Université Mohamed Khider de Biskra
Faculté des Sciences et de la Technologie
Département de génie électrique

MÉMOIRE DE MASTER

Sciences et Technologies
Automatique
Automatique et informatique industrielle

Réf. :

Présenté et soutenu par :
Kateb AbdelMoula / Deghiche Mohamed Sami

Le : lundi 2 juin 2025

A Comparative Study Of The MPPT Techniques In Photovoltaic Systems

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Dedication

First and foremost, I thank Almighty Allah for granting me strength, patience, and guidance throughout this journey. Without His grace, this achievement would not have been possible. I dedicate this thesis to my beloved parents and dear family, whose endless love, encouragement, and support have been the foundation of my success. I also extend my heartfelt appreciation to everyone who assisted me in any way during the completion of this work. Your contributions, no matter how big or small, are deeply valued and sincerely acknowledged.

Acknowledgments

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Abstract

In our study, we analyze and implement MPPT techniques to enhance photovoltaic (PV)system performance using MATLAB/Simulink. We improve standard Perturb and observe (P&O) and Particle Swarm Optimization (PSO) algorithms, and develop hybrid approaches like fuzzy logic with P&O and an Incremental Conductance (IC) method. These techniques are tested under varying environmental conditions to ensure consistent operation at the maximum power point. The goal is to evaluate and improve MPPT strategies for more efficient and reliable solar energy systems.

Keywords : MPPT,P&O,IC,FLC,PSO,PV

ملخص

في دراستنا، نقوم بتحليل وتطبيق تقنيات MPPT لتحسين أداء أنظمة الطاقة الكهروضوئية (PV) باستخدام MATLAB/Simulink. ونُحسّن خوارزميات P&O و PSOالقياسية، ونطور أساليب هجينة مثل المنطق الضبابي مع P&Oوطريقة التوصيل التزايدي .(IC) تُختبر هذه التقنيات في ظروف بيئية متنوعة لضمان ثبات التشغيل عند أقصى نقطة قدرة. الهدف هو تقييم وتحسين استراتيجيات MPPT لأنظمة طاقة شمسية أكثر كفاءة وموثوقية.

كلمات مفتاحية:MPPT,P&O,IC,FLC,PSO,PV

Résumé

Dans notre étude, nous analysons et mettons en œuvre des techniques MPPT pour améliorer les performances des systèmes photovoltaïques (PV) grâce à MATLAB/Simulink. Nous améliorons les algorithmes P&O et PSO standard, et développons des approches hybrides comme la logique floue avec P&O et une méthode de conductance incrémentale (IC). Ces techniques sont testées dans des conditions environnementales variables afin de garantir un fonctionnement constant au point de puissance maximale. L'objectif est d'évaluer et d'améliorer les stratégies MPPT pour des systèmes d'énergie solaire plus efficaces et plus fiables.

Mote-cles: **MPPT,P&O,IC,FLC,PSO,PV**

Chapter I: Generality on photovoltaic system

Chapter II: MPPT and Power Converters in Solar Energy Systems

Chapter III: Simulation & Results

I	Current
V	Voltage
PV	Photovoltaics
PVG	Photovoltaics Generator
MPPT	Maximum power point tracking
MPP	Maximum power point
DC	Direct Current
AC	Alternating current
Isc	short circuit
Voc	Voltage Open Circuit
I(ph)	the photogenerated current sunlight.
I0	the saturation current of the diode, which is a function of temperature.
q	the elementary charge (1.602×10^{-19} C).
V	the output voltage of the cell.
n	the ideality factor (typically between 1 and 2).
k	Boltzmann's constant (1.38×10^{-23} J/K).
T	the temperature in Kelvin (K).
P&O	Perturb and Observe
IC	Incremental Conductance
PSO	Particle Swarm Optimization
IGBT	Insulated Gate Bipolar Transistor
MOSFET	metal oxide semiconductor field effect transistor
PWM	Pulse Width Modulation
D	duty cycle
NB	Negative Big

NM	Negative Medium
NS	Negative Small
ZE	Zero
PS	Positive Small
PM	Positive Medium
PB	Positive Big

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Chapter II: MPPT and Power Converters in Solar Energy System

Chapter III: Simulation & Results

General Introduction

General Introduction

The rapid growth of industry and population around the world has led to a huge increase in energy demand. Traditional energy sources are struggling to meet these needs, and at the same time, concerns about climate change are pushing us towards cleaner and more sustainable solutions. Among the different renewable energy options, solar energy stands out as one of the most promising. It is abundant, clean, and offers the possibility of producing electricity in a decentralized way through photovoltaic systems. **[1]**

However, the efficiency of PV systems depends heavily on environmental conditions like sunlight intensity and temperature. Changes in these factors can cause the output power of PV panels to drop if the system isn't properly controlled. To ensure that PV systems always deliver their maximum possible power, it is essential to use Maximum Power Point Tracking techniques. **[1]**

In this thesis, we focus on studying and improving MPPT methods. Traditional MPPT techniques like Perturb and Observe and Incremental Conductance are widely used because they are simple and easy to implement. P&O works by slightly changing the voltage and observing if the power increases or decreases, while IC uses calculations based on the slope of the power-voltage curve. Even though these methods are effective, they have some drawbacks, especially when environmental conditions change quickly. They can cause oscillations around the maximum point or slow tracking speeds, leading to energy losses. **[1]**

To overcome these issues, we also explore intelligent MPPT methods such as Fuzzy Logic Control and Particle Swarm Optimization. Fuzzy Logic Control uses human-like reasoning to deal with the nonlinear and uncertain behavior of PV systems, improving stability and response time. PSO, inspired by the social behavior of animals like birds and fish, offers a powerful optimization technique that can find the maximum power point more quickly and accurately than traditional methods. **[1]**

The main objective of our research is to study various MPPT techniques and apply them in MATLAB/Simulink, in order to compare their performance under different environmental conditions and explore possible improvements or hybrid solutions. By combining the strengths of traditional and intelligent methods, we aim to enhance the reliability, efficiency, and energy output of photovoltaic systems, contributing to the advancement of clean energy technologies. **[1]**

Chapter I: Generality on photovoltaic system

I. Introduction

I.1 History of Photovoltaic Technology

Photovoltaic (PV) technology has a long and fascinating history that began with the discovery of the photovoltaic effect by Edmond Becquerel in 1839, when he found that light could generate an electric current in certain materials. This discovery was further developed in 1876 by William Grylls Adams and Richard Evans Day, who observed the effect in solid selenium. A major milestone came in 1905 when Albert Einstein explained the photoelectric effect, offering a deeper understanding of how light interacts with matter—an achievement that earned him the Nobel Prize. In 1954, Bell Laboratories built the first efficient silicon-based solar cell, achieving about 6% efficiency. This innovation marked the beginning of practical solar power applications, such as powering satellites like Vanguard I in 1958.

The global energy crisis in the 1970s sparked a renewed focus on renewable energy sources, leading to the development of thin-film solar cells, which were cheaper and more versatile. As technology continued to evolve, the 1990s saw major improvements in efficiency and a significant drop in manufacturing costs, making PV systems more accessible and widely adopted. From large-scale solar farms to rooftop installations and off-grid uses like solar water pumps, PV technology became a key player in clean energy. Today, the field continues to advance, with researchers exploring new materials like perovskites, integrating energy storage systems, and pushing for even higher efficiencies to meet the world's growing demand for sustainable power. **[1]**

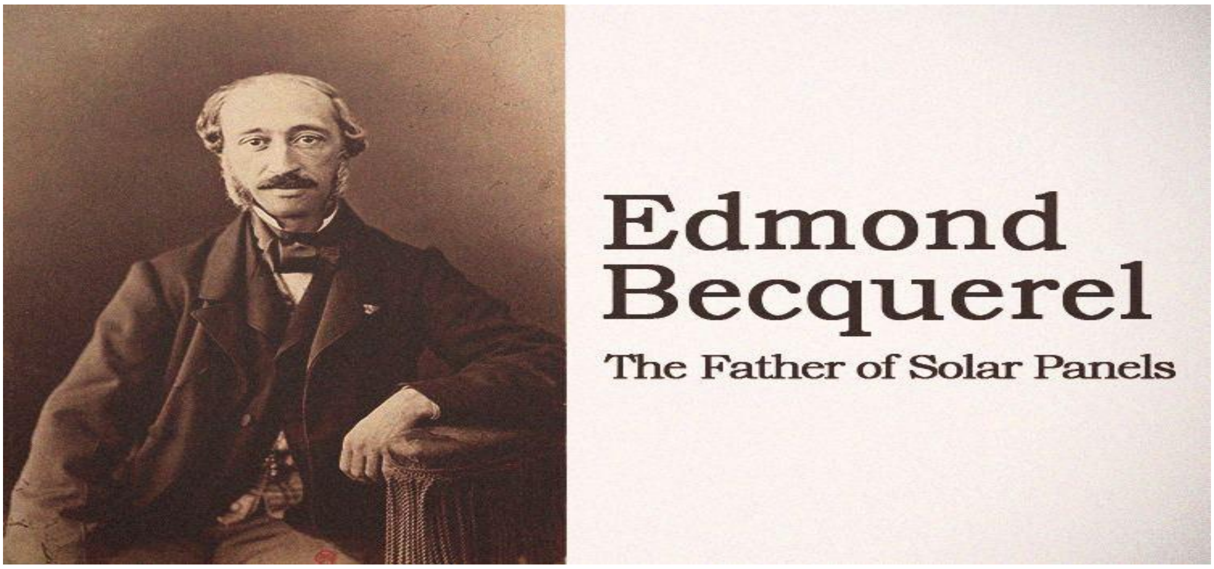


Figure.I.1: Father of PV [**3**]

I.2 Components of Solar PV system

The major component of a solar PV system is the solar panel itself. After the solar panel, there are many components that are needed to provide power to appliances, store the additional energy, and provide power to the grid itself. The major components of a solar PV system are mentioned below. **[3]**

I.2.1 Solar panels

The solar panels are the primary component of any photovoltaic system. Solar panels are primarily responsible for generating power through the photovoltaic effect. The advantage of solar panels is that they generate power without creating any side effects and the resource which they use (solar energy) is renewable. Therefore, energy generated from solar panels is termed renewable energy. Since the solar panels are the first step towards a photovoltaic system. **[3]**

I.2.2 Charge controller

The charge controller is a device that draws maximum voltage from the solar panels. It uses a MPPT algorithm to track the maximum voltage that can be obtained from strings of solar panels and sets the operating point of the PV system at that voltage. Another important function of the charge controller is to regulate the charging of the batteries (battery bank) employed to store the electrical energy. It stops the batteries to be overcharged and therefore, preserves them. The DC power from the charge controller can also be used to power DC appliances. **[3]**

I.2.3 Battery bank

The batteries are used in photovoltaic system to store electrical energy. The batteries are employed where the electrical energy is required in the evening. Moreover, one battery is usually not enough to store the electrical energy that may be required by the consumer, therefore, usually a number of batteries are connected to store the required energy. Batteries are the most inefficient system in the PV system, and they also need to be replaced after every three to five years. **[3]**

I.2.4 Inverter

The inverter is a device used to convert DC output from the charge controller to AC. They are employed in the PV system to supply the power to AC appliances of the consumer and to supply the surplus electrical energy generated to the grid. The inverter is one of the major components of the solar PV systems and it is required by most PV installations.

Modern inverters carry the functionality of charge controllers as well, where they implement the MPPT algorithm and regulate the charging of the battery bank. **[3]**

I.2.5 Power meter

A power meter is a device that measures the electrical energy (in kWh) generated by the solar PV system and supplies this energy to the grid. It also implements the concept of net metering where the number of units of electricity consumed from the grid is deducted by the number of units produced by the PV system. This scheme reduces the total amount of electricity consumed by the user of the PV system and therefore reduces the electricity bill. **[3]**

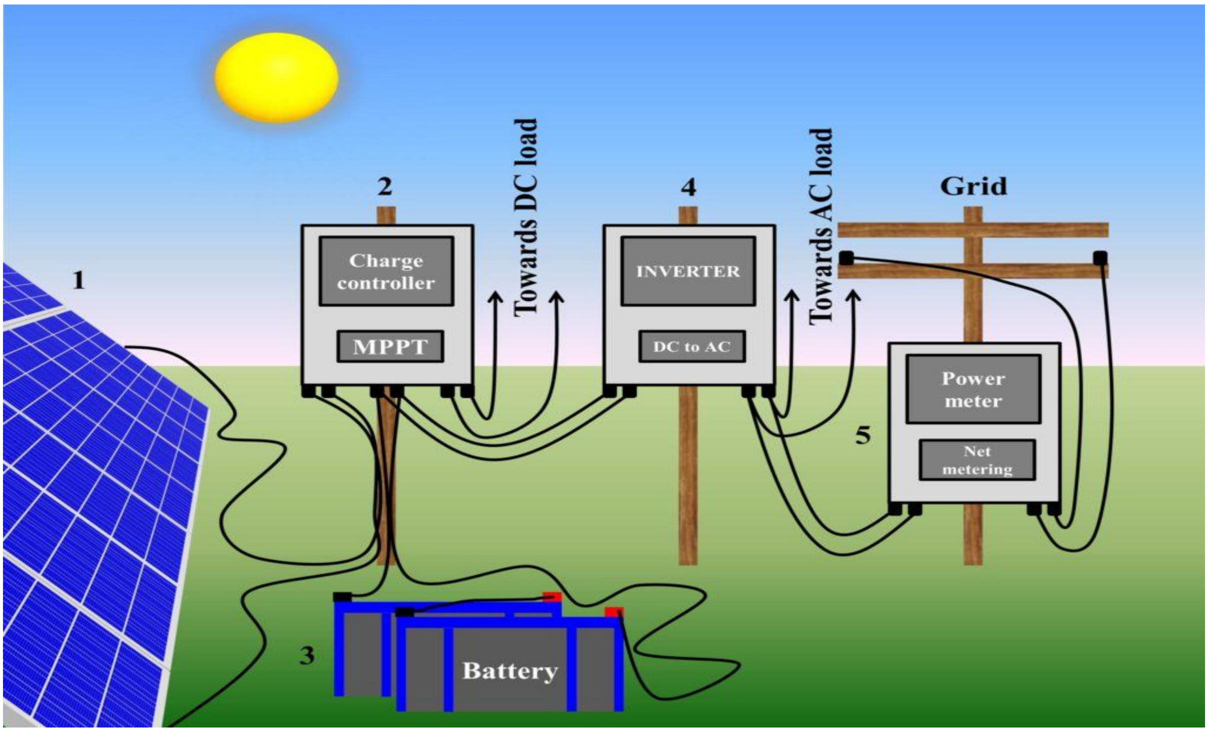


Figure.I.2: Components of solar PV system.**[15]**

I.2.6 Photovoltaic Generator:

Photovoltaic solar energy comes from the direct conversion of energy from photons, contained in solar radiation, into electrical energy through sensors made from materials sensitive to visible wavelengths (called PV cells). The combination of multiple PV cells in series/parallel forms a photovoltaic generator (PVG), which has a nonlinear current-voltage (I-V) static characteristic and exhibits a MPP. This characteristic depends on the illumination level, the cell's temperature and the aging of the system.

The operating point of the PVG can vary between the extreme points corresponding to the short-circuit current (Isc) and the open-circuit voltage (Voc). The determination of the PVG's operating point directly depends on the load to which it is connected. It is either closer to or farther from the MPP, which is characterized by the optimal current and voltage denoted as (Iopt, Vopt).**[4]**

I.3 A String of PV Modules: Series, Parallel Configurations

To meet the energy requirements for different applications, multiple photovoltaic cells or modules are combined into specific configurations: series, parallel, Each configuration impacts the voltage, current, and power output of the system in different ways.

I.3.1 Series Configuration of PV Modules

In a series configuration, PV modules are connected end-to-end, with the positive terminal of one module connected to the negative terminal of the next. This setup increases the voltage while keeping the current the same as that of a single module.

- **Key Characteristics:**
- **Voltage Addition:** The total voltage of the string is the sum of the voltages of the individual modules :

  $$\mathbf{V_{total} = V1 + V2 + \cdots + Vn} \quad \text{(Equ.I.1)}$$
- **Same Current:** The current remains equal to the current of a single module.

  $$\mathbf{I_{total} = I1 = I2 = \cdots = In} \quad \text{(Equ.I.2)}$$
- **Shadowing Effect:** If one module is shaded, it reduces the current of the entire string, significantly affecting power output.
- **Usage:** Series connections are used when higher voltage is needed, such as in grid-connected PV systems.

I.3.2 Parallel Configuration of PV Modules

In a parallel configuration, PV modules are connected with their positive terminals together and negative terminals together. This setup increases the current while keeping the voltage the same as a single module.

- **Key Characteristics:**
- **Current Addition**: The total current is the sum of the currents of all modules.

  $$\mathbf{I_{total} = I1 + I2 + \cdots + In} \quad \text{(Equ.I.3)}$$
- **Same Voltage**: The voltage remains equal to that of a single module.

  $$\mathbf{V_{total} = V1 = V2 = \cdots = Vn} \quad \text{(Equ.I.4)}$$
- **Less Impact of Shading**: If one panel is shaded, the rest can still generate power effectively.
- **Usage**: Parallel connections are used when higher current is needed, such as in battery charging applications.

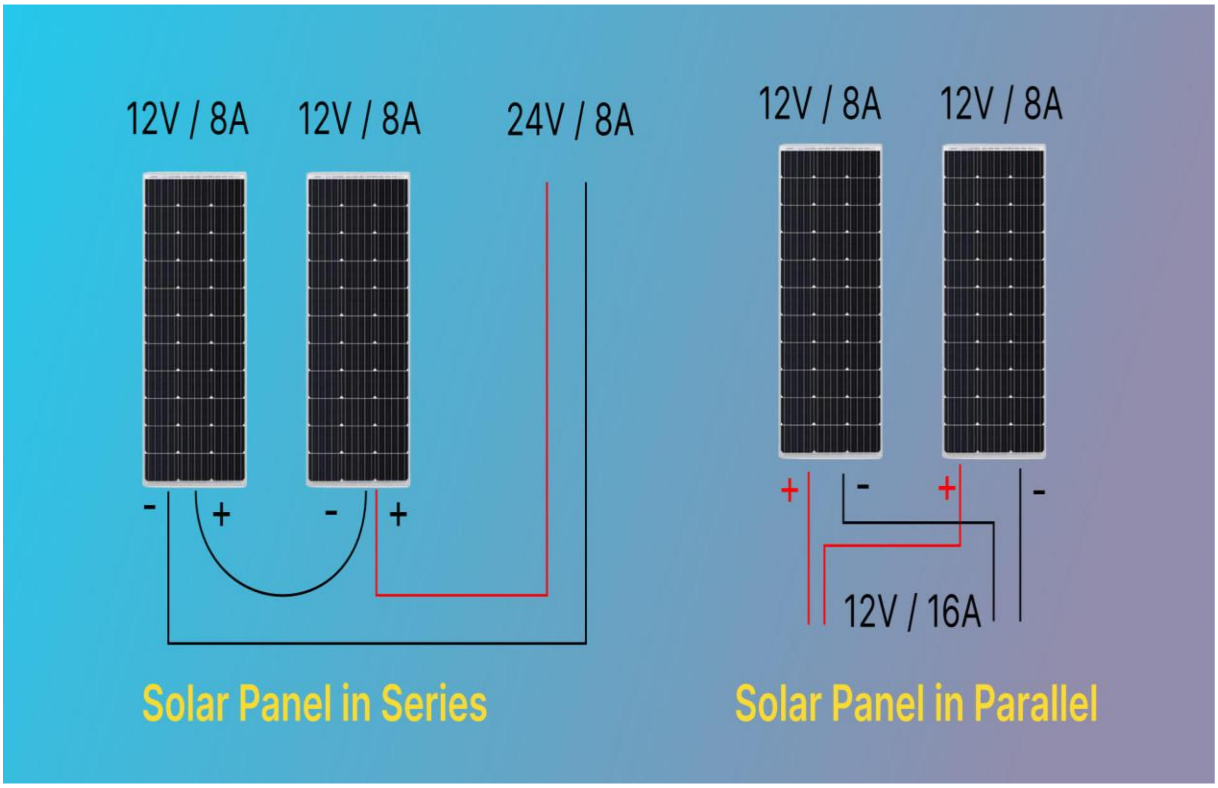


Figure.I.3: String of PV Modules: Series, Parallel Configurations **[5]**

I.4 Comprehensive Explanation of Photovoltaics

Photovoltaic technology converts sunlight into electricity via the photoelectric effect, where photons transfer energy to electrons in a semiconductor, typically silicon. This excitation liberates electrons, generating electron-hole pairs that drive electrical current.

At the core of a PV cell is a p-n junction, formed by doping silicon with impurities to create an n-type layer (rich in free electrons) and a p-type layer (with abundant holes). The built-in electric field at this junction directs electrons toward the n-type side and holes toward the p-type side, inducing charge separation. When an external circuit is connected, electrons flow, producing (DC) electricity. This is often converted to alternating current (AC) via an inverter for practical applications.

