc of PV system connected to Grid

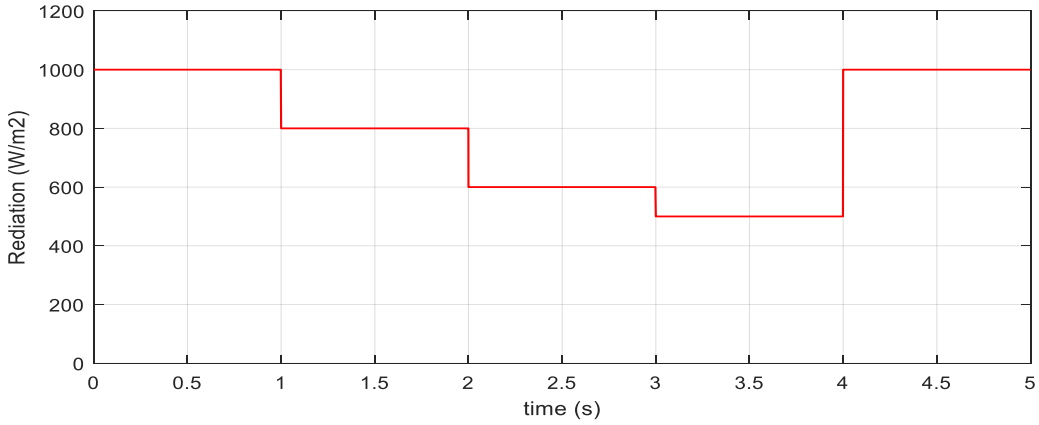


Figure IV.6 Radiation varies

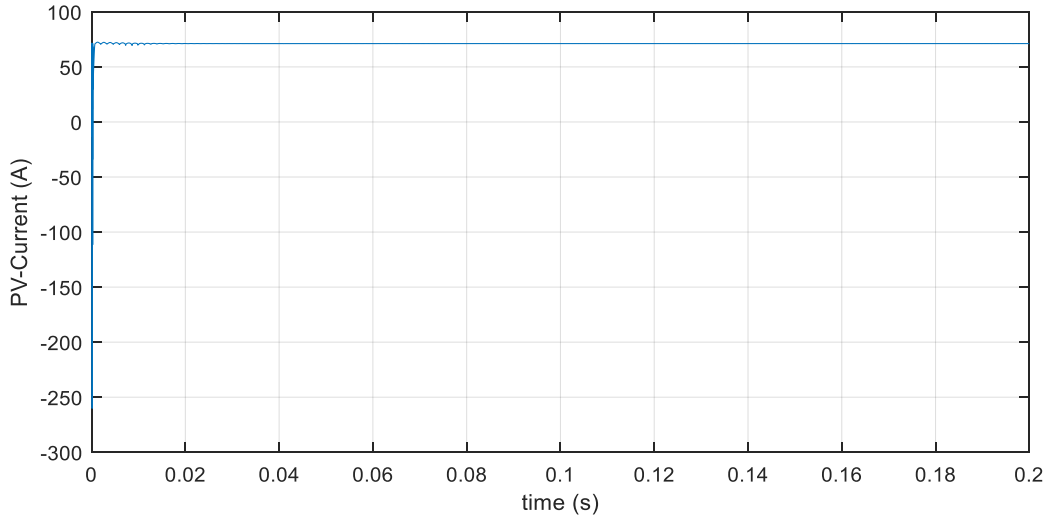


Figure IV.7 PV current

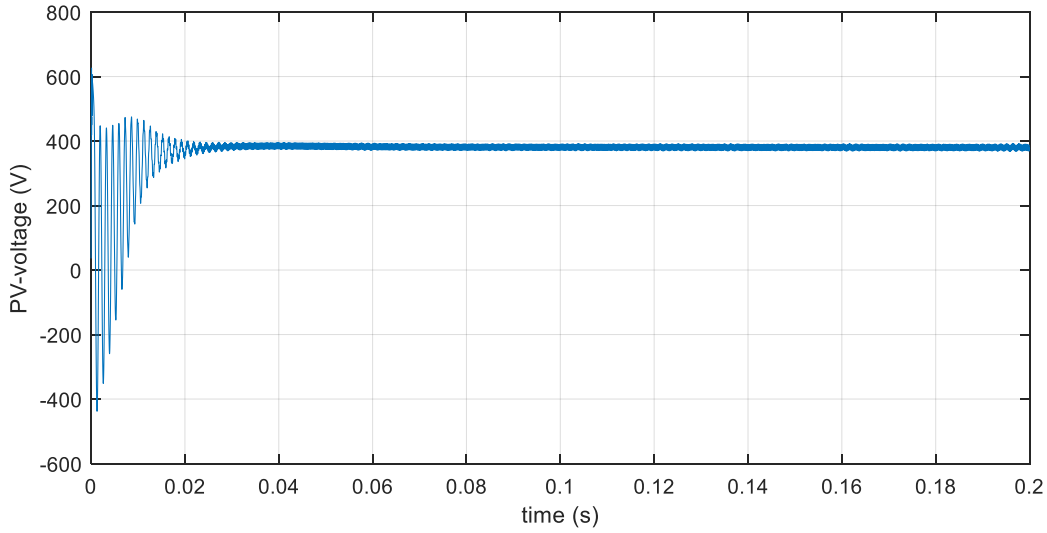


Figure IV.8 PV voltage

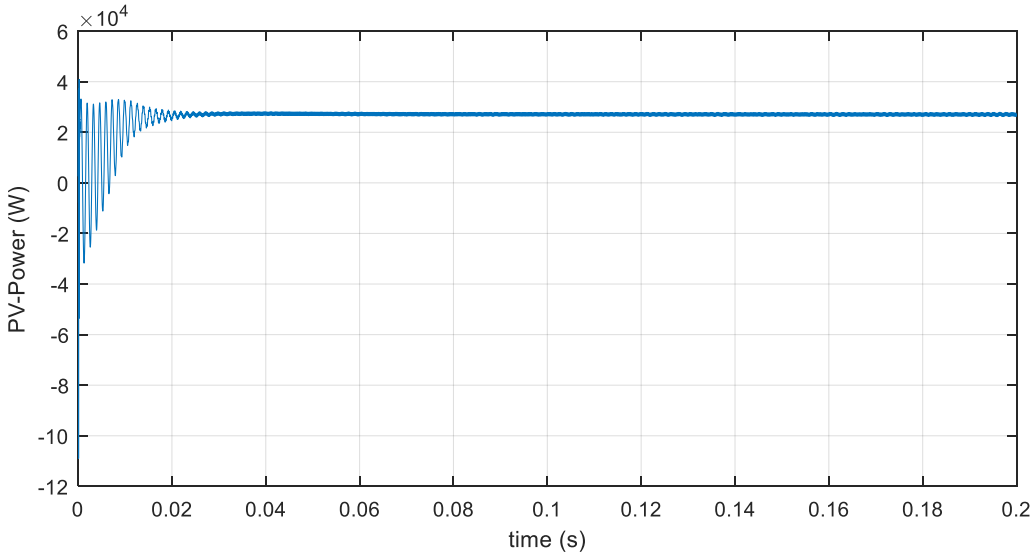


Figure IV.9 PV power

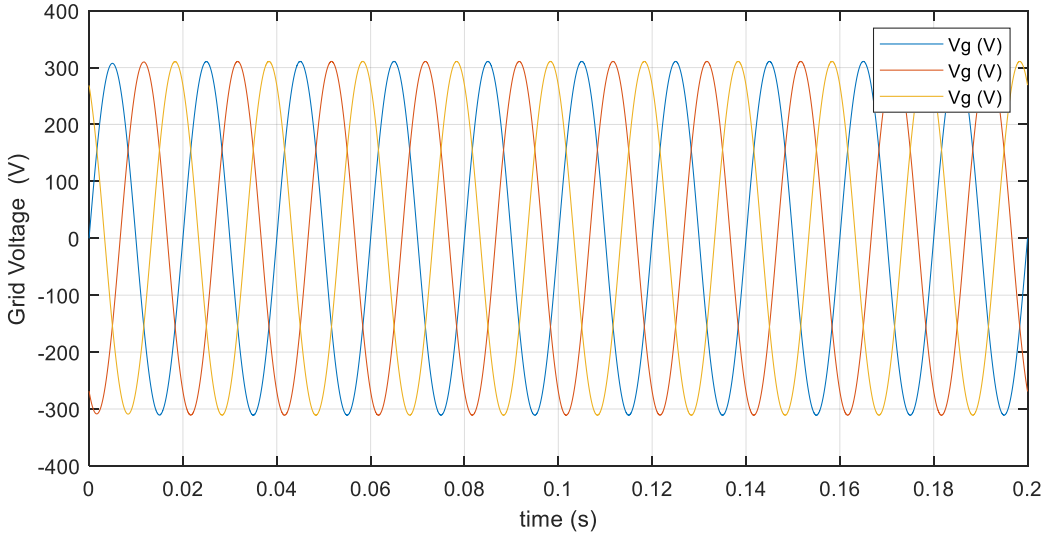


Figure IV.10 Grid Voltage

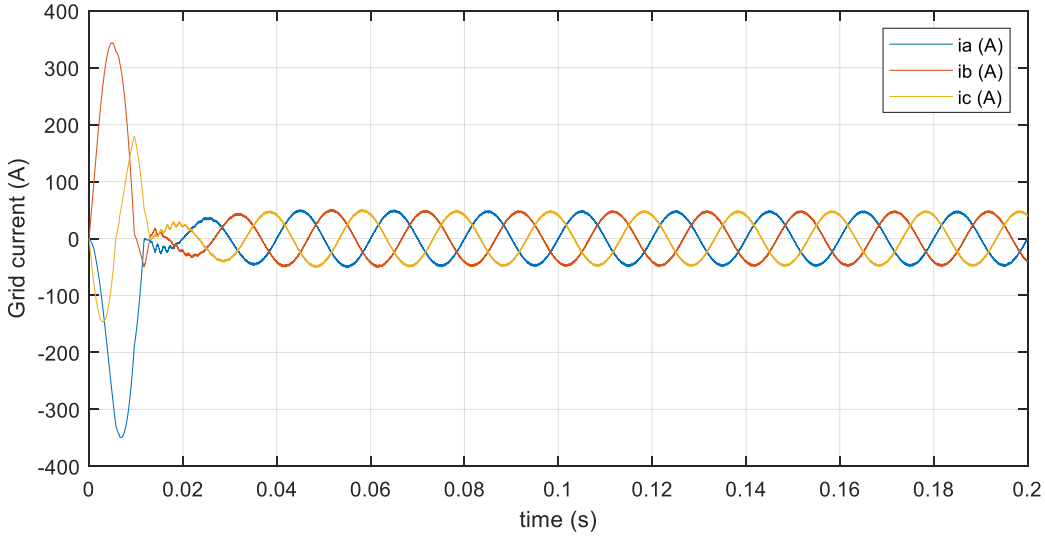


Figure IV.11 Grid current

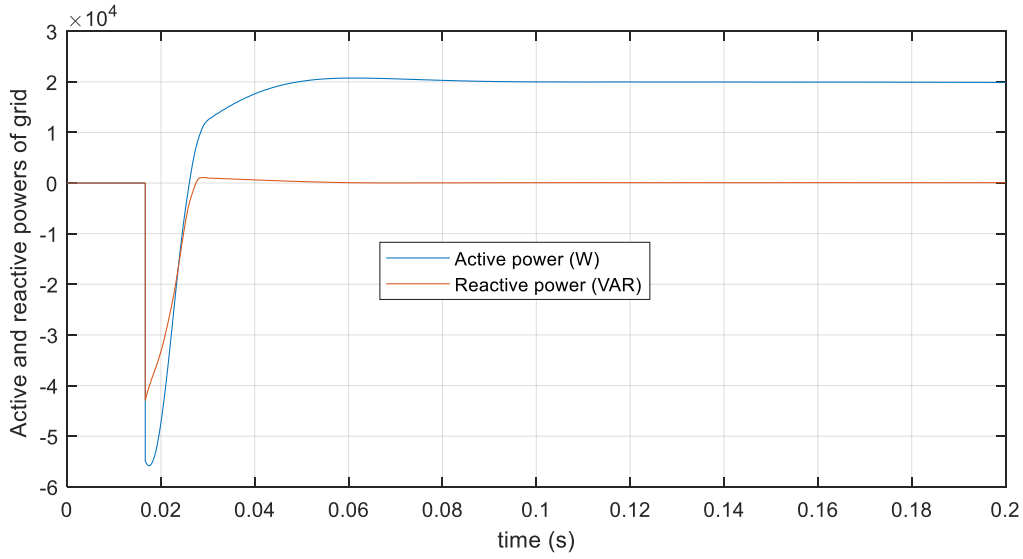


Figure IV.12 Active and reactive powers of grid connected to PV system

The simulation results highlight the benefits of connecting a photovoltaic (PV) system to the electrical grid. It is observed that, despite a variation in irradiance from 1000 W/m² to 500 W/m² and a constant temperature of 25 °C, the electrical parameters of the solar panel (current, voltage, and power see figures 7, 8 and 9) remain nearly unchanged. This stability is due to the compensation of reactive power provided by the electrical grid, see figures 10,11 and 12.

Furthermore, a similar behavior is observed on the grid side. An important observation from the last three figures is that both voltage and current waveforms are perfectly sinusoidal, while the active power remains constant and the reactive power is consistently zero.

IV. Conclusion

In this chapter, we examined the performance of a grid-connected photovoltaic (PV) system using a fuzzy logic-based MPPT algorithm. The simulation results confirm the effectiveness of this control method in maximizing power extraction from the solar panels, even under varying irradiance conditions. The connection to the electrical grid ensures continuous energy supply and reactive power compensation, contributing to system stability and improved power quality.

GENERAL CONCLUSION

This thesis has addressed the modeling, simulation, and performance evaluation of photovoltaic (PV) systems, with a particular emphasis on the application of various Maximum Power Point Tracking (MPPT) algorithms under dynamic environmental conditions. The objective was to ensure optimal energy extraction from PV systems while maintaining system efficiency, stability, and adaptability across different configurations.

In the first chapter, a general overview of photovoltaic energy was presented, including the physical principles of the photovoltaic effect, historical advancements, and classification of PV systems into standalone, grid-connected, and hybrid types. The chapter also introduced the modeling of key components such as the PV generator and the DC-DC boost converter, followed by simulations that evaluated system behavior under variable irradiance and temperature. Additionally, the advantages and limitations of PV systems were discussed with respect to reliability, cost, and environmental impact.

The second chapter focused on the concept of Maximum Power Point (MPP) tracking. Two widely used conventional techniques Perturb and Observe (P&O) and Incremental Conductance (INC) were implemented and analyzed. Simulation results demonstrated that while both algorithms are effective under stable operating conditions, their performance is impacted by environmental variability. The comparative analysis showed that the P&O method is simpler to implement but suffers from oscillations around the MPP, whereas the INC method provides better accuracy at the expense of computational complexity.

In the third chapter, an intelligent MPPT technique based on fuzzy logic control (FLC) was proposed. The design of the fuzzy logic controller was detailed, including the definition of input/output variables, membership functions, and rule base. Simulation results confirmed that the FLC algorithm significantly improves system response under rapidly changing irradiance and temperature. It also minimizes steady-state oscillations and enhances tracking precision compared to conventional methods.

The fourth and final chapter extended the study to a grid-connected PV system controlled by fuzzy logic-based MPPT. The simulation of this system demonstrated its ability to maintain high power quality and ensure stable energy injection into the grid. The results highlighted the benefits of reactive power compensation and sinusoidal voltage and current waveforms, regardless of irradiance fluctuations.

In conclusion, each MPPT technique presents distinct characteristics:

- Perturb and Observe (P&O) is advantageous for its simplicity and low computational cost but is less efficient under dynamic weather conditions.
- Incremental Conductance (INC) offers improved accuracy in MPP tracking but introduces increased algorithmic complexity and slower response times under rapid changes.
- Fuzzy Logic Control (FLC) outperforms both conventional methods in terms of adaptability, responsiveness, and accuracy, particularly in nonlinear and time-varying environments. However, it requires higher processing capabilities and increases implementation complexity.