A PV cell's structure is optimized for efficiency. An anti-reflective coating minimizes light loss, while front and back contacts collect and transport charge carriers. The semiconductor layers, where energy conversion occurs, are protected by encapsulants and a durable outer cover, often glass, to ensure longevity.**[4]**

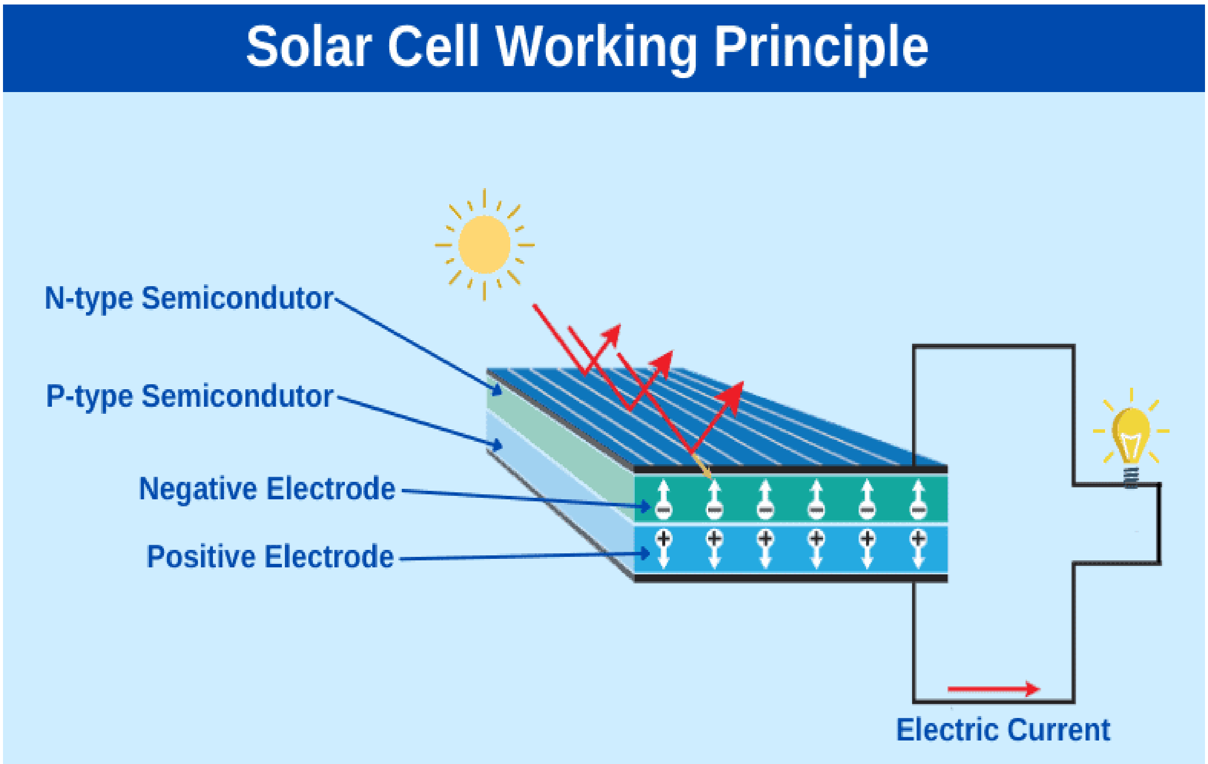


Figure.I.4: Solar cell working principle **[6]**

I.5 Photovoltaic Cells

A photovoltaic cell is a semiconductor device, typically made of silicon, that converts sunlight into electricity through the photoelectric effect, where absorbed photons excite electrons, creating electron-hole pairs that are separated by an internal electric field at the p-n junction, generating a voltage difference that drives an electric current when connected to an external circuit. **[9]**

I.5.1 Types of Photovoltaic Cells

- **Monocrystalline Silicon (Mono-Si)**

Monocrystalline silicon cells are made from a single, pure silicon crystal, giving them a uniform structure and a dark black appearance. They have the highest efficiency (13-24%) among silicon-based cells due to minimal defects, allowing electrons to move more freely. These cells perform well in low-light conditions and have a long lifespan (25+ years), but they are expensive due to the complex manufacturing process. **[9]**

- **Polycrystalline Silicon (Poly-Si)**

Polycrystalline silicon cells are made by melting multiple silicon fragments together, resulting in a grainy blue appearance with visible crystal boundaries. They are cheaper to produce than monocrystalline cells but have a lower efficiency (11-18%) due to electron scattering at grain boundaries. They offer a good balance between cost and performance but are slightly less efficient in high temperatures. **[9]**

- **Thin-Film Solar Cells (TFSC)**

Thin-film solar cells are made by depositing a thin semiconductor layer (such as amorphous silicon, cadmium telluride (CdTe), or (CIGS) onto a flexible substrate. These cells are lightweight, flexible, and cost-effective, making them suitable for portable applications, curved surfaces, and building-integrated photovoltaics (BIPV). However, they have lower efficiency (6-12%) compared to silicon-based cells and degrade faster over time. **[9]**

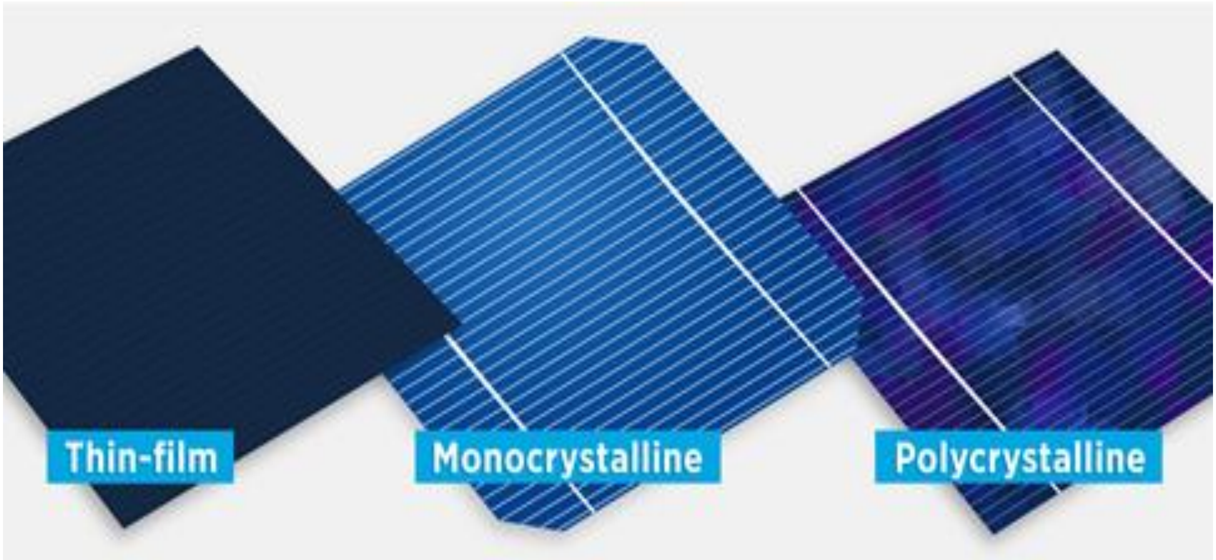


Figure.I.5: Types of Photovoltaic (PV) Cells.**[7]**

I.5.2 Composition of a PV cell :

- **Semiconductor**: The semiconductor, typically made of ultra-pure silicon, is the core component of a photovoltaic cell. It serves as the material in which the photovoltaic effect occurs, enabling the conversion of sunlight into electricity. When sunlight strikes the semiconductor, the energy from photons excites electrons, freeing them from their atomic bonds and allowing them to move, forming the foundation for the generation of electric current. This process is what makes the semiconductor the heart of every PV cell, as it transforms solar energy into usable electrical energy. **[1]**

- **Anti-Reflective Coating**: The anti-reflective coating is a specially engineered thin layer applied to the surface of the photovoltaic cell to minimize the reflection of sunlight. Without this coating, a significant portion of sunlight would bounce off the cell's surface, greatly reducing its efficiency. By allowing more sunlight to penetrate into the cell, the anti-reflective coating ensures maximum light absorption, enabling the semiconductor beneath to capture more energy and convert it into electricity. This layer is critical in improving the overall performance of the PV cell by enhancing its light-absorbing capabilities. **[1]**
- **N-Type Layer**: The n-type layer in a photovoltaic cell is a region of silicon that has been doped with elements such as phosphorus. These elements introduce extra electrons into the silicon's structure, giving the material a negative charge. The n-type layer is responsible for providing free electrons that can move when the cell is exposed to sunlight. It forms one half of the p-n junction, which is the key interface in the cell where an electric field is generated to guide the flow of electrons, ultimately producing electricity. **[1]**
- **P-Type Layer**: The p-type layer is a region of silicon that has been doped with elements such as boron, which creates "holes" or spaces for electrons, resulting in a positive charge. This layer works in tandem with the n-type layer to form the p-n junction, which is essential for establishing the electric field within the PV cell. When sunlight excites electrons in the semiconductor, this electric field pushes electrons toward the n-type side and holes toward the p-type side, facilitating the flow of electric current. The p-type layer

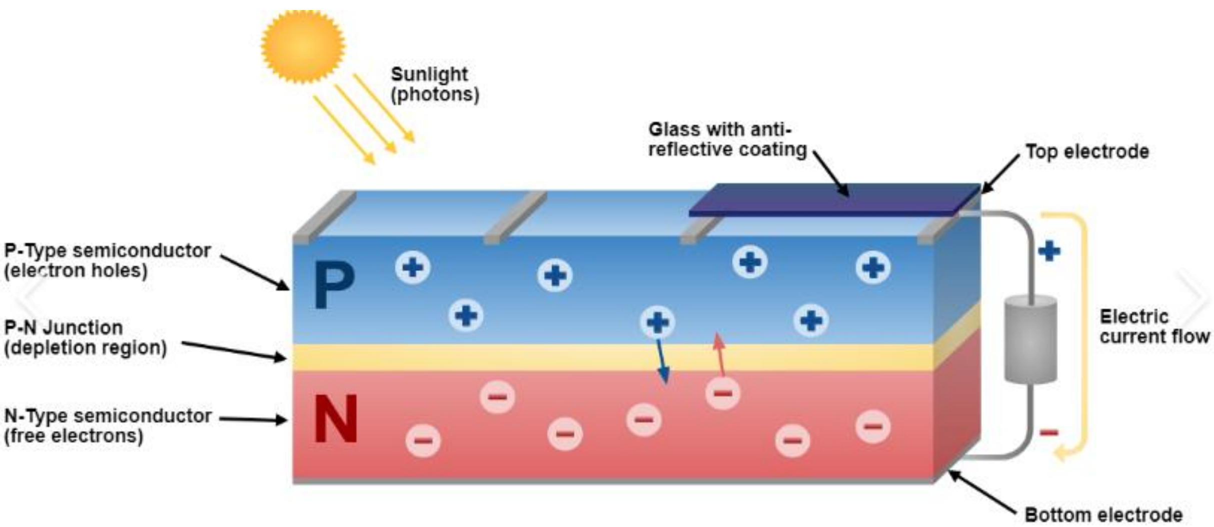


Figure.I.6: Composition of a PV cell **[8]**

is thus integral to the operation of the photovoltaic cell, ensuring the proper separation and movement of charge carriers to generate electricity.**[1]**

I.1 Photovoltaic module

Photovoltaic modules, commonly known as solar panels, are devices that convert sunlight into electricity using semiconductor materials. They are fundamental components in solar energy systems, providing a renewable and sustainable source of power.

I.1.1 Types of Photovoltaic Modules:

Photovoltaic panels are distinguished by their manufacturing technology and their efficiency in converting solar energy into electricity. They consist of cells that generate an electric current when exposed to sunlight. These cells are assembled into modules and can vary in performance, cost, and durability depending on their design and the materials used. Some offer higher energy efficiency, while others prioritize flexibility or architectural integration. The choice depends on specific needs, whether for residential, industrial installations, or specialized applications such as powering isolated devices.

Figure.I.7: Types of Photovoltaic Modules

I.2 Association of Cells :

Photovoltaic cells can be connected in different ways depending on the required electrical output. The three main configurations are series, parallel, and hybrid (series-parallel) connections. Each has a specific effect on voltage, current, and power. **[11]**

I.2.1 Series Connection

In a series connection, the positive terminal of one PV cell is connected to the negative terminal of the next. This arrangement adds up the voltage while keeping the current the same as a single cell.

This type of connection is used when a higher voltage is required, such as in grid-connected solar systems that need a certain voltage level to operate efficiently.

If we have Ncells connected in series, each with:

- **Voltage**: Vcell
- **Current**: Icell

Then, the total output is:

$$\mathbf{V_{total} = N \times V_{cell}} \qquad \text{(Equ.I.5)}$$

$$\mathbf{I_{total} = I_{cell}} \qquad \text{(Equ.I.6)}$$

$$\mathbf{P_{total} = V_{total} \times I_{total} V} \qquad \text{(Equ.I.7)}$$

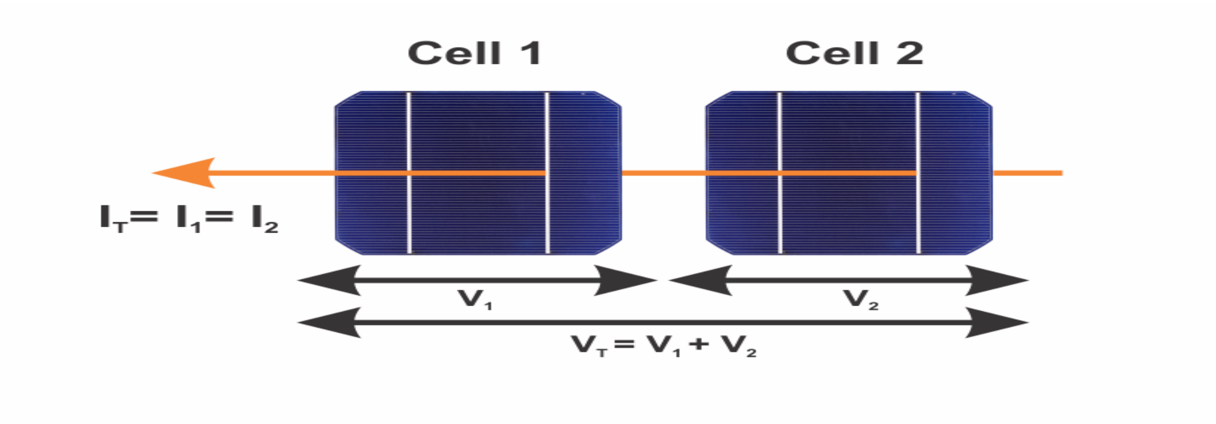


Figure.I.8: Series Connection **[10]**

I.2.2 Parallel Connection

In a parallel connection, all positive terminals are connected together, and all negative terminals are connected together. This setup adds up the current while keeping the voltage the same as a single cell.

This type of connection is used when a higher current is needed, such as in off-grid battery charging systems where power demand is high.

For Ncells connected in parallel, each with:

- **Voltage**: Vcell
- **Current**: Icell

Then, the total output is:

$$\mathbf{V_{total} = V_{cell}} \qquad \text{(I.8)}$$

$$I_{total} = N \times Icell \quad (I.9)$$

$$P_{(total)} = V_{total} \times I_{total} \quad (I.10)$$

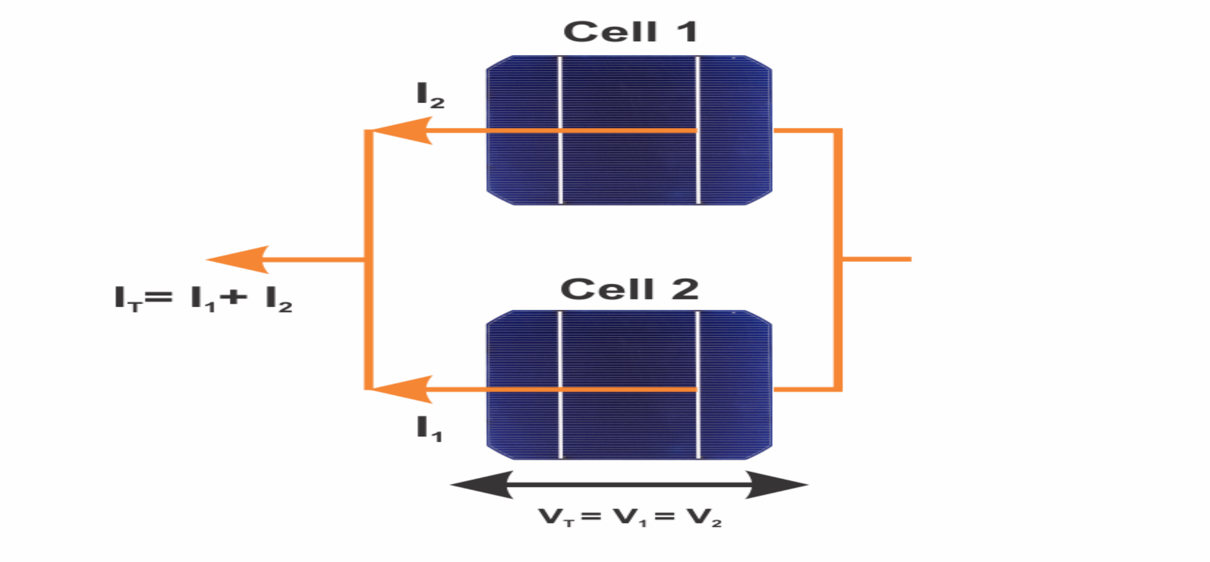


Figure.I.9: Parallel Connection **[10]**

I.3 Solar Panels

A solar panel is a technological device designed to convert sunlight into electricity through the use of photovoltaic cells. These PV cells are primarily composed of semiconductor materials, such as silicon, which have the ability to generate an electric current when exposed to light.

This process, known as the photovoltaic effect, is the foundation of solar energy technology and plays a crucial role in harnessing renewable energy for various applications, ranging from residential power generation to large-scale industrial and commercial energy systems. **[4]**

I.3.1 Types of Solar Panels:

There are three main types of PV panels:

Table.I.1 : Types of PV panels **[4]**

Type	**efficacity**	**Cost**	**Advantage**	**disadvantage**
Monocrystalline	18-22%	High	Highest efficiency, space-saving, durable	Expensive, performance drops in shade
Polycrystalline	15-18%	Medium	Affordable, good performance	Less efficient than monocrystalline
Thin-Film	10-12%	Low	Lightweight, flexible, works in low light	Lower efficiency, larger space required

I.4 Photovoltaic Field

The Photovoltaic (PV) field refers to the technology, systems, and applications related to converting solar energy into electricity using photovoltaic cells. It is a crucial part of the renewable energy sector, enabling sustainable electricity generation for various applications, from small-scale residential use to large-scale solar farms.**[12]**

Figure.I.10: Photovoltaic Field

I.5 Different Types of Photovoltaic (PV) Systems

Photovoltaic systems are classified based on their connection to the grid and their energy storage capabilities. The main types include grid-tied, off-grid, hybrid, and floating PV systems. Each type has its own applications, advantages, and limitations.

I.5.1 Grid-Tied Photovoltaic System

A grid-tied PV system is a solar power setup that is directly connected to the main electricity grid, allowing homeowners, businesses, and industries to generate their own electricity while still having access to utility power. This system works by producing solar energy during the day, and if excess energy is generated, it is fed into the grid through net metering, which provides credits for future electricity use. It is one of the most cost-effective and widely used solar solutions, as it eliminates the need for battery storage while reducing electricity bills. However, during a power outage, grid-tied systems do not function unless they are equipped with a backup solution. **[13]**

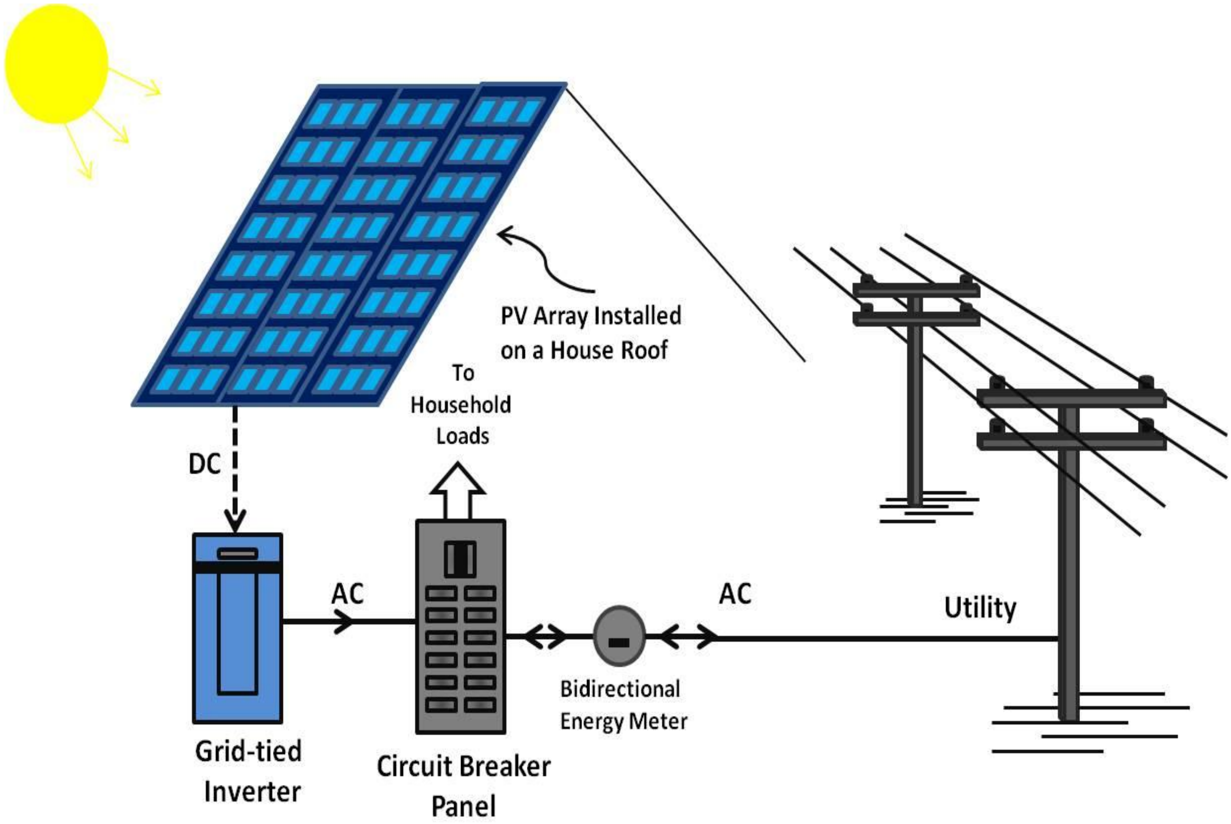


Figure.I.11: Grid-Tied Photovoltaic.**[13]**

I.5.2 Off-Grid Photovoltaic System

An off-grid PV system operates completely independently of the utility grid, making it the ideal choice for remote areas and locations without electricity access. These systems rely on solar panels to generate power, battery banks to store excess energy, and inverters to convert the stored energy into usable electricity. Off-grid systems ensure energy independence, allowing users to power their homes, businesses, or agricultural systems even in isolated regions. However, they require a large battery capacity to supply electricity during nighttime or cloudy days, making them more expensive and complex than grid-tied systems. **[14]**

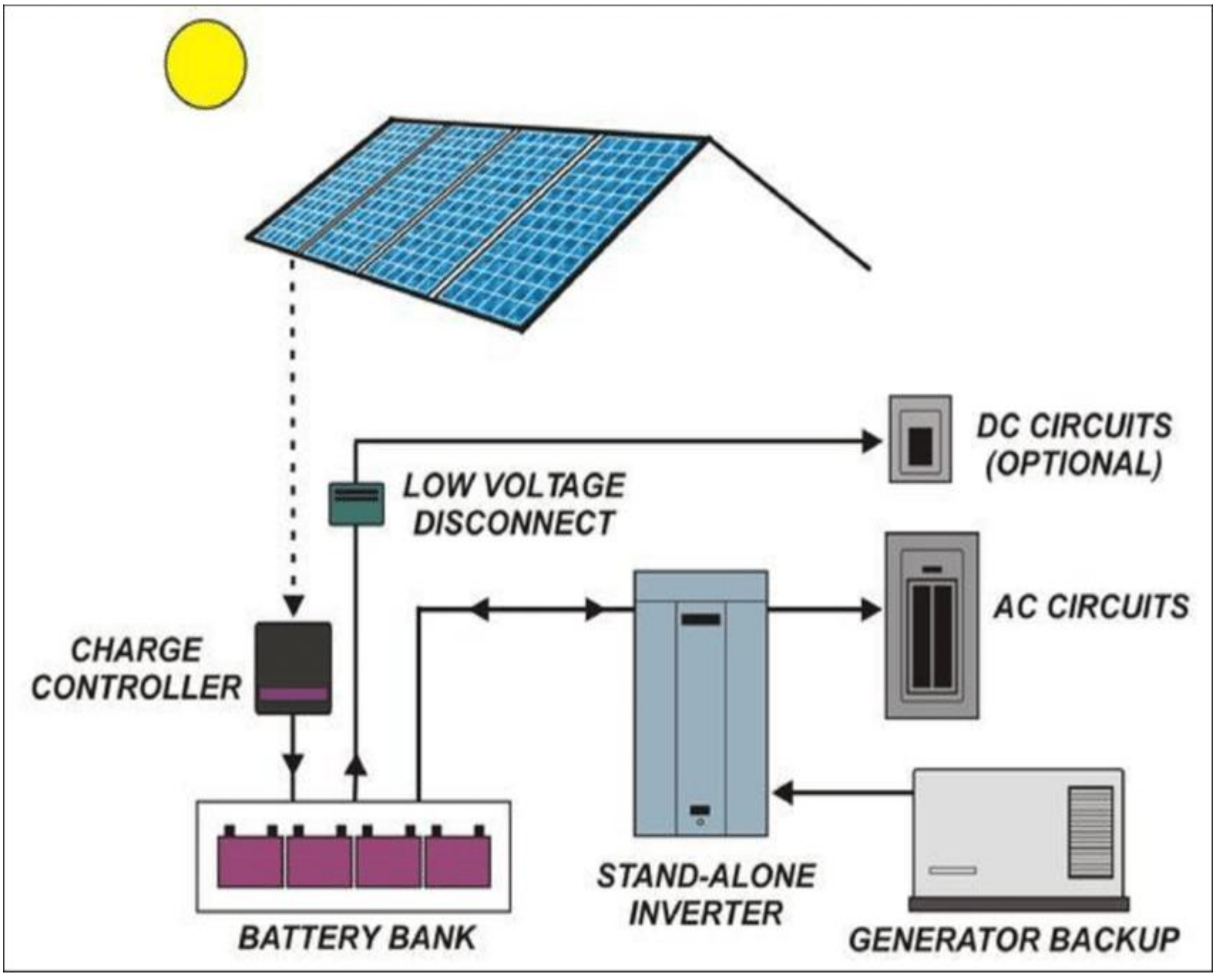


Figure.I.12: Off-Grid Photovoltaic**[14]**

I.5.3 Hybrid Photovoltaic System

A hybrid PV system is an advanced solar power solution that integrates solar panels, battery storage, and grid connection, ensuring an uninterrupted power supply. This system allows users to store excess solar energy for later use, such as during the night or grid failures, providing a reliable backup source of electricity. Hybrid systems are particularly useful in areas with an unreliable grid, as they automatically switch between solar power, battery storage, and grid electricity to maximize efficiency and cost savings. Although more expensive than traditional grid-tied systems, hybrid PV systems enhance energy security and reduce dependence on utility providers. **[14]**

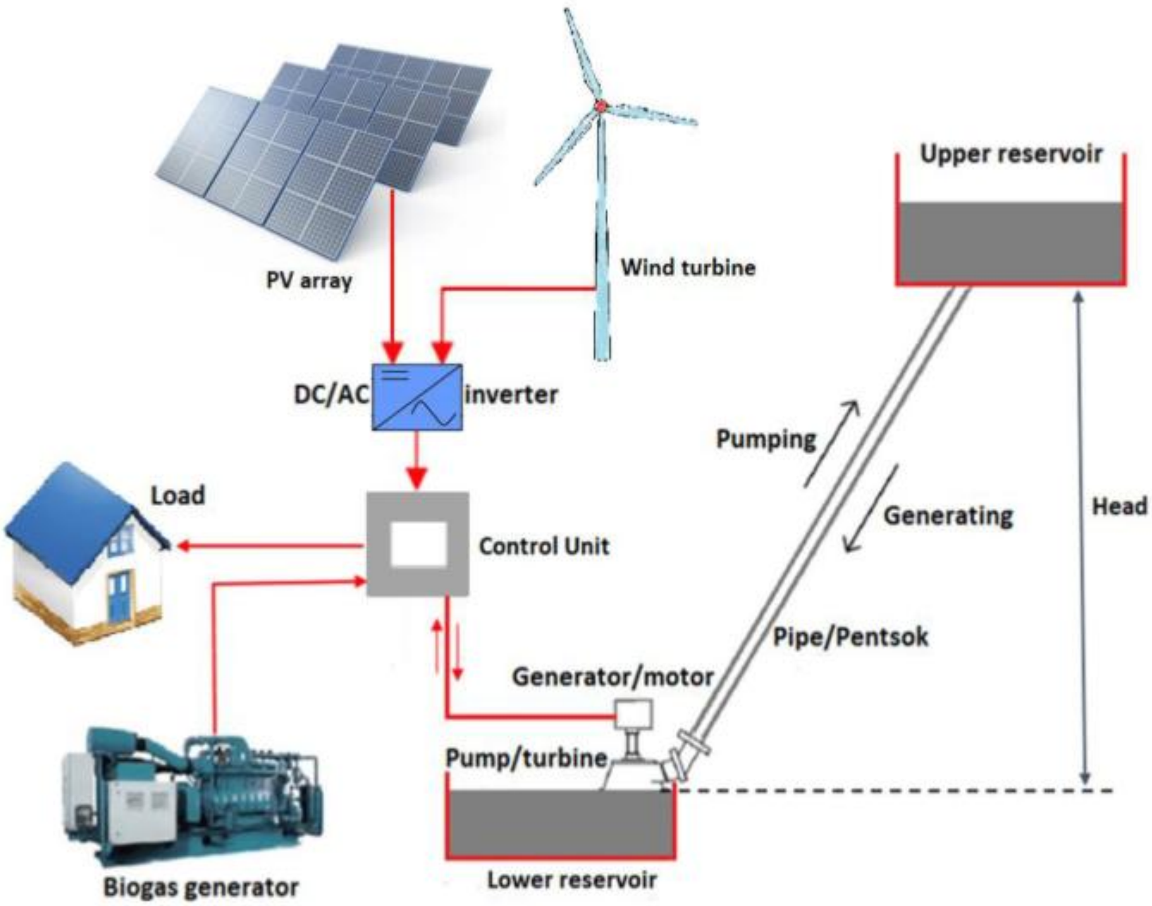


Figure.I.13: Hybrid Photovoltaic**[15]**

I.5.4 Floating Photovoltaic (FPV) System

A floating photovoltaic system is an innovative solar power solution where solar panels are installed on water surfaces, such as lakes, reservoirs, and oceans. This type of system is designed to save land space, improve solar efficiency through natural cooling, and reduce water evaporation, making it an environmentally friendly and highly effective solution for large-scale solar farms. Floating PV systems are increasingly used in countries with limited land availability, and they can be integrated with hydroelectric dams for optimized energy production. However, installation and maintenance costs are higher due to the need for floating structures and waterproof components**. [16]**

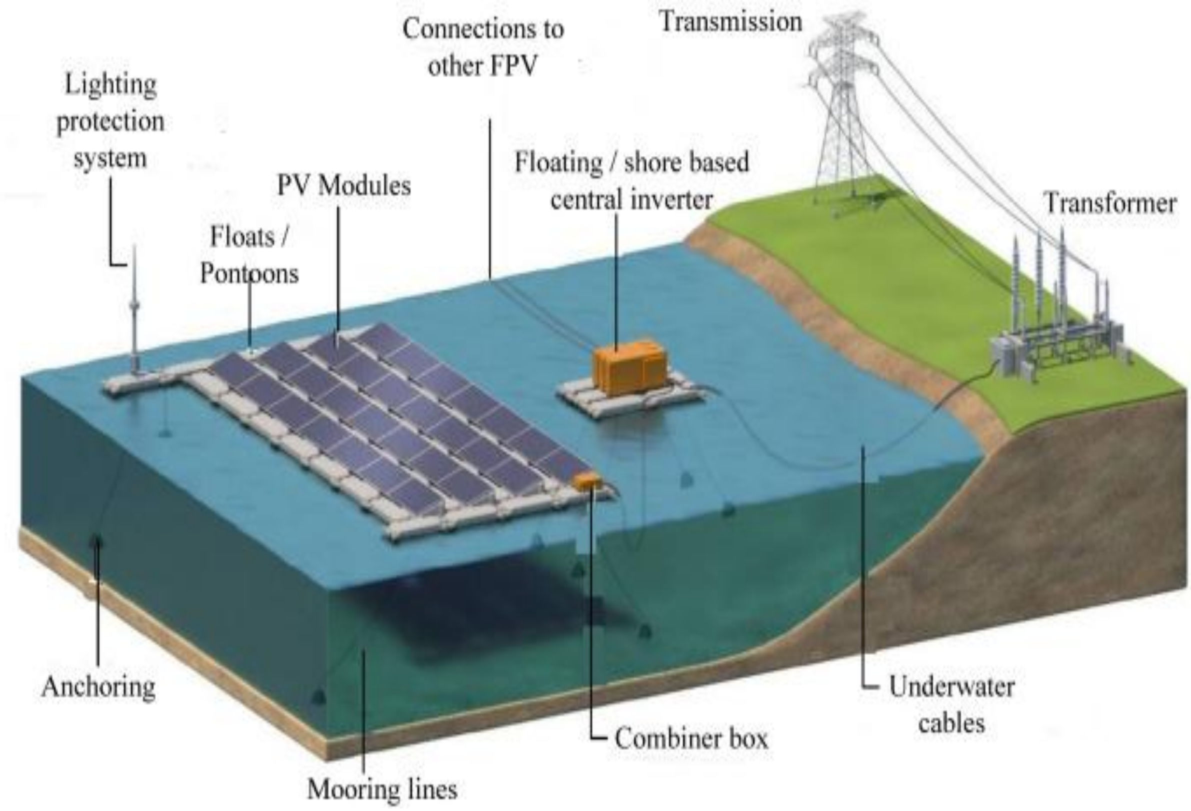


Figure.I.14: Floating Photovoltaic**[16]**

I.6 Operating Principle of a Photovoltaic Installation

A photovoltaic installation operates by capturing sunlight through solar panels composed of semiconductor materials, where the photovoltaic effect generates DC electricity, which is then converted into AC by an inverter to power homes, businesses, and industries, with excess energy either stored in batteries for later use in off-grid and hybrid systems or fed into the utility grid in grid-tied systems, while advanced monitoring and smart grid integration optimize energy production, consumption, and efficiency.

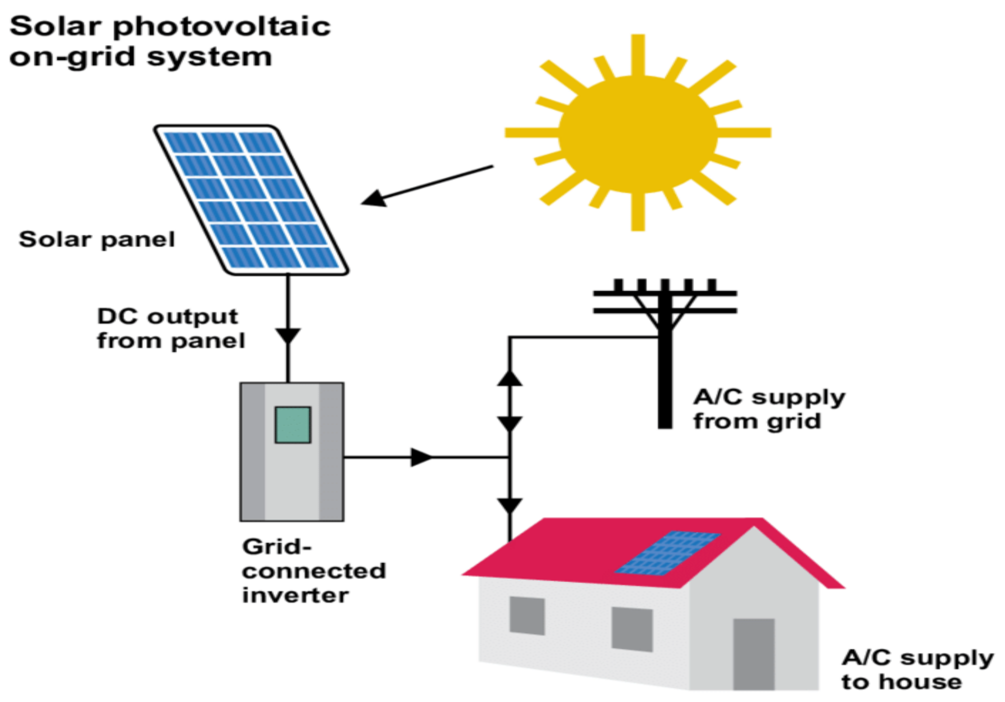


Figure.I.15: Operating Principle of a Photovoltaic Installation **[15]**

I.7 Current-Voltage (I-V) Characteristic of a Photovoltaic Cell

The current-voltage (I-V) characteristic of a (PV) cell is a fundamental representation of how a solar cell converts sunlight into electrical energy, illustrating the relationship between the output current and output voltage under varying environmental and operating conditions, with the curve beginning at the short-circuit current, which represents the maximum possible current generated by the cell when the voltage is zero (i.e., when the terminals are short-circuited), and extending to the open-circuit voltage , which is the highest voltage the cell can provide when no current is flowing (i.e., when the circuit is open), both of which are key parameters in defining the performance of a solar cell, where the general I-V relationship of a photovoltaic cell can be described by the Shockley diode equation with additional photovoltaic terms as follows **[15]**

$$I = I_{ph} - I_0(e^{\frac{qV}{nkT}} - 1) \qquad \text{(Equ.I.11)}$$

where:

- **I(ph)** is the photogenerated current, which depends on the intensity of incident sunlight.
- **I0** is the saturation current of the diode, which is a function of temperature.
- **q** is the elementary charge (1.602×10^{-19} C).
- **V** is the output voltage of the cell.
- **n** is the ideality factor (typically between 1 and 2).
- **k** is Boltzmann's constant (1.38×10^{-23} J/K).
- **T** is the temperature in Kelvin (K).

The most crucial operating point on this curve is the Maximum Power Point, which represents the unique voltage (Vmp) and current (ImpI) combination where the cell delivers its highest possible power output, calculated as:

$$\boldsymbol{P_{max} = V_{mp} \times I_{mp}} \qquad \text{(Equ.I.12)}$$

This maximum power point is dynamic, shifting based on solar irradiance, temperature, and cell aging, making Maximum Power Point Tracking techniques essential in modern photovoltaic systems to continuously adjust the operating voltage and extract the maximum available power under changing conditions; solar inverters and charge controllers employ MPPT algorithms such as Perturb and Observe , Incremental Conductance , and Fuzzy Logic-based MPPT to keep the system operating at or near the MPP, improving overall efficiency. **[15]**

Another key performance parameter derived from the I-V characteristic is the fill factor (FF), which is a measure of how "square" the I-V curve appears and indicates the quality and efficiency of the PV cell, calculated as:

$$FF = \frac{\mathbf{Voc \times Isc}}{\mathbf{Vmp \times Imp}} \qquad \text{(Equ.I.13)}$$

where a higher fill factor (typically between 0.7 and 0.85 for high-efficiency silicon solar cells) indicates lower internal resistive losses and better overall performance. The overall efficiency (η) of the photovoltaic cell, which determines how effectively it converts sunlight into electrical power, **[15]**

is given by:

$$\eta = \frac{\mathbf{P_{max}}}{\mathbf{P_{input}}} = \frac{(\mathbf{V_{mp} \times I_{mp}})}{\mathbf{P_{input}}} \qquad \text{(Equ.I.14)}$$

where Pinput is the incident solar power per unit area, typically taken as 1000 W/m² under standard test conditions (STC).

The shape of the I-V curve and the location of MPP are significantly influenced by external factors such as solar irradiance and temperature, where:

- Increasing irradiance results in a higher short-circuit current and overall power output, shifting the MPP upwards.
- Increasing temperature leads to a decrease in open-circuit voltage , reducing efficiency and shifting the MPP slightly to the left.