The choice of MPPT algorithm must therefore be guided by the specific requirements of the PV system, such as desired precision, available hardware, and environmental context. Additionally, the integration of fuzzy logic-based MPPT into grid-connected systems further enhances energy efficiency and power quality, confirming its potential for advanced renewable energy applications.

This study contributes to the ongoing development of intelligent control strategies for photovoltaic systems and highlights the importance of accurate modeling and adaptive algorithms in achieving optimal and sustainable solar energy production.

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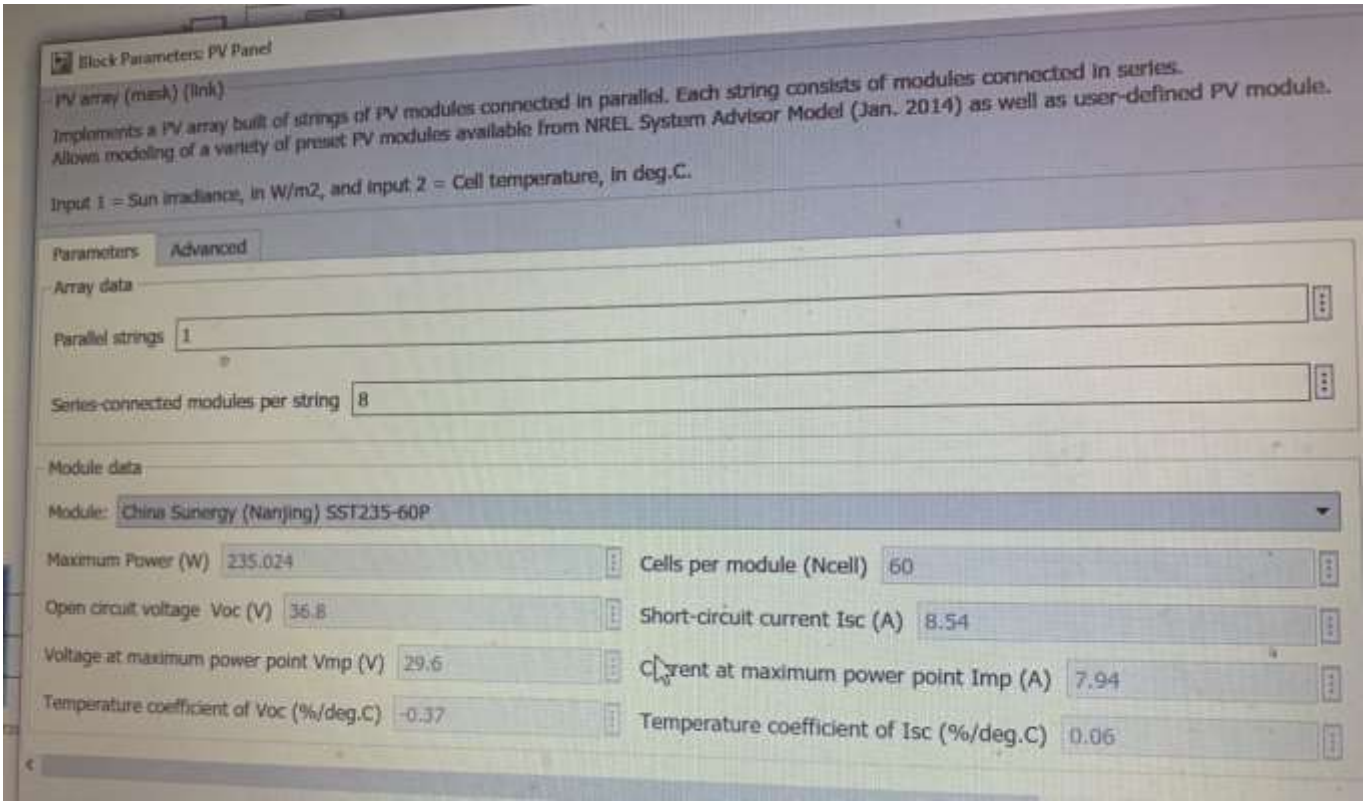
Appendix A