Therefore, advanced thermal management solutions and adaptive MPPT algorithms are essential in maintaining high energy conversion efficiency in photovoltaic installations, ensuring that solar cells operate at optimal conditions despite environmental fluctuations. **[15]**

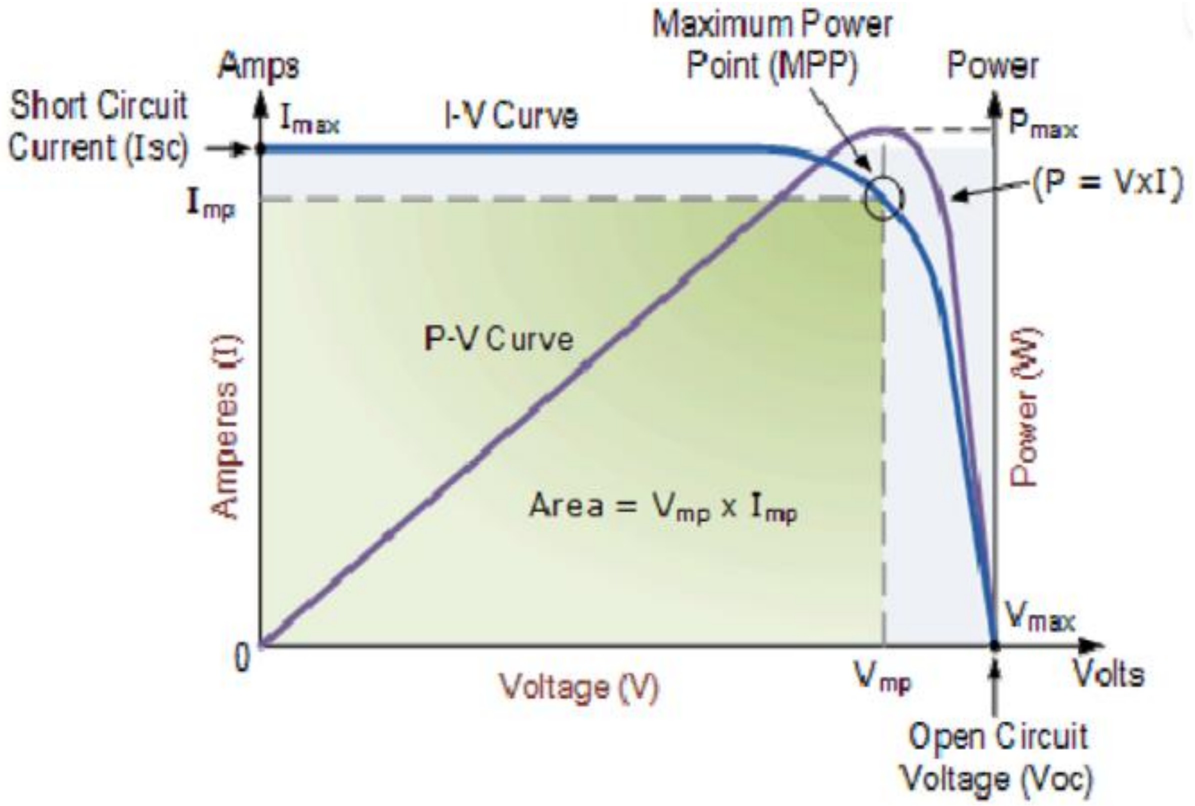


Figure.I.16: (I-V) Characteristic of a Photovoltaic Cell.**[15]**

I.8 Modeling of a Photovoltaic Module

When modeling a photovoltaic module, we can consider two cases: ideal and real (practical). The ideal model assumes perfect conditions with no losses, while the real model accounts for various imperfections that affect performance. **[12]**

I.8.1 Ideal Photovoltaic Model

The ideal photovoltaic model assumes perfect operating conditions without considering any losses due to material imperfections, resistances, or external factors like temperature variations. In this model, the PV cell is represented as a simple current source connected in parallel with an ideal diode, where all the generated photocurrent (Iph) is directly converted into electrical energy without any power dissipation. The governing equation of an ideal PV cell, **[12]**
is given by:

$$I = I_{ph} - I_0(e^{\frac{qV}{nkt}} - 1) \quad \text{(Equ.I.15)}$$

where:

I is the output current of the PV cell

I_{ph} is the photocurrent, directly proportional to incident solar irradiance

I_0 is the diode's reverse saturation current,

q is the elementary charge of an electron (1.602×10−19C1.602 \times 10^{-19} C1.602×10−19C)

V is the terminal voltage of the PV cell

n is the diode ideality factor (typically between 1 and 2),

k is Boltzmann's constant (1.38×10−23J/K1.38 \times 10^{-23} J/K1.38×10−23J/K),

T is the absolute temperature in Kelvin

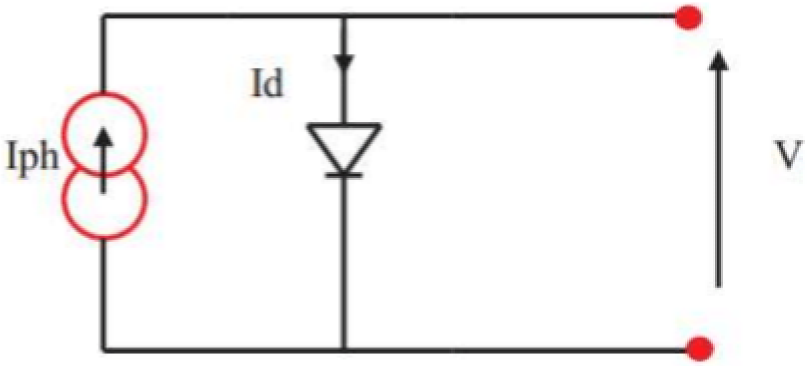


Figure.I.17: Equivalent diagram of an ideal cell. **[15]**

This ideal model predicts **100% efficiency**, assuming that all the absorbed photons contribute to the current generation without any recombination losses, resistive losses, or shading effects. The I-V characteristics of an ideal PV cell are perfectly smooth, and the power output follows a well-defined Maximum Power Point (MPP). However, in practical applications, no PV module behaves ideally due to multiple loss mechanisms that must be considered in real-world modeling. **[12]**

I.8.2 Real (Practical) Photovoltaic Model

In reality, PV modules are affected by various losses, including resistive losses in electrical connections, leakage currents within the semiconductor material, recombination of charge carriers, and environmental factors such as temperature fluctuations and partial shading. To accurately model a real PV module, the single-diode model is extended by incorporating series resistance (Rs) and shunt resistance (Rsh), which account for power dissipation and leakage currents, respectively. The output current of a real PV module is given by:

$$I = I_{ph} - I_0\left(e^{\frac{q(V+IR_S)}{nkT}} - 1\right) - \frac{V+IR_S}{R_{sh}} \qquad \text{(Equ.I.16)}$$

where:

Rs represents the **series resistance**, which models the internal resistance of the cell, interconnections, and contact resistances, causing a voltage drop and reducing the maximum output power.

Rsh represents the **shunt resistance**, which accounts for leakage paths within the semiconductor material due to defects, lowering the module efficiency by allowing unwanted current to bypass the load.

Additionally, temperature effects significantly impact the PV performance

Higher temperatures decrease the open-circuit voltage (Voc) due to increased intrinsic carrier concentration, reducing efficiency.

Higher temperatures slightly increase the short-circuit current (Isc), but the overall effect is a net reduction in power output.

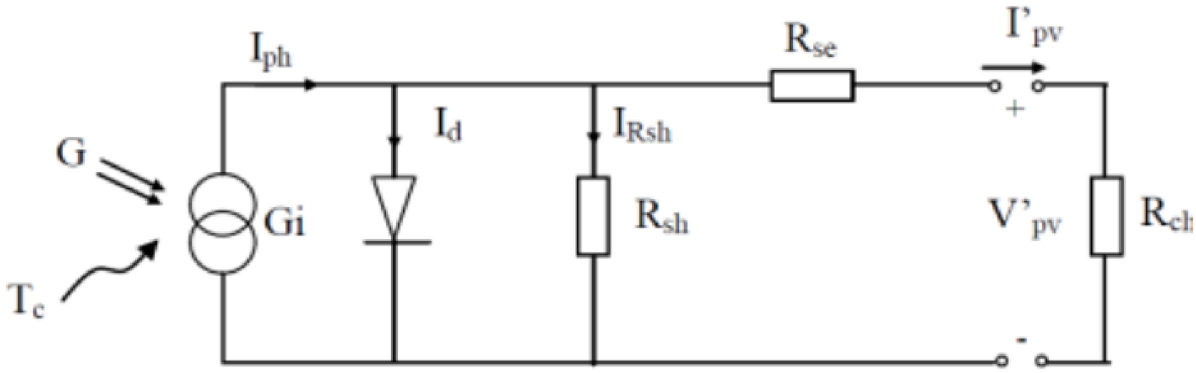


Figure.I.18: Equivalent diagram of a real photovoltaic cell. **[15]**

In practical PV systems, power losses, shading, and aging effects further degrade the module's performance, requiring advanced power management techniques like Maximum Power Point Tracking and bypass diodes to optimize energy extraction. Unlike the ideal case, real PV modules exhibit nonlinear I-V and P-V characteristics, with deviations due to the presence of resistances and temperature dependencies. **[12]**

I.9 Advantages and disadvantages of photovoltaic systems

Photovoltaic systems have many advantages and disadvantages. Here's a detailed breakdown:

I.9.1 Advantages of Photovoltaic Systems

- **Renewable Energy Source** – Solar energy is abundant and inexhaustible.
- **Eco-Friendly** – PV systems generate electricity without emitting greenhouse gases.
- **Low Operating Costs** – Once installed, maintenance and operational costs are minimal.
- **Energy Independence** – Reduces dependence on fossil fuels and enhances energy security.
- **Scalability & Modularity** – PV systems can be installed in small or large capacities depending on needs.
- **Off-Grid Capability** – Ideal for remote areas without access to the power grid.

- **Technological Advancements** – Efficiency improvements and cost reductions continue to make PV more competitive.

I.9.2 Disadvantages of Photovoltaic Systems

- **Intermittency** – Energy production depends on sunlight, making it less reliable at night or during cloudy weather.
- **High Initial Cost** – Although prices are decreasing, the upfront cost of PV panels, inverters, and installation can be high.
- **Energy Storage Requirement** – Batteries are needed for nighttime or backup power, adding to costs and maintenance.
- **Space Requirements** – Large-scale PV systems require significant land or roof space.
- **Efficiency Limitations** – Current PV panels have efficiency limitations, typically ranging between 15-22%.
- **Manufacturing Impact** – The production of PV panels involves energy-intensive processes and materials like silicon and rare metals.
- **Degradation Over Time** – PV panels lose efficiency over the years, typically degrading at about 0.5-1% per year.

I.10 Conclusion

In this chapter, we have provided an in-depth exploration of photovoltaic technology, covering its historical development, fundamental principles, and key components. We examined the structure and types of PV cells, highlighting their role in converting solar energy into electrical power. Additionally, we discussed the various configurations of PV modules and their impact on system performance. The chapter also addressed practical considerations, including efficiency limitations, environmental influences, and real-world challenges associated with PV technology. By understanding these foundational concepts, we establish a strong basis for further research and technological advancements aimed at optimizing photovoltaic systems for broader applications in renewable energy generation and sustainable development

Chapter II: MPPT and Power Converters in Solar Energy Systems

II. Introduction

Maximum Power Point Tracking is an advanced technique used in photovoltaic systems to optimize energy harvesting from solar panels. The efficiency of a solar panel depends on external conditions such as sunlight intensity and temperature, which constantly fluctuate throughout the day. These variations affect the Voltage-Current (V-I) and Power-Voltage (P - V) characteristics of the panel, making it necessary to use an MPPT system to ensure the panel operates at its highest possible efficiency.

Without MPPT, solar panels may not work at their optimal power point, leading to energy losses and reduced system performance. MPPT controllers continuously monitor and adjust the voltage and current of the solar array to extract the maximum available power at any given time. This is particularly important in standalone solar power systems, hybrid energy systems, and grid-connected PV installations, where efficient power conversion is essential for meeting energy demands.

MPPT controllers are commonly used in conjunction with DC-DC converters such as buck, boost, or buck-boost converters, which help regulate the power output and ensure compatibility with batteries, inverters, or electrical loads. These controllers are fundamental in modern solar energy applications, as they significantly improve power efficiency and enhance the overall reliability of solar power systems.

To achieve optimal power extraction, engineers and researchers have developed several MPPT algorithms. Among the most widely used methods, two stand out due to their effectiveness and simplicity:

- Perturbation and Observation (P&O) Method
- Incremental Conductance (IC) Method
- Fuzzy logic Controller (FLC) Method
- Particle Swarm Optimization (PSO) Method

Both methods aim to track the Maximum Power Point of a PV system, but they operate differently and have unique advantages depending on the system's requirements and environmental conditions. Regardless of the approach used, MPPT technology is essential in ensuring that photovoltaic systems produce the highest possible energy output, making solar power a more viable and efficient renewable energy source.

Here is an example of how MPPT works in a solar energy system:

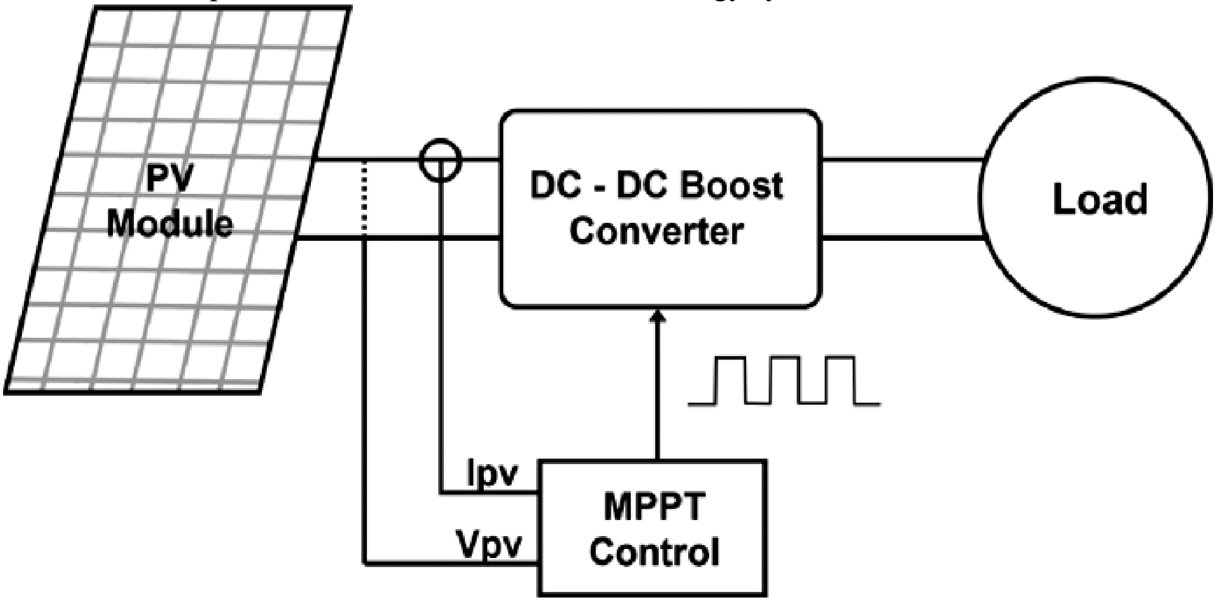


Figure.II.1: PV System With MPPT Control.**[15]**

II.1 DC-DC Converters and Their Role in MPPT and Solar Energy Systems

MPPT alone is not enough to control the power transfer. The system requires a DC-DC converter, which is an electronic circuit that adjusts the voltage and current levels to match the optimal operating point of the solar panel and efficiently deliver power to the load or battery storage system.

This combination of MPPT algorithms and DC-DC converters allows a solar power system to operate with higher efficiency, ensuring that no energy is wasted. **[4]**

II.1.1 Converters in Solar MPPT Systems

Solar panel has a specific voltage at which it delivers maximum power this is called the Maximum Power Point . However, in real-world conditions, the MPP voltage does not always match the voltage required by the load or battery.

If the load voltage is lower than the MPP voltage, a step-down (buck) converter is needed.

If the load voltage is higher, a step-up (boost) converter is required.

If the solar panel voltage varies significantly, a buck-boost converter is the best choice.

The MPPT controller continuously adjusts the duty cycle of the DC-DC converter to keep the system operating at the MPP, maximizing efficiency and ensuring that the system always extracts the highest possible energy from the solar panel. **[18]**

II.1.1.1 General Working Principle of DC-DC Converters

In MPPT-based solar systems, DC-DC converters operate using a common principle:

- **Switch ON**
  The switch (MOSFET or IGBT) closes, allowing current to flow into the inductor, which stores energy.
- **Switch OFF**
  The switch opens, and the inductor releases stored energy to the load through the diode, adjusting the output voltage as needed.

Main Components:

- **Switching Device** (MOSFET/IGBT)
- **Inductor (L)**
- **Diode (D)**
- **Capacitor (C)**

This process is controlled through Pulse Width Modulation (PWM) to regulate the duty cycle (D), adjusting voltage and current levels.

II.1.1.2 Mathematical Analysis

It's same mathematical in other converters, The output voltage V_{out} related to the input voltage V_{in} and the duty cycle (D) by converter specific formulas:

- **Buck converter:**

$$V_{out} = D * V_{in} \quad \text{(Equ.II.1)}$$

- **Boost converter:**

$$V_{out} = \frac{V_{in}}{1-D} \quad \text{(Equ.II.2)}$$

- **Buck-Boost Converter:**

$$V_{out} = \frac{D}{1-D} * V_{in} \quad \text{(Equ.II.3)}$$

The MPPT controller dynamically adjusts D to operate at the Maximum Power Point .

II.1.1.3 Types of DC-DC Converters Used in MPPT-Based Solar Energy Systems

DC-DC converters regulate voltage and current to ensure the system operates efficiently. The three main types used in solar power systems are:

II.2 Buck Converter (Step-Down Converter)

A Buck Converter is a step-down DC-DC converter that reduces the input voltage while increasing the output current. It is widely used in MPPT-based solar energy systems when the PV panel voltage is higher than the required load or battery voltage.

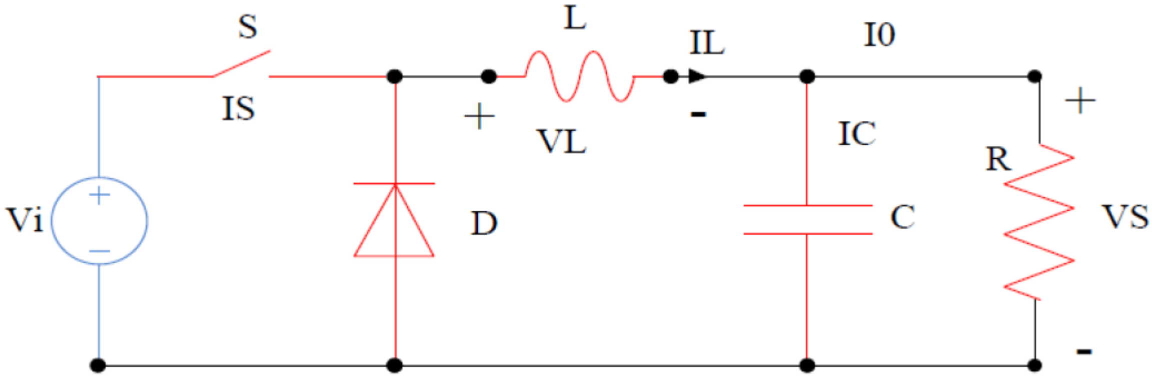


Figure.II.2 : Electrical Circuit Buck Converter **[4]**

✓ **Advantages:**

➢ High Efficiency and Simple Design

The Buck converter offers high efficiency (up to 95%), a simple circuit design, a low component count, effective voltage regulation, and reduced power loss.

- High efficiency (up to 95%)
- Simple circuit design
- Low component count
- Effective voltage regulation
- Reduced power loss

II.2.1 Applications in Solar MPPT System

- Battery charging **(**when PV voltage > battery voltage**)**
- Grid-tied solar inverters
- DC microgrids
- Powering DC loads with lower voltage requirements

II.3 Boost Converter (Step-Up Converter)

A Boost Converter is a step-up DC-DC converter that increases the input voltage while decreasing the output current. It is widely used in MPPT-based solar energy systems when the PV panel voltage is lower than the required load or battery voltage.

The Boost converter is known as a voltage step-up converter. The diagram in (Figure.II.3) represents the electrical circuit of the Boost converter. During the first interval (αT), the transistor (S) is closed, the current in the inductor gradually increases, and as time passes, it stores energy until the end of the first period. Then, the transistor (S) opens, and the inductor (L), opposing the decrease in current (IL), generates a voltage that adds to the source voltage, which is applied to the load (R) through the diode (D). **[4]**

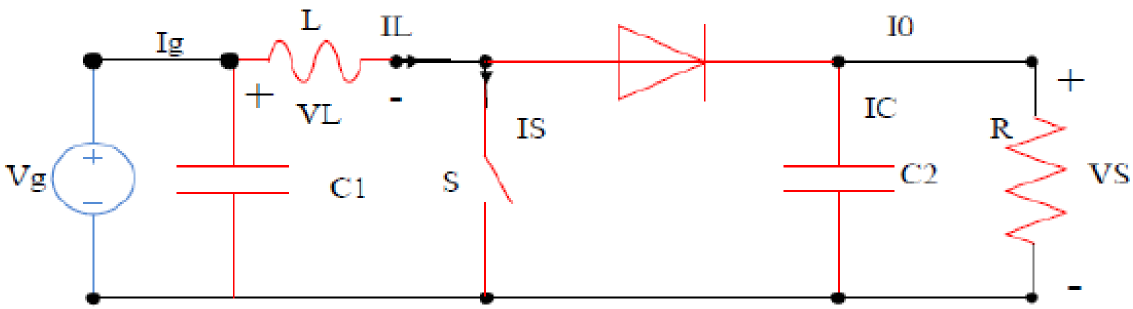


Figure.II.3 : Electrical Circuit Boost Converter **[4]**

- ✓ **Advantages**

- Enables voltage boosting for low-voltage PV panels.
- High efficiency (up to 95%).
- Simple circuit design with minimal components.
- Effective voltage regulation.
- Compact and suitable for various MPPT applications.

II.3.1 Applications in Solar MPPT Systems

- Boosting PV voltage for battery charging when PV voltage < battery voltage.
- Increasing voltage for grid-tied solar inverters.
- Powering DC loads that require higher voltage.
- Used in DC microgrids and hybrid solar energy systems

II.4 Buck-Boost Converter in MPPT-Based Solar Energy Systems

A Buck-Boost Converter is a DC-DC converter capable of both stepping up and stepping down the input voltage, making it highly versatile for MPPT-based solar energy systems. It is used when the PV panel voltage fluctuates above and below the required load or battery voltage.

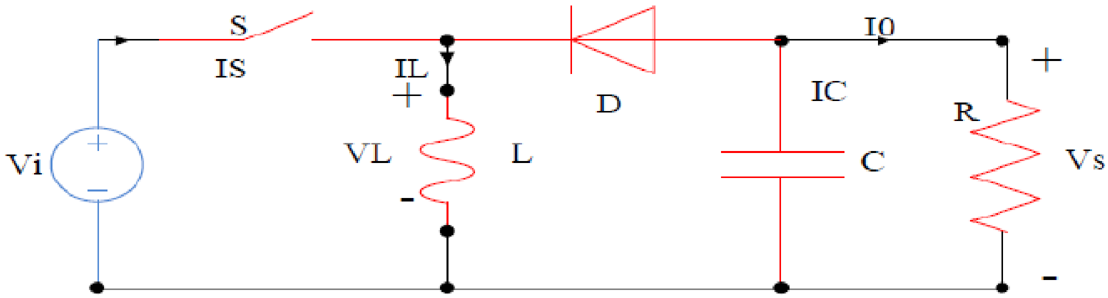


Figure.II.4: Electrical Circuit Buck-Boost Converter **[4]**

✓ Advantages

- Capable of both step-up and step-down voltage conversion.
- Ideal for applications where the PV voltage varies widely.
- High efficiency and effective voltage regulation.
- Provides flexibility for different load and battery requirements.

II.4.1 Applications in Solar MPPT Systems

- Used in PV battery charging systems where the panel voltage fluctuates.
- Employed in standalone solar power systems.
- Integrated into hybrid solar systems requiring variable voltage control.
- Used in off-grid applications where PV voltage variations are significant.

Buck, Boost, and Buck-Boost converters each play a crucial role in MPPT-based solar energy systems, ensuring efficient power conversion based on varying PV panel voltages. The Buck Converter is used when the PV voltage is higher than the required load or battery voltage, stepping it down efficiently. The Boost Converter is ideal when the PV voltage is lower than the required voltage, stepping it up to meet system needs. The Buck-Boost Converter provides the most flexibility by adjusting the voltage in both directions, making it suitable for systems where the PV voltage fluctuates above and below the desired level.

Each converter type has its advantages and limitations, and their selection depends on the specific application requirements. While Buck and Boost converters offer simpler designs and high efficiency, the Buck-Boost converter provides greater adaptability at the cost of increased complexity. In MPPT-based solar energy systems, choosing the right converter ensures optimal energy extraction, efficient power delivery, and improved system performance. **[4]**

II.5 DC-AC Converters (Inverters) in PV Systems

In photovoltaic systems, DC-AC converters, also known as inverters, are essential for converting the DC power generated by solar panels into AC power suitable for use in homes, industries, and the grid. Different types of inverters are used depending on the application, efficiency requirements, and grid connection. **[4]**

II.5.1 Overview

A DC-AC converter (inverter) transforms the direct current from a solar panel or battery storage system into alternating current . This conversion is necessary because most electrical appliances and the power grid operate on AC voltage.

II.5.2 Types of DC-AC Converters Used in PV Systems

- **Working Principle of a DC-AC Converter (Inverter):**

A DC-AC converter operates in several key stages:

- **DC Input Regulation:** The inverter receives a steady DC voltage from the PV array or battery.
- **Switching and Pulse-Width Modulation (PWM):** High-speed electronic switches (MOSFETs or IGBTs) create a high-frequency AC signal.
- **Filtering and Output Conversion:** The generated waveform is processed using filters to produce a sinusoidal AC voltage.

II.5.3 Types of Output Waveforms

- **Square Wave Inverter:** Simple and low-cost but inefficient for most applications.
- **Modified Sine Wave Inverter:** Improved efficiency but may not be compatible with sensitive equipment.
- **Pure Sine Wave Inverter:** Produces high-quality AC similar to the grid, suitable for all types of appliances.

✓ Advantages of DC-AC Converters in PV Systems

- Enables solar energy to be used in standard AC electrical systems.
- Supports integration with the grid, allowing net metering and feed-in tariffs.
- Improves energy management through smart monitoring and control.
- Provides power backup during outages (hybrid and off-grid systems).

II.5.4 Applications of DC-AC Converters in PV Systems

- **Residential solar power systems** for homes and small businesses.
- **Industrial solar plants** to reduce energy costs and reliance on fossil fuels.

- **Utility-scale solar farms** that feed electricity directly into the grid.
- **Remote and rural electrification** using standalone solar inverters.

DC-AC inverters play a critical role in PV systems by enabling efficient power conversion and integration with electrical networks. The choice of inverter depends on the system type, power requirements, and application. Advancements in inverter technology continue to improve efficiency, reliability, and smart grid compatibility, making solar energy more accessible and effective**. [18]**

II.6 Different type of MPPT algorithm

Maximum Power Point Tracking algorithms are designed to ensure that a photovoltaic (PV) system operates at its MPP, where the output power is maximized. The two most widely used MPPT techniques are:

- Perturbation and Observation
- Incremental Conductance

Both methods work by dynamically adjusting the operating voltage and current to track the MPP, but they differ in their approach and accuracy. **[19]**

II.6.1 Perturbation and Observation MPPT Algorithm

The Perturbation and Observation algorithm is one of the most commonly used MPPT techniques in photovoltaic systems. It is widely favored due to its simplicity, ease of implementation, and low computational requirements. However, it has some limitations, such as oscillations around the MPP and reduced performance under rapidly changing environmental conditions. **[19]**

The P&O algorithm operates by periodically perturbing the voltage or current of the solar panel and observing the corresponding change in power output. Based on this observation, it adjusts the operating point to move toward the MPP. **[19]**

II.6.1.1 Principle of Operation

The power-voltage (P-V) characteristic curve of a solar panel has a distinct maximum power point. The general rule is:

- **Before the MPP** → Increasing voltage **increases power**
- **After the MPP** → Increasing voltage **decreases power**

This means that by **perturbing** the voltage slightly and **observing** the resulting power change (P), the algorithm can determine whether to increase or decrease the operating voltage to reach the MPP.

$$P = V \cdot I \qquad \text{(Equ.II.4)}$$

The change in power is calculated as:

$$\Delta P = P(k) - P(k-1) \qquad \text{(Equ.II.5)}$$

Where:

P(k) is the power at the current instant

P(k−1) is the power at the previous instant

❖ **Decision-Making Process**

The P&O algorithm follows these four main conditions:

- If $\Delta P > 0$ and $\Delta V > 0 \rightarrow$ Increase V
- If $\Delta P > 0$ and $\Delta V < 0 \rightarrow$ Decrease V
- If $\Delta P < 0$ and $\Delta V > 0 \rightarrow$ Decrease V
- If $\Delta P < 0$ and $\Delta V < 0 \rightarrow$ Increase V

This process is continuously repeated, making the system oscillate around the MPP. **[20]**

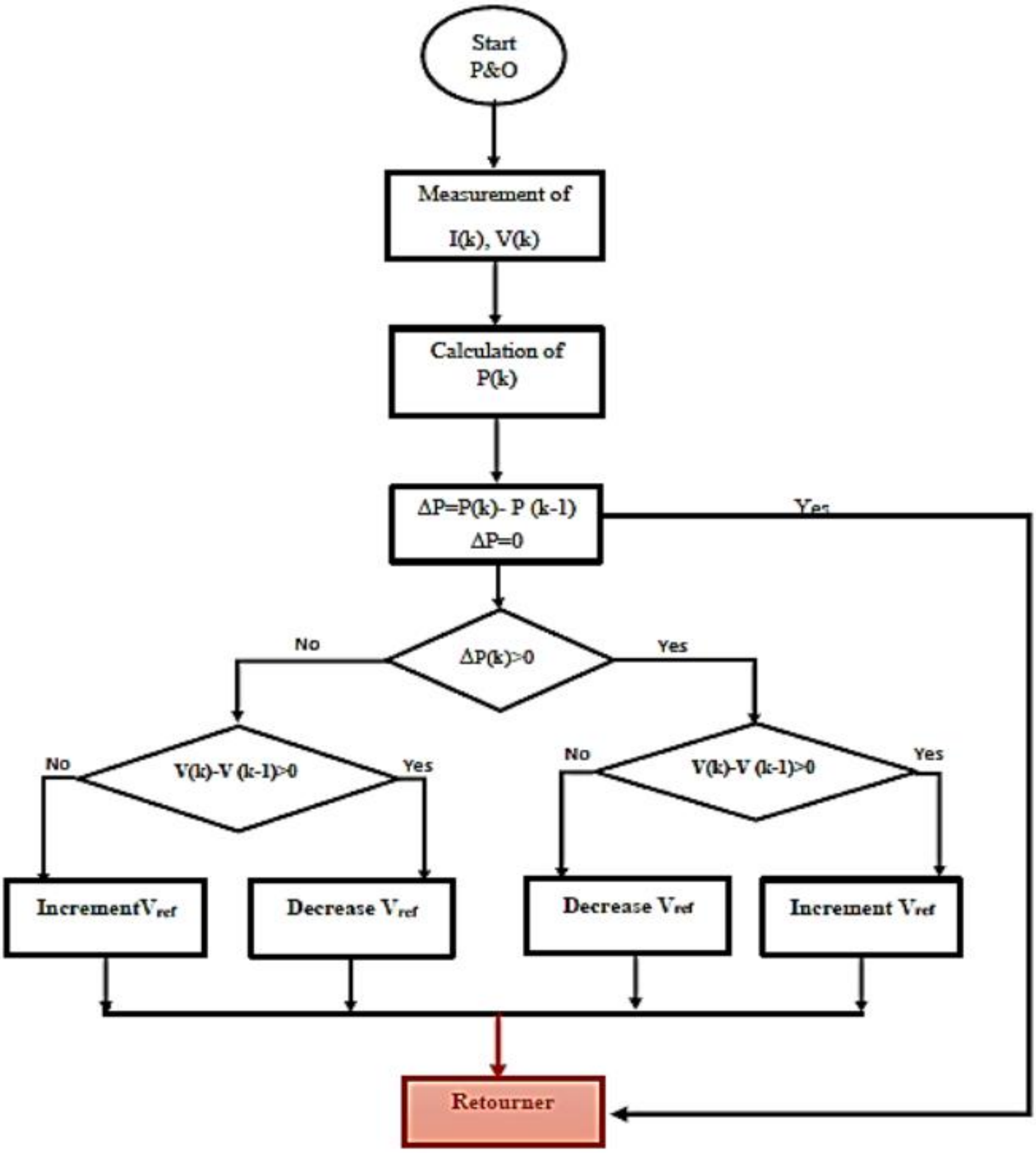


Figure.II.5: Flow Chart Of P&O Algorithm**. [15]**

II.6.2 Applications of P&O MPPT

- **Solar charge controllers** for battery charging.
- **Grid-tied PV systems** to optimize energy transfer.
- **Hybrid renewable energy systems** (solar + wind).

II.7 Incremental Conductance MPPT Algorithm

Introduction

The Incremental Conductance method is an advanced MPPT algorithm that overcomes some of the limitations of the P&O method. Unlike P&O, which relies on periodic perturbations, IC determines the exact location of the MPP by analyzing the conductance of the solar panel. This method provides higher accuracy and faster response under rapidly changing irradiance conditions, making it a preferred choice for more sophisticated solar energy systems. **[20]**

II.7.1 Principle of Operation

The IC algorithm is based on the fact that the slope of the Power-Voltage (P-V) curve of a PV system provides information about the location of the MPP:

At the MPP:

$$\frac{dP}{dV} = 0 \qquad \text{(Equ.II.6)}$$

To the left of the MPP:

$$\frac{dP}{dV} > 0 \ \ (Increase\ Voltage) \qquad \text{(Equ.II.7)}$$

To the right of the MPP:

$$\frac{dP}{dV} < 0 \ (\text{Decrease Voltage}) \qquad \text{(Equ.II.8)}$$

Since $P = V.I$, Differentiating Both Sides Gives

$$\frac{dP}{dV} = I + V\frac{dI}{dV} \qquad \text{(Equ.II.9)}$$

Settings this equal to zero at the MPP Condition:

$$I + V\frac{dI}{dV} = 0 \qquad \text{(Equ.II.10)}$$

Which simplifies to

$$\frac{dI}{dV} = -\frac{I}{V} \qquad \text{(Equ.II.11)}$$

The equation is the core condition used in the incremental Conductance algorithm to decide whether to Increase or Decrease the voltage.

❖ **Decision Making Process**

The algorithm follows these rules to track the MPP:

- If $\frac{dI}{dV} = -\frac{I}{V} \rightarrow$ MPP is reached
- If $\frac{dI}{dV} > -\frac{I}{V} \rightarrow$ Increase voltage

- If $\frac{dI}{dV} < -\frac{I}{V} \rightarrow$ Decrease voltage

The system continuously updates the voltage based on these conditios,
Ensuring that it always operates at or near the MPP. **[20]**

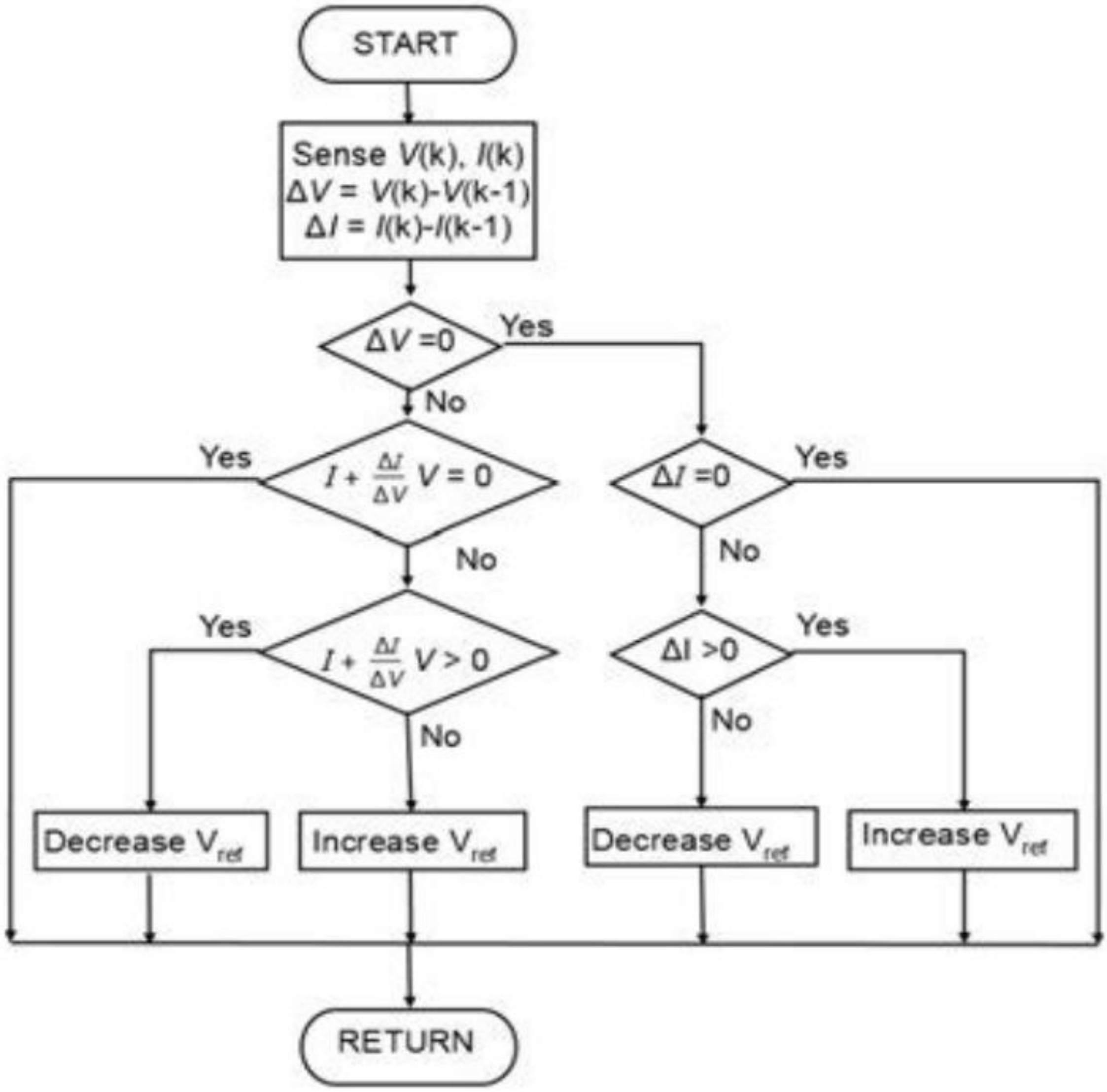


Figure.II.6: Flow Chart of IC Algorithm. **[15]**

II.7.2 Applications of IC MPPT

- High-efficiency solar energy systems
- Smart grid-connected PV inverters
- Battery charging applications
- Hybrid renewable energy system

II.8 Fuzzy Logic Controller

Introduction

In recent years, intelligent control methods such as Fuzzy Logic Control have gained significant attention for Maximum Power Point Tracking in photovoltaic systems. Unlike conventional techniques such as Perturb and Observe or Incremental Conductance that rely on precise mathematical modeling, FLC offers a rule-based, nonlinear approach capable of handling uncertainties and imprecise inputs, which are inherent in real-world PV environments due to dynamic irradiance and temperature fluctuations

Fuzzy logic, first introduced by **Lotfi Zadeh** in **1965**, is based on the concept of approximate reasoning, allowing decision-making with incomplete or imprecise information. This feature makes it well-suited for control applications where a precise model is either unavailable or too complex.

II.8.1 Operating Principle of FLC in MPPT

The structure of fuzzy logic systems is simple and understandable. It can also be used confidently, especially when faced with imprecise inputs. The advantage of this controller is that it works with imprecise inputs. Also, not needing a precise mathematical model and being non-linear are other features of this algorithm. FLC for MPPT uses two input parameters, *E* error and *CE* error change at time *k.* **[21]**, which are defined by the following equations:

Error (E): Defined as the instantaneous change in power with respect to voltage

$$E(k) = \frac{P(k) - P(k-1)}{V(k) - V(k-1)} \qquad \text{(Equ. II. 12)}$$

Change in Error (CE): Difference between successive error values

$$CE(k) = E(k) - E(k-1) \qquad \text{(Equ. II. 13)}$$

while the system output cycle of this algorithm is task *D*.

The output is generally a control signal used to adjust the duty cycle (D) of the DC-DC converter or to modify the reference voltage toward the Maximum Power Point.

II.8.2 Structure of the Fuzzy Logic Controller

Fuzzification: Converts crisp input values (E, ΔE) into linguistic variables using membership functions. Triangular or trapezoidal functions are commonly used.

Rule Base: A set of IF-THEN rules derived from expert knowledge or system behavior. An example rule might be:

Example:

IF Error is Positive Small AND ΔError is Negative THEN Output is Zero.

IF temperature is high AND sunlight is low THEN voltage adjustment is small.

Inference Mechanism: Applies logical reasoning to the fuzzy inputs and rules to determine fuzzy outputs.

Defuzzification: Converts the fuzzy output into a crisp control signal. The Centroid Method is frequently used due to its accuracy and simplicity.

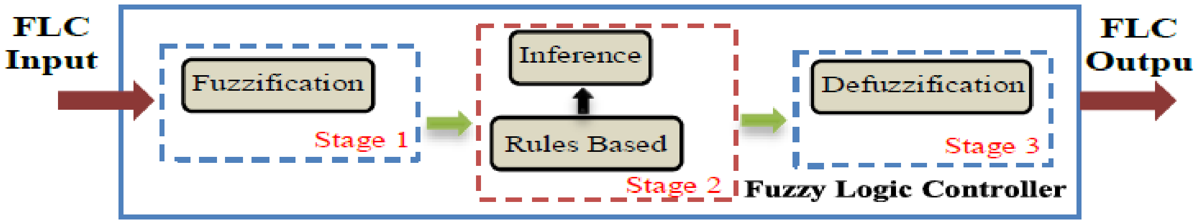


Figure.II.7: Block diagram MPPT of FLC algorithm.**[21]**

II.8.3 Design of Membership Functions and Rule Base

For MPPT, both inputs and the output are typically divided into seven fuzzy subsets

- Negative Big (NB), Negative Medium (NM), Negative Small (NS), Zero (ZE), Positive Small (PS), Positive Medium (PM), Positive Big (PB)

The rule base consists of 49 (7×7) rules that describe the system behavior under various conditions. These rules are carefully designed to minimize oscillations and ensure fast convergence to the MPP.