❖ Photovoltaic (PV) System Parameters

Parameter	Symbol	Value	Unit
Peak power of PV panel	Pmax	250	W
Voltage at maximum power	Vmpp	30	V
Current at maximum power	Impp	8.33	A
Open-circuit voltage	Voc	37	V
Short-circuit current	Isc	8.8	A
Nominal operating cell temperature	TNOCT	45	°C
Temperature coefficient (Pmax)	—	-0.45	%/°C
Standard irradiance	G	1000	W/m²
Ambient temperature	T	25	°C
DC load voltage	—	24	V

❖ China Sunergy (Nanjing) SST235-60P - Technical Specifications

Parameter	Value
Rated Power (Pmax)	235 W
Maximum Power Voltage (Vmpp)	29.6 V
Maximum Power Current (Impp)	7.97 A
Open-Circuit Voltage (Voc)	36.8 V
Short-Circuit Current (Isc)	8.54 A
Module Efficiency	14.5 %
Dimensions	1638 × 982 × 40 mm
Weight	19 kg
Cell Type	Polycrystalline (156×156 mm), 60 cells
Glass	3.2 mm tempered, anti-reflective
Frame	Anodized aluminium, silver or black
Operating Temperature	-40 °C to +85 °C
Temperature Coefficient (Pmax)	-0.43 %/°C
Temperature Coefficient (Voc)	-0.40 %/°C
Temperature Coefficient (Isc)	+0.08 %/°C
Max System Voltage	1000 V
Bypass Diodes	3 included
Certifications	IEC 61215, IEC 61730, TÜV, UL
Warranty	10 years product, 25 years performance
Performance Guarantee	≥97.5% (1st yr), ≥80% (25 yrs)
Wind Load	2400 Pa
Snow Load	7200 Pa
Corrosion Tests	Passed salt-mist and ammonia tests



Appendix B

Algorithm MPPT using P&O

```
function D = PO(Vpv,Ipv)
 Dmax=0.9;
 Dmin=0.1;
 Dinit=0.9;
 deltaD=1e-4;
 persistent Dpre Ppre Vpre;

 %first run
     if isempty(Dpre)
         Dpre=Dinit;
         Vpre=0;
         Ppre=0;
     end
 Ppv=Vpv*Ipv;
 dp=Ppv-Ppre;
 dv=Vpv-Vpre;

     if dp~=0
             if(dp>0)
                     if(dv<0)
                         D=Dpre+deltaD;
                     else
                         D=Dpre-deltaD;
                     end
             else
                     if(dv<0)
```

```
                        D=Dpre-deltaD;
                    else
                        D=Dpre+deltaD;
                    end
                end
    else
          D=Dpre;
    end

    if D>=Dmax || D <= Dmin
        D=Dpre;
    end

    Ppre=Ppv;
    Vpre=Vpv;
    Dpre=D;
end
```

Algorithm MPPT using INC

```
% f= 10000hz (G)
function D  = ModINC(V, I)

Dinit = 0.3;  %Initial value for D output
Dmax = 0.45;   %Maximum value for D
Dmin = 0.2;   %Minimum value for D
deltaD =2e-5 ; %Increment value used to increase/decrease the duty cycle D


persistent Vold Pold Dold M Iold;

dataType = 'double';

if isempty(Vold)
    Vold=0;
    Pold=0;
    Iold=0;
    Dold=Dinit;
    M=1;
end
P= V*I;
dV= V - Vold;
dP= P - Pold;
dI= I - Iold;
M=abs(dP);

if M < 0.005
    D=Dold;
else
    if dV == 0
        if dI == 0
            D=Dold;
        elseif dI>0
            D=Dold - (M*deltaD);
        else
            D=Dold + (M*deltaD);
        end
    else
```

```
        if dI/dV == -I/V
            D=Dold;
        elseif dI/dV>-I/V
           D=Dold - (M*deltaD);
        else
           D=Dold + (M*deltaD);
        end
    end
end

if D >= Dmax | D<= Dmin
    D=Dold;
end

Dold=D;
Vold=V;
Pold=P;
Iold=I;
```