Table.II.1: Rule base for the FLC Algorithm. **[22]**

E / Δe	NB	NM	NS	ZE	PS	PM	PB
NB	NB	NB	NB	NB	NM	NS	ZE
NM	NB	NB	NB	NM	NS	ZE	PS
NS	NB	NB	NM	NS	ZE	PS	PM
ZE	NB	NM	NS	ZE	PS	PM	PB
PS	NM	NS	ZE	PS	PM	PB	PB
PM	NS	ZE	PS	PM	PB	PB	PB
PB	ZE	PS	PM	PB	PB	PB	PB

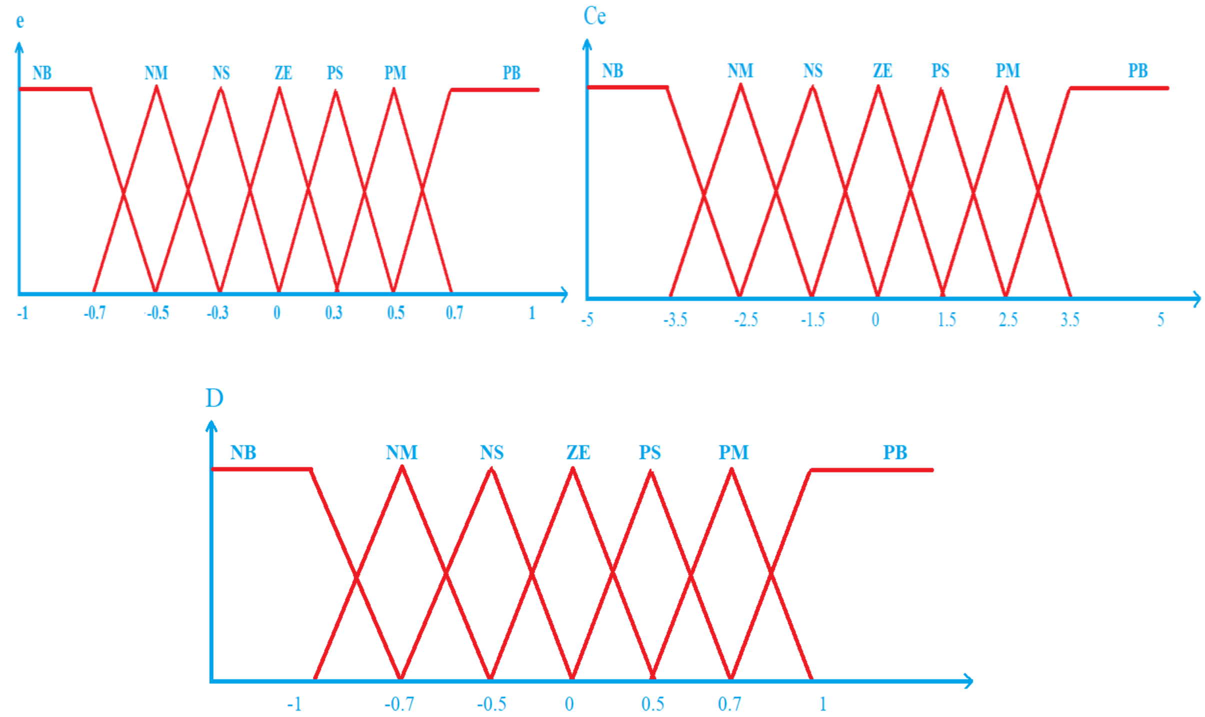


Figure.II.8: Membership Functions of Input and Output

✓ Advantages of Fuzzy Logic in MPPT

- No requirement for an accurate mathematical model
- Fast dynamic response to changing irradiance or temperature
- Smooth control output with minimal oscillations near MPP
- Robustness against measurement noise and environmental variability

II.8.4 Applications and Integration

FLC is particularly suitable for stand-alone and grid-connected PV systems, and has also been successfully integrated with hybrid MPPT strategies, such as fuzzy-P&O or fuzzy-neural combinations, to further enhance tracking performance under rapidly fluctuating conditions.

II.9 Particle Swarm Optimization (PSO) for MPPT

Introduction

Particle Swarm Optimization is a population-based, metaheuristic optimization algorithm inspired by the social behavior of bird flocks and fish schools, introduced by Kennedy and Eberhart in 1995. Due to its simplicity, convergence speed, and effectiveness in solving nonlinear optimization problems, PSO has been increasingly adopted for Maximum Power Point Tracking in photovoltaic systems.In the context of MPPT, PSO searches for the optimal operating point—corresponding to the maximum power—by iteratively adjusting a group of potential solutions (particles), each representing a duty cycle
or voltage reference value for the DC-DC converter.

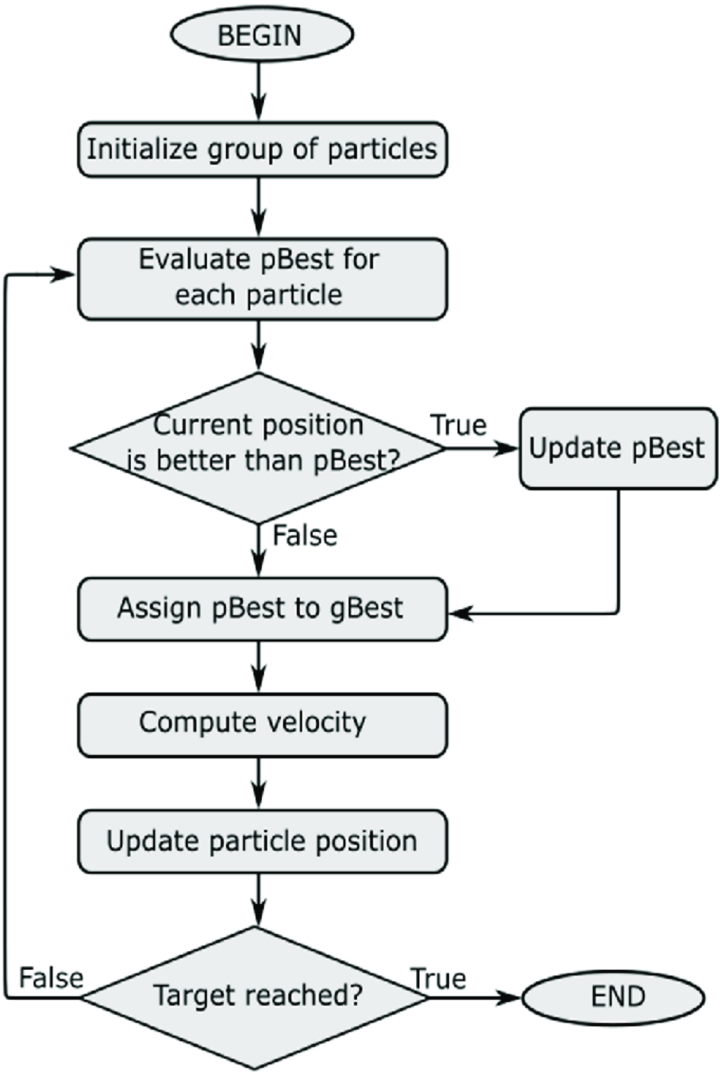


Figure.II.9: Flow Chart of PSO algorithm.**[15]**

II.9.1 PSO Algorithm in MPPT

In PSO, a population of particles is initialized with random positions and velocities in the search space. Each particle updates its position based on two main factors:

Personal Best (pBest): The best position (solution) the particle has found so far.

Global Best (gBest): The best position discovered by any particle in the swarm.

The position and velocity of each particle are updated using the following equations:

$$v_i(k+1) = w * v_i(k) + c_1 * r_1\left(pBest_i - x_i(k)\right) + c_2 * r_2 * \left(gBest - x_i(k)\right) \quad \text{(Equ.II.14)}$$

$$x_i(k+1) = x_i(k) + v_i(k+1) \quad \text{(Equ.II.15)}$$

Where :

- x_i and v_i: position and velocity of particle i
- w: inertia weight (balances expolration and exploitation)
- c_1, c_2: cognitive and social acceleration constants
- r_1, r_2: random numbers between 0 and 1

In MPPT applications the fitness functions is typically the output power of the PV system, which the algorithm seeks to maximize. **[18]**

II.9.2 Advantages of PSO in MPPT

- **Global search capability**: Less likely to get trapped in local optima compared to P&O and IC.
- **Fast convergence**: Can reach MPP in fewer iterations.
- **Robust performance**: Effective under partial shading and rapidly changing weather conditions.
- **Parameter flexibility**: Adaptable to different system configurations through tuning of algorithm constants. **[18]**

II.9.3 Disadvantges of PSO :

- **Parameter tuning**: Performance depends heavily on proper selection of swarm size, inertia weight, and acceleration coefficients.
- **Computational load**: More complex than traditional methods, requiring more processing power especially when implemented in real-time on embedded systems.
- **Oscillations**: May still cause fluctuations around MPP if not properly damped. **[18]**

II.9.4 Practical Implementation in MPPT

To apply PSO in MPPT:

- Initialize a swarm of particles with random duty cycles or voltage references.

- Evaluate the power output at each particle's position.
- Update pBest and gBest.
- Adjust velocities and positions.
- Apply the best position (gBest) to control the converter.

PSO is particularly suitable for offline optimization**,** hybrid MPPT**,** or advanced embedded systems with sufficient computational resources.

PSO offers a powerful and intelligent optimization-based approach to MPPT in PV systems. Its ability to perform global search and handle complex, nonlinear PV characteristics makes it especially valuable under partial shading and dynamic environmental conditions. However, its real-time implementation requires careful consideration of computational constraints and parameter tuning. **[18]**

II.10 Conclusion

This chapter provided a comprehensive overview of several Maximum Power Point Tracking algorithms applied in photovoltaic systems, focusing on both traditional and intelligent methods. The classical techniques, Perturb and Observe and Incremental Conductance , are commonly used due to their straightforward implementation and low computational requirements. However, they exhibit notable drawbacks, such as steady-state oscillations and diminished tracking performance during sudden environmental changes like fluctuating irradiance or temperature.

To overcome these limitations, Fuzzy Logic Control was explored as a more adaptive and intelligent approach. FLC does not require an exact mathematical model of the system and offers a smoother and faster response, particularly in dynamic conditions. Nevertheless, its effectiveness depends heavily on the proper design of membership functions and rule bases, which may require expert knowledge.

In addition, the chapter examined Particle Swarm Optimization, a population-based metaheuristic algorithm inspired by social behavior in nature. PSO has shown promising results in tracking the global maximum power point, especially under non-uniform operating conditions such as partial shading. Its main advantages lie in its strong global search capability and relatively simple structure, although it may involve more computational effort compared to traditional methods.

To efficiently regulate power, DC-DC converters are used. The Buck Converter steps down voltage when the PV voltage is higher than the load, the Boost Converter steps up voltage when the PV voltage is lower, and the Buck-Boost Converter can adjust voltage in both directions, providing greater flexibility. Additionally, DC-AC inverters are essential for converting solar DC power into AC, making it compatible with household appliances, industries, and the grid.

By integrating MPPT with appropriate power converters, solar energy systems achieve higher efficiency, improved power management, and better adaptation to varying environmental conditions, ensuring reliable and optimized energy generation

Each algorithm discussed demonstrates unique strengths and limitations in terms of tracking accuracy, speed, stability, and implementation complexity. The selection of an appropriate MPPT technique should therefore be based on the specific requirements and constraints of the PV system, including environmental variability, desired efficiency, and available computational resources.

Chapter III: Simulation & Results

III. Introduction

This chapter presents the simulation results of the MPPT control methods developed and analyzed throughout this work. The simulations were performed under varying environmental conditions, including changes in solar irradiance (up to 1000 W/m²) and temperature (starting from 25°C), to assess the dynamic performance and robustness of the proposed approaches.

The goal is to evaluate how efficiently each algorithm can track the maximum power point of a photovoltaic system under real-world fluctuations. Simulations were carried out using **MATLAB/Simulink**, a widely recognized tool for modeling and simulating dynamic systems, particularly in control engineering and renewable energy applications.

By analyzing the power output, convergence speed, and stability of each method, we aim to determine the most effective MPPT strategy under non-uniform operating conditions.

III.1 MATLAB Environment

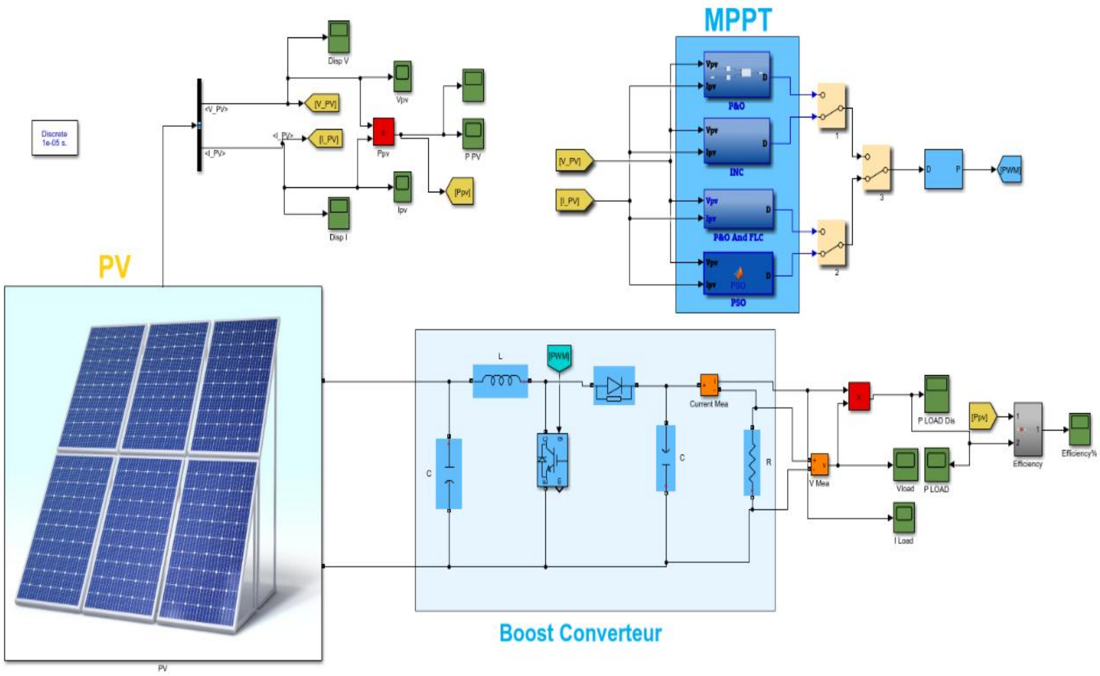
MATLAB (Matrix Laboratory) is a powerful software environment used for technical computing and model-based design. It provides a flexible interface for algorithm development, data visualization, and simulation of complex systems.

❖ Notable Features of MATLAB:

- Intuitive matrix-based syntax that simplifies mathematical modeling;
- Acts as both a programming language and an interactive computational environment;
- Executes commands in real time, allowing step-by-step debugging and testing;
- Offers extensive graphical tools for visualizing data and results clearly;
- Can integrate external code written in languages such as C or FORTRAN;
- Operates across multiple platforms including Windows, macOS, and Linux.

Simulink, an extension of MATLAB, is a block-diagram-based environment that allows for the design and simulation of multi-domain dynamic systems. It is especially suited for control systems, power electronics, and real-time implementation.

III.2 System Description



The system consists of:

- **PV Array : Trina Solar TSM-215DA01A**
- **A photovoltaic generator**: Modeled using a user-defined module with 1 module per string and 10 strings in parallel. It delivers a total power of approximately **2131.5 W** under standard irradiance and temperature.
- **An MPPT controller**: Designed to extract the maximum power from the PV generator. The controller can implement various algorithms for tracking the maximum power point.
- **A boost converter**: Controlled by a PWM signal generated from the MPPT algorithm. It consists of an inductor, diode, switch, and output capacitor, and is used to step up the PV voltage.
- **A resistive load**: Connected to the converter's output, representing the DC load. Voltage, current, and power are measured across the load.
- **Measurement and display blocks**: Used to monitor PV performance, duty cycle, output voltage, and power during the simulation.
- We used **Matlab 2021a** In the Simulation

The blocks and Circuits we used :

- PV ARRAY

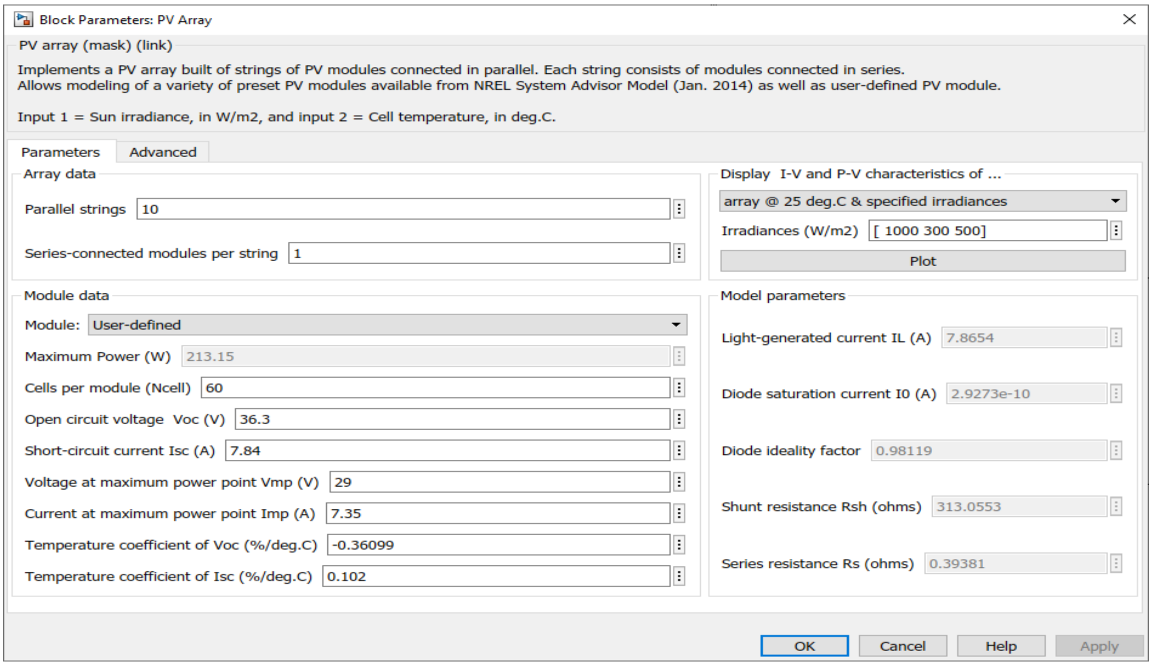


Figure.III.1: PV ARRAY

- BOOST CONVERTER

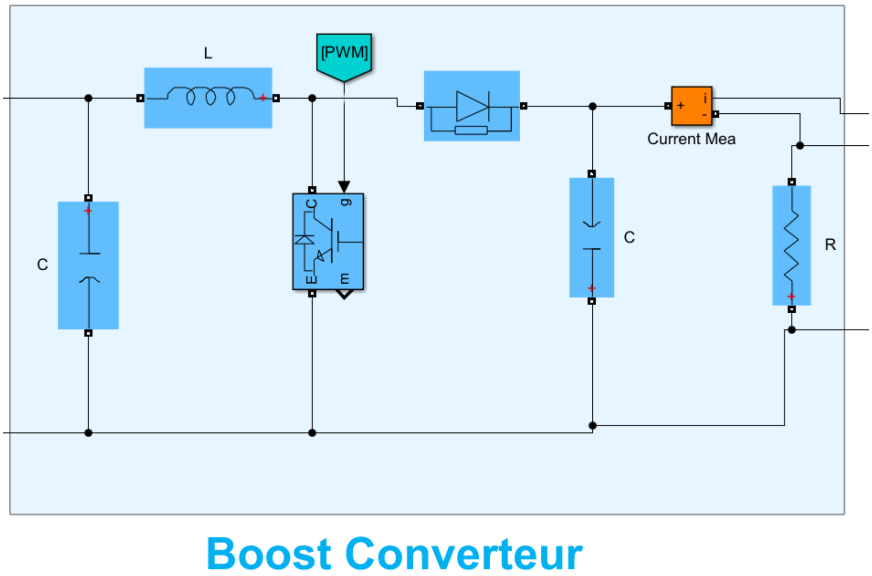


Figure.III.2: Boost Converter

L= 1.25e-3 (H)

C1= 1000e-6 (C)

C2=4000e-6 (C)

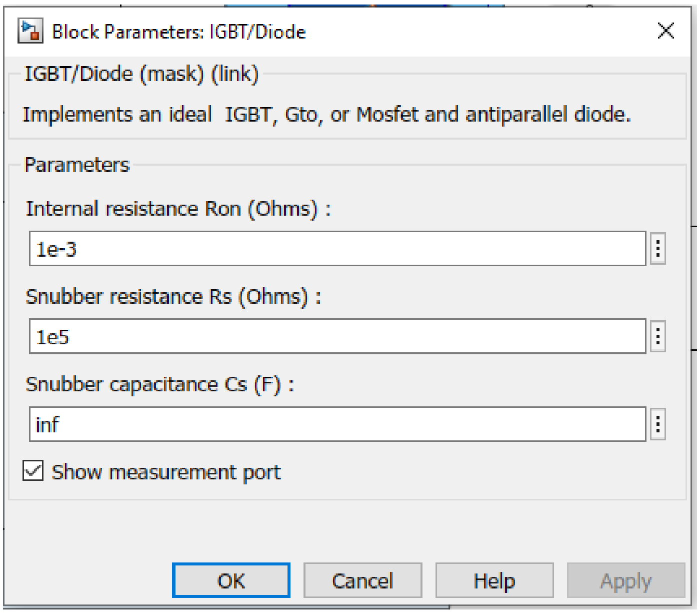


Figure.III.3: IGBT/Diode

This block represents a PWM Generator (DC-DC) : This is the functional block generating the PWM signal based on the given duty cycle input. It's used to regulate the output voltage/current of a DC-DC converter by controlling the time the switch stays ON versus OFF.

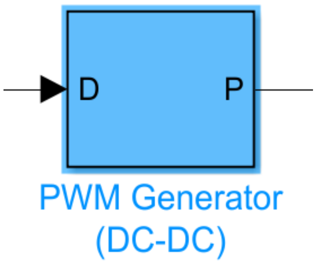


Figure.III.4: PWM Generator Block

Environmental Conditions:

The simulations were conducted under fixed irradiance (1000) and dynamic irradiance changes following the profile: 1000 → 850 → 500 → 1000 W/m². Additionally, the temperature was set to change slightly, which causes small variations in the PV module's voltage output. It's known that an increase in temperature typically leads to a reduction in the open-circuit voltage (Voc) of the PV array, slightly shifting the MPP. Therefore, the MPPT algorithm must adapt not only to changing irradiance but also to the thermal effect, which further complicates power tracking.

III.3 MPPT Techniques

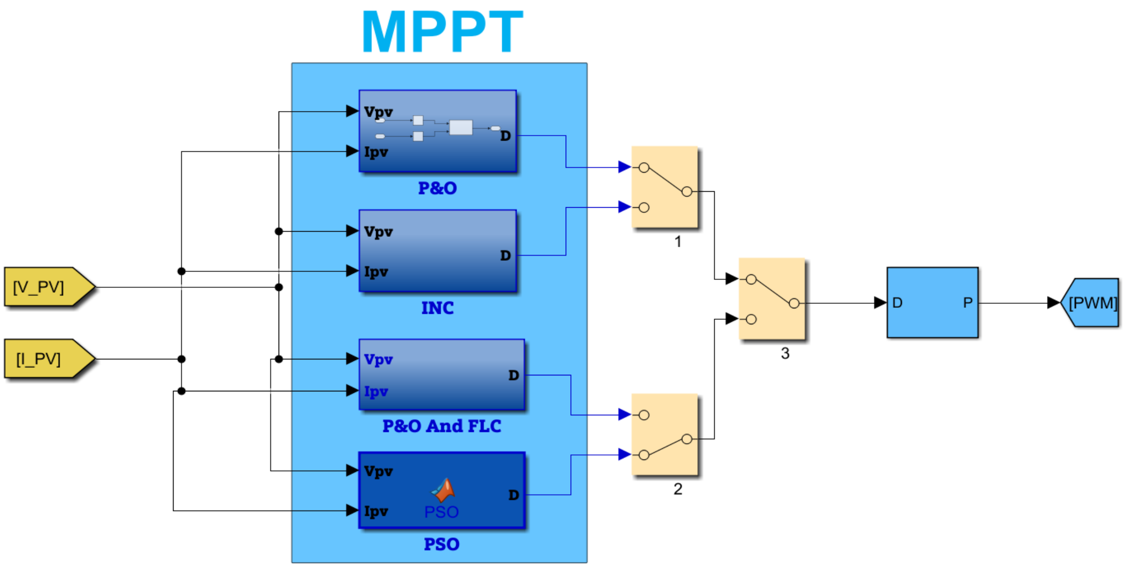


Figure.III.5: Diagram of MPPT Techniques

III.3.1 Description of MPPT Diagram

This diagram represents a **Multi-Algorithm Maximum Power Point Tracking system** for a **Photovoltaic system**, connected to a **PWM Generator** that controls a DC-DC converter (likely a boost converter)

- ❖ **INPUTS:**
  - ➢ **V_{PV}:** PV array voltage.
  - ➢ **I_{PV}:** PV array current.

These inputs are fed into all the MPPT algorithms in parallel.

❖ **MPPT Algorithms Blocks:**

This block contains four MPPT techniques, all receiving the same PV voltage and current as inputs, Each algorithm outputs a **duty cycle** signal

❖ **Selector Switches:**

- ➢ **Switches 1, 2, and 3** are used to choose which MPPT algorithm's output will be passed on:
- Switch 1 selects between **P&O and INC**.
- Switch 2 selects between **P&O And FLC and PSO**.
- Switch 3 chooses between the outputs of Switch 1 and Switch 2.

This setup allows dynamic selection of any one of the four MPPT algorithms at runtime.

- **Output :**
  - **PWM**: Final pulse-width modulated signal Goes to IGBT/Diode

III.4 P&O

The Perturb and Observe method is widely used due to its simplicity and ease of implementation. It operates by applying a small perturbation to the voltage and monitoring the change in power. If the power increases, the perturbation continues in the same direction; otherwise, it is reversed.

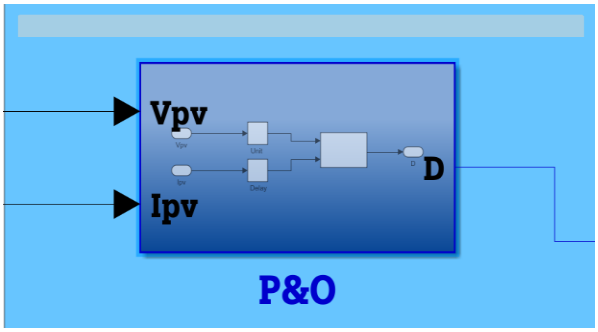


Figure.III.6: P&O Subsystem

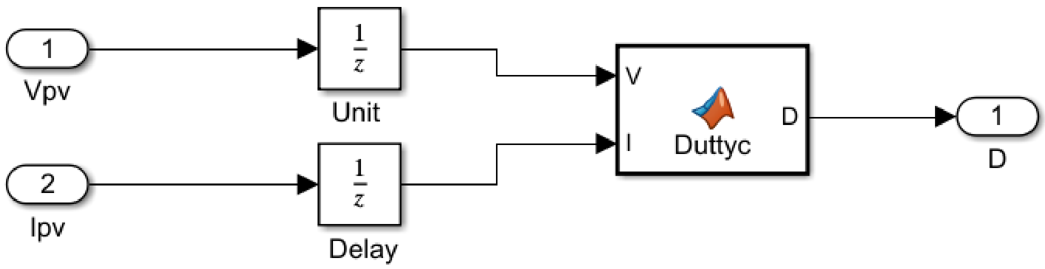


Figure.III.7: Diagram of MPPT P&O

This diagram is a Simulink subsystem implementing **a P&O** MPPT control algorithm that Generating the **Duty Cycle.**

- Delay (unit) Blocks these are used to compute **differences or past values** needed for P&O.
- **Duttyc Block** is **MatlabFunction** Block it's contains Our P&O Code to Calucate The optimale DutyCycle for PWM .

III.4.1 Result of simulation :

- <u>**Note**</u> **: Simulation time in Seconds**

- **Fixed 1000 irradiance 25° Temperture**

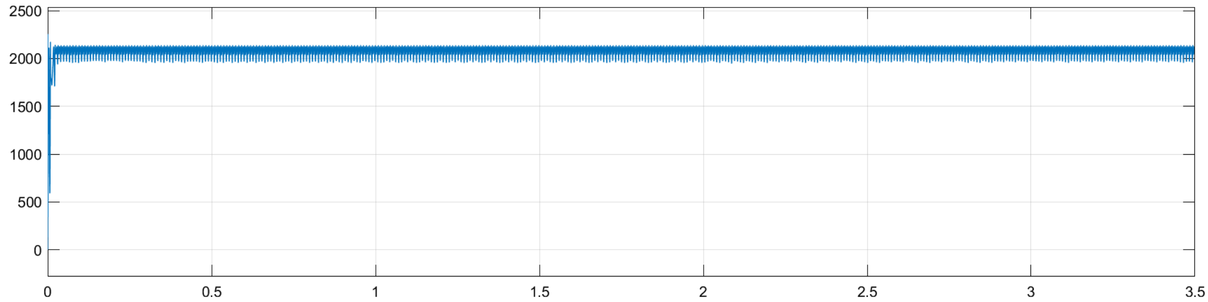


Figure.III.8 : Power PV Perturb and Observe (1000 Irradiance 25°)

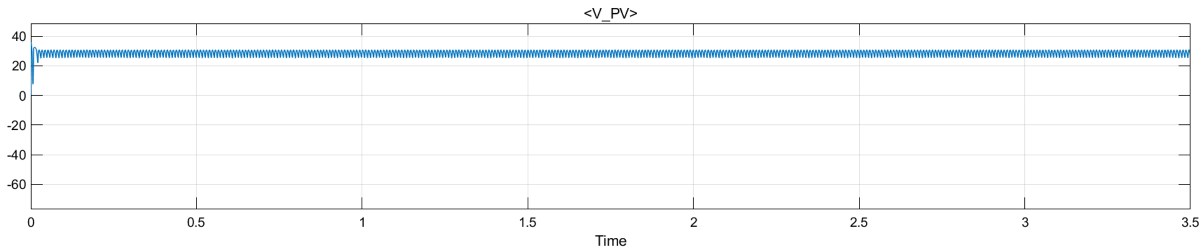


Figure.III.9 : Voltage PV Perturb and Observe (1000 Irradiance 25°)

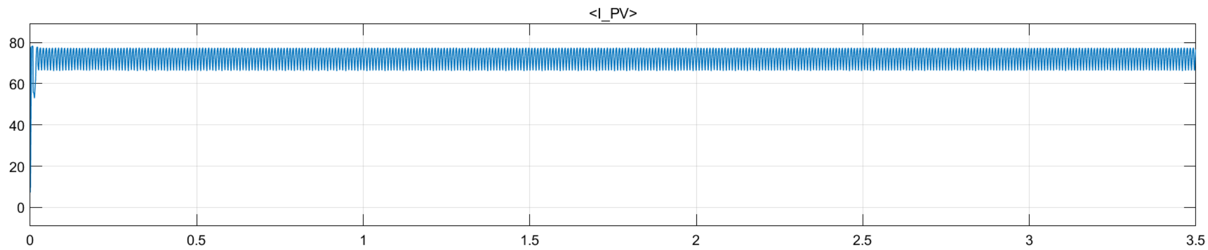


Figure.III.10 : Current PV Perturb and Observe (1000 Irradiance 25°)

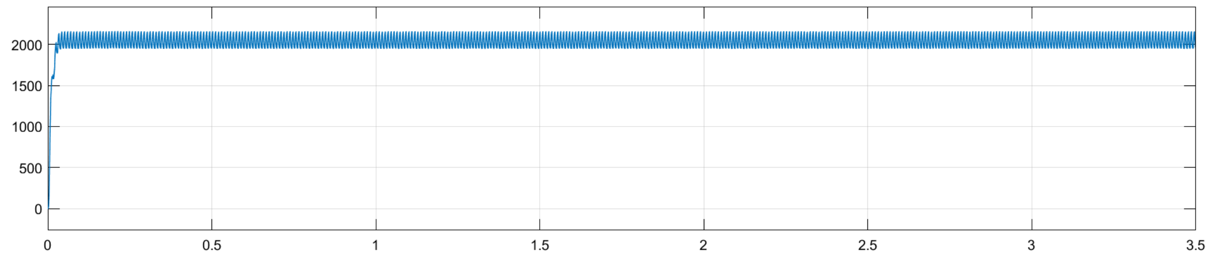


Figure.III.11 : Power LOAD Perturb and Observe (1000 Irradiance 25°)

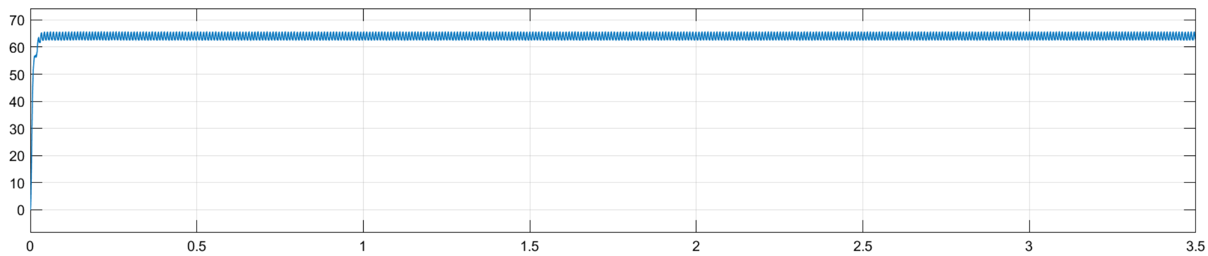


Figure.III.12 : Voltage Load Perturb and Observe (1000 Irradiance 25°)

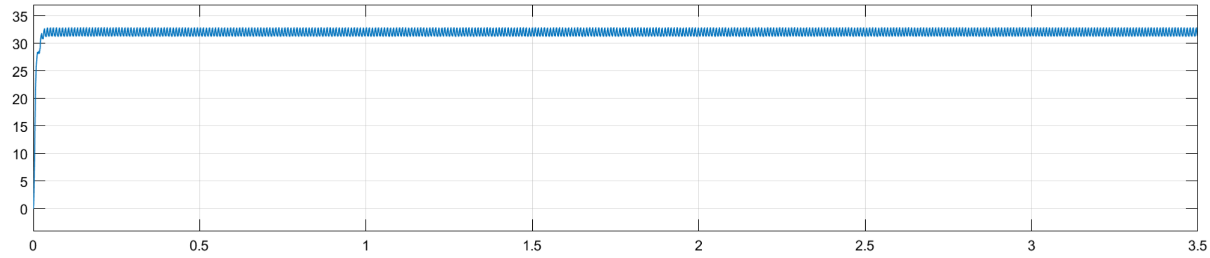


Figure.III.13 : Current Load Perturb and Observe (1000 Irradiance 25°)

- **Fixed Temperture 25°C and variable irradiance**

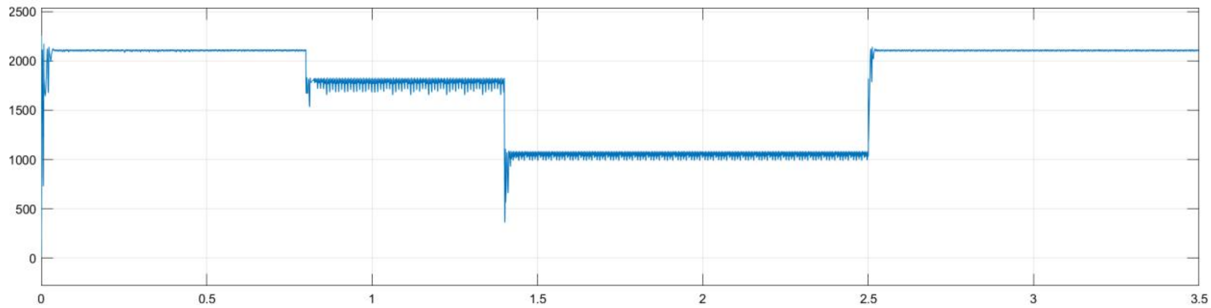


Figure.III.14 : Power PV Perturb and Observe

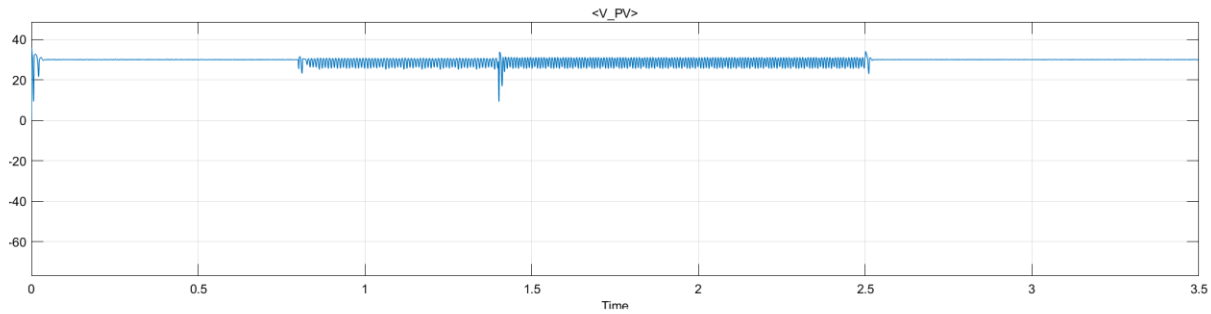


Figure.III.15 : Voltage PV Perturb and Observe

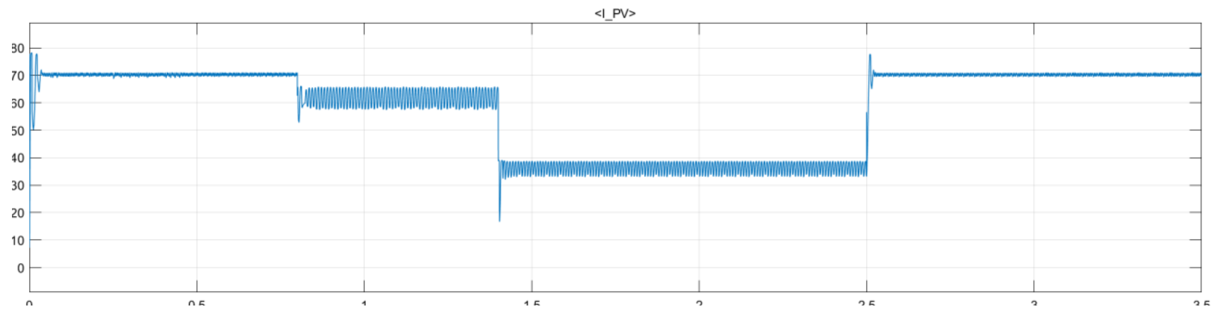


Figure.III.16 : Current PV Perturb and Observe

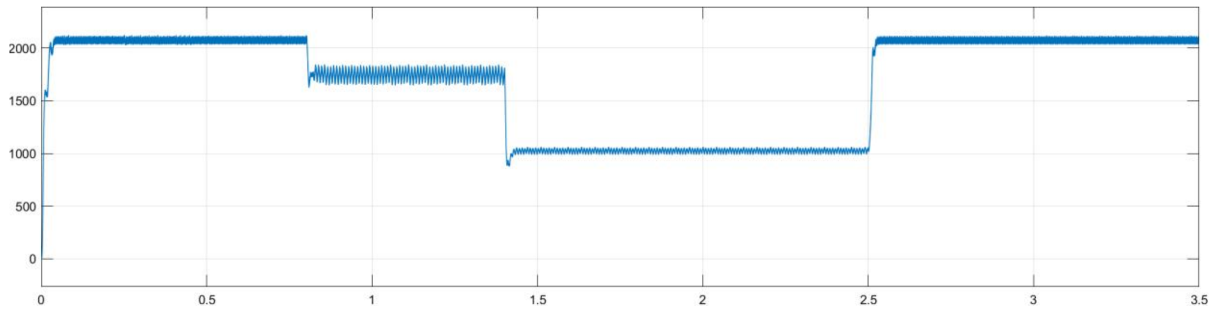


Figure.III.17 : Power Load Perturb and Observe

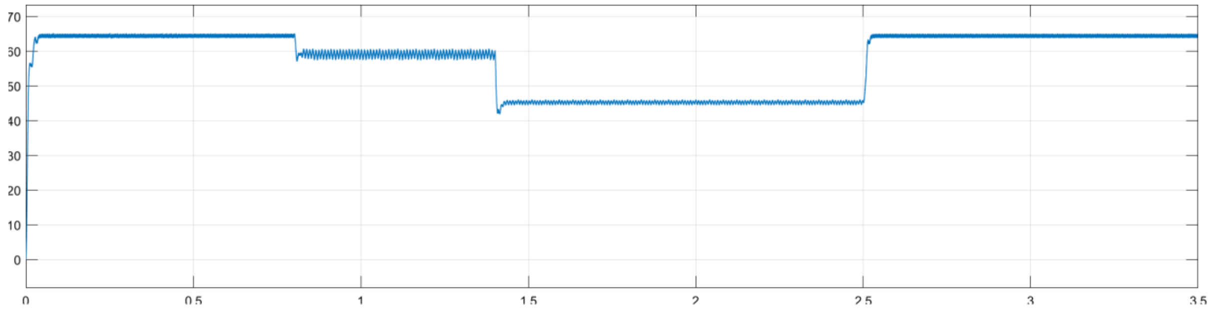


Figure.III.18 : Voltage Load Perturb and Observe

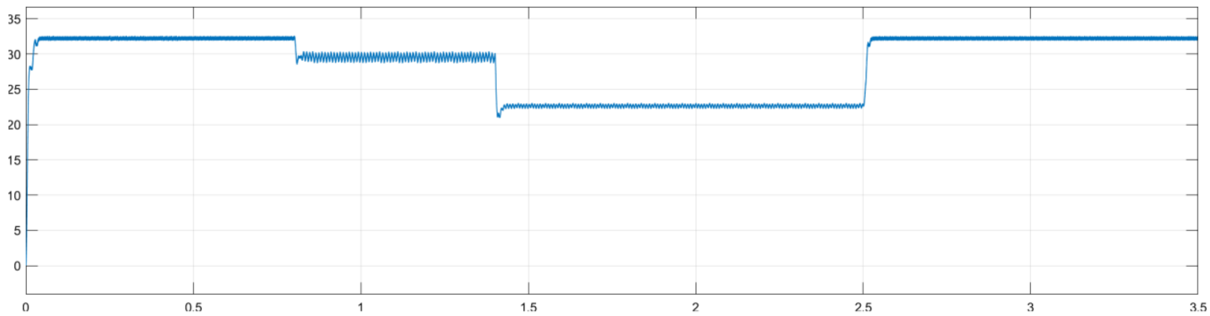


Figure.III.19 : Current Load Perturb and Observe

- **Modify and implement P&O**

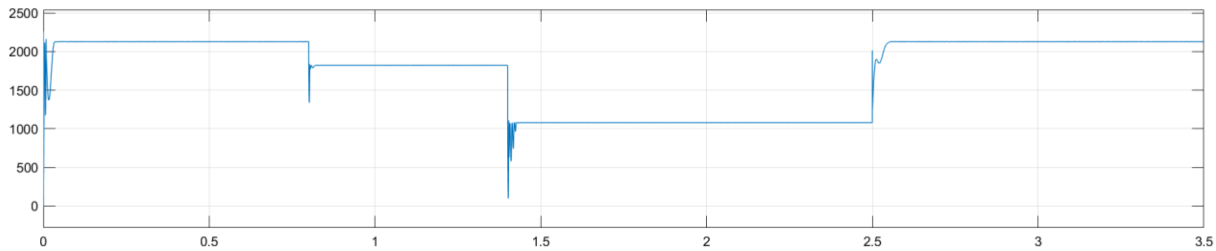


Figure.III.20: Power PV Perturb and Observe (Modifed)

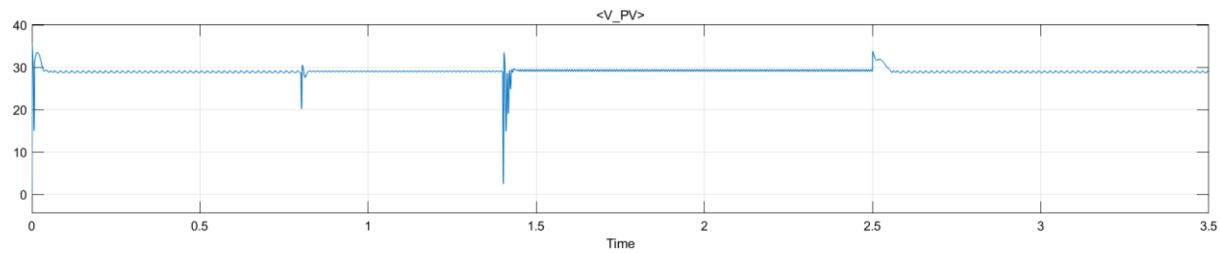


Figure.III.21 : Voltage PV Perturb and Observe (Modifed)

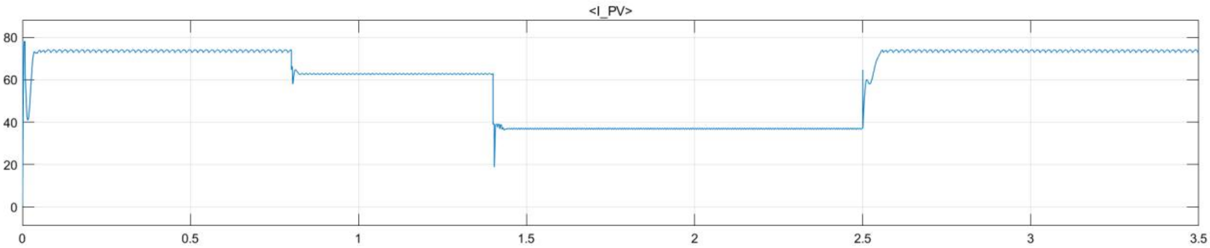


Figure.III.22 : Current PV Perturb and Observe (Modifed)

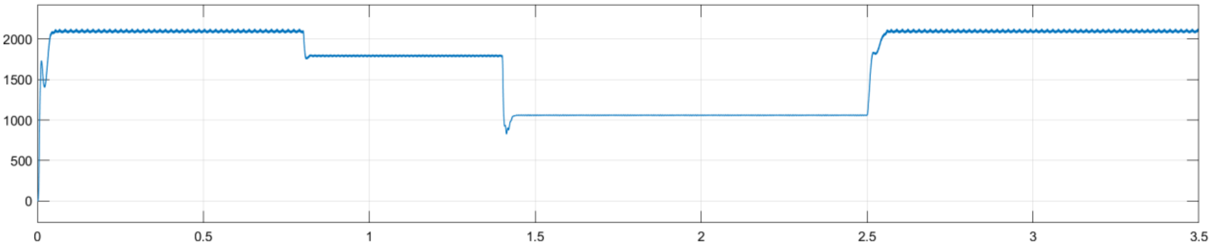


Figure.III.23 : Power Load Perturb and Observe (Modifed)

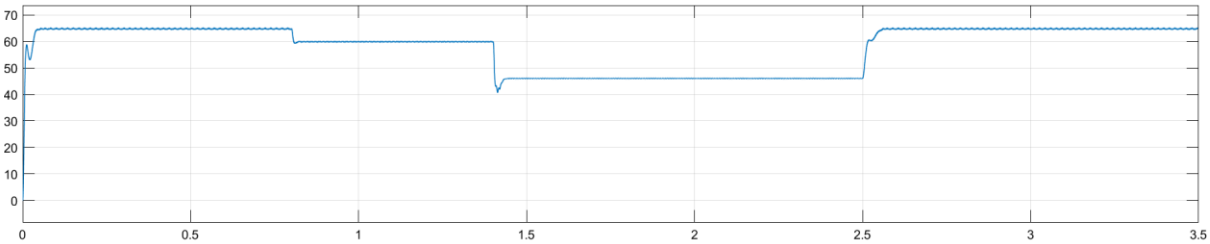


Figure.III.24 : Voltage Load Perturb and Observe (Modifed)

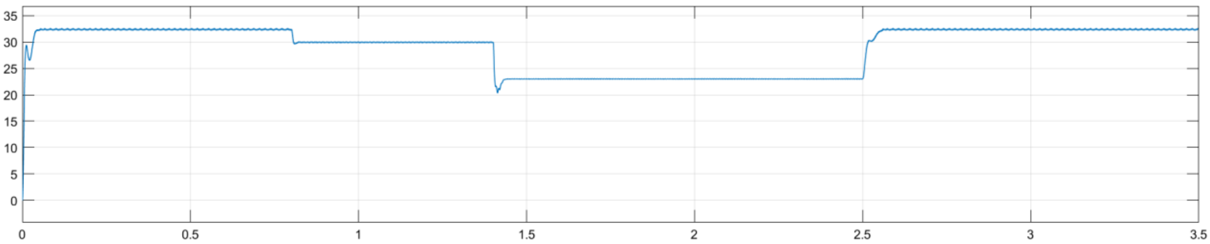


Figure.III.25 : Current Load Perturb and Observe (Modifed)

III.4.1 Observations

- **Fixed Conditions**

Under stable conditions with constant irradiance and temperature, the classical P&O algorithm performs effectively. The power, voltage, and current remain stable with minimal oscillation. This confirms the algorithm's reliability and accuracy when environmental parameters do not change.

- **Variable Irradiance**

When the irradiance varies over time, the limitations of the classical algorithm become more evident. Noticeable oscillations occur, and the system takes longer to reach the new maximum power point. This slower adaptation leads to decreased tracking efficiency in dynamic conditions.

- **Performance of the Modified Algorithm**

The improved P&O algorithm demonstrates better responsiveness to irradiance changes. It reduces power oscillations and achieves faster convergence to the optimal operating point. This makes it more suitable for real-world photovoltaic applications where environmental conditions frequently fluctuate.

III.5 Incremental Conductance

Incremental Conductance improves upon P&O by using the relationship between the incremental and instantaneous conductance to determine the direction of the operating point. The algorithm halts perturbations when the condition dP/dV=0 is satisfied.

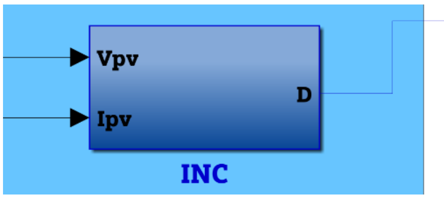


Figure.III.26: IC SubSystem

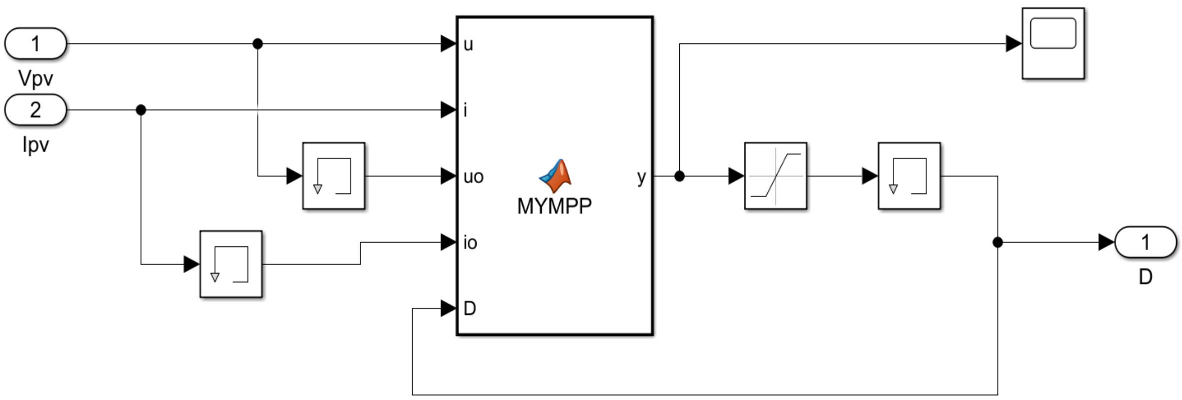


Figure.III.27: Diagram of MPPT Incremental Conductance

This diagram represent The IC Algorithm:

- **u**: PV voltage input (Vpv)
- **i:** PV current input (Ipv)
- **uo**: Delayed version of Vpv (previous voltage)
- **io**: Delayed version of Ipv (previous current)
- **D**: Previous duty cycle

Based on these, it calculates a new value y, which is the **updated duty cycle** to control the DC-DC (PWM Generator) converter

1. Memory & Delay Blocks:

- The delay/memory blocks store the previous values of Vpv, Ipv, and D so that the controller can calculate the difference (deltaV, deltaI) needed for MPPT (Incremental Conductance).

2. Output path:

- The controller output y goes through a **saturation block** (to limit its range), then a **memory block**, and is fed back as the new D input.

3. Feedback Loop:

The loop ensures the system operates iteratively, adjusting the duty cycle in real time to track the PV panel's maximum power point.

➢ **<u>Note</u>: Simulation time in Seconds**

III.5.1 Result of simulation :

- **Fixed 1000 irradiance 25° Temperture**

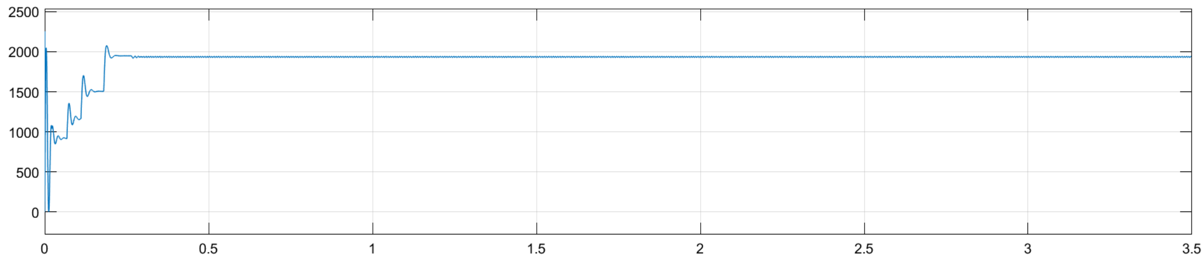


Figure.III.28 : Power PV Incremental Conductance

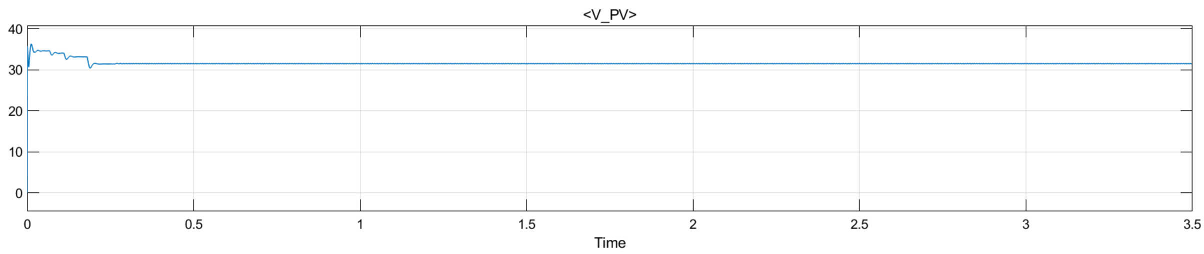


Figure.III.29 : Voltage PV Incremental Conductance

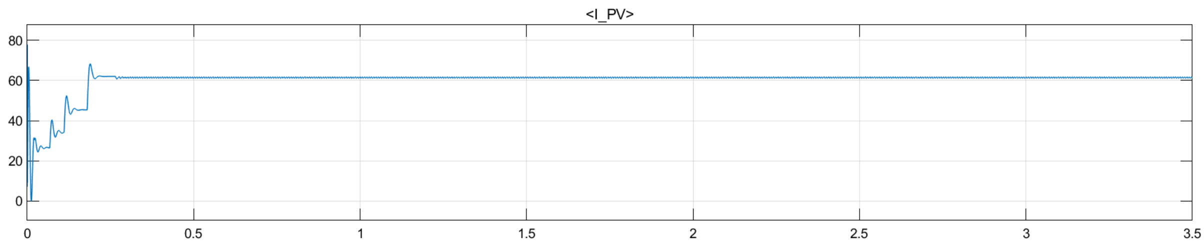


Figure.III.30 : Current PV Incremental Conductance

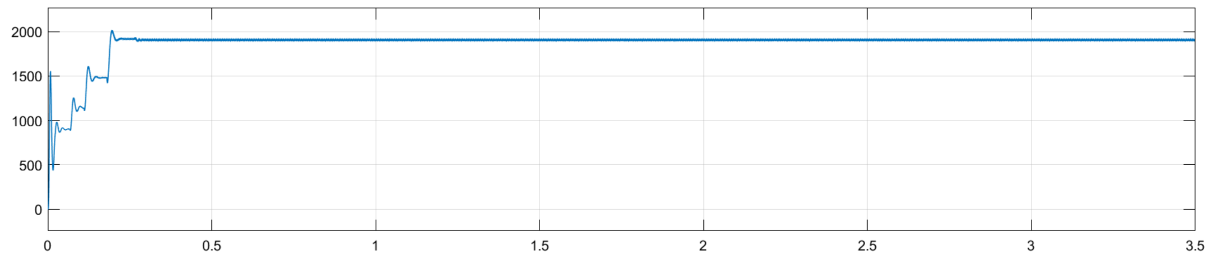


Figure.III.31 : Power Load Incremental Conductance

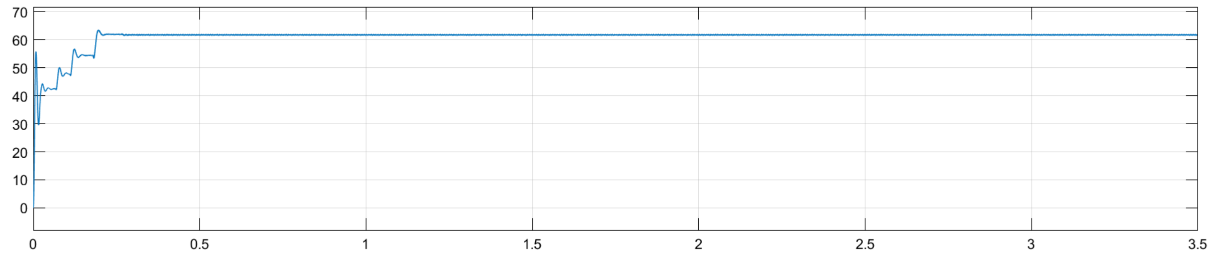


Figure.III.32 : Voltage Load Incremental Conductance

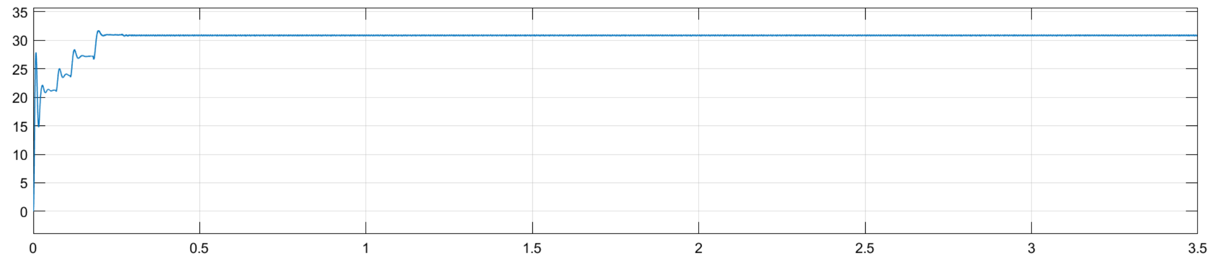


Figure.III.33 : Current Load Incremental Conductance

- **Fixed Temperture 25°C and variable irradiance**

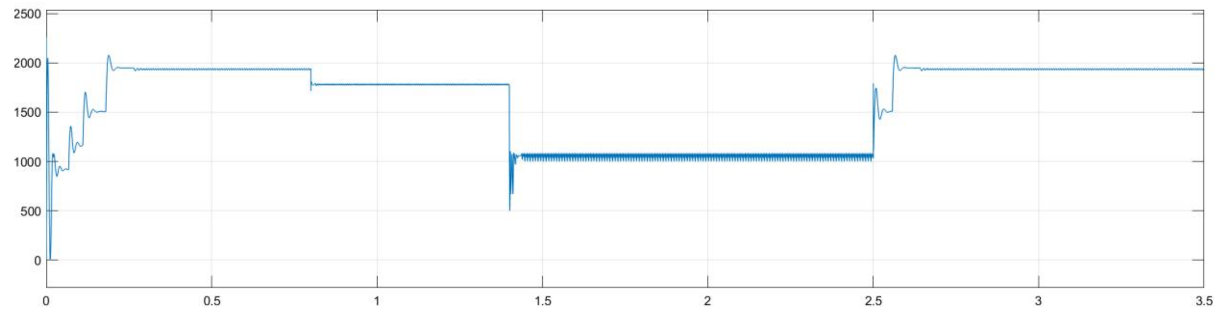


Figure.III.34 : Power PV Incremental Conductance

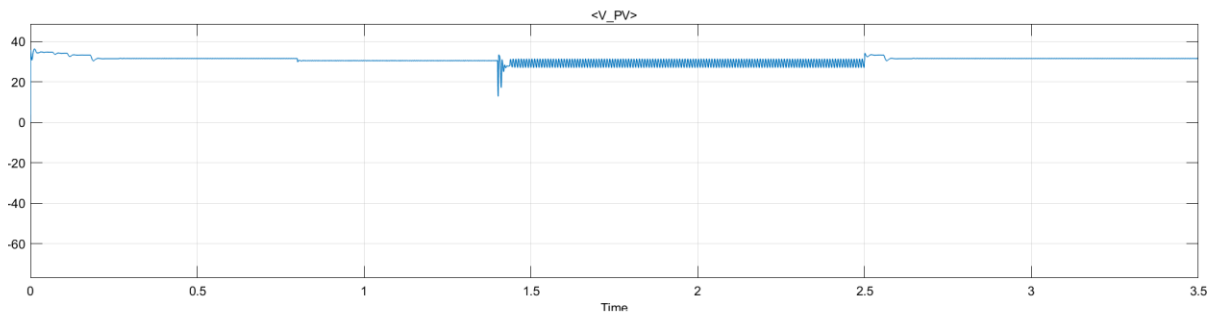


Figure.III.35 : Voltage PV Incremental Conductance

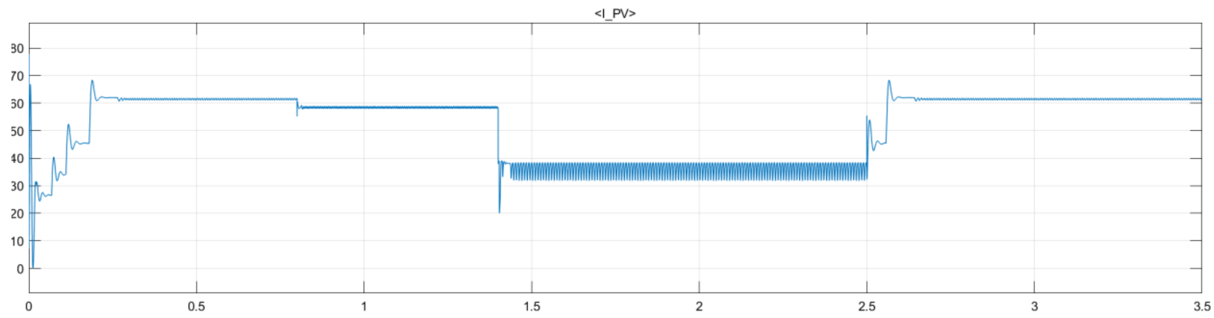


Figure.III.36 : Current PV Incremental Conductance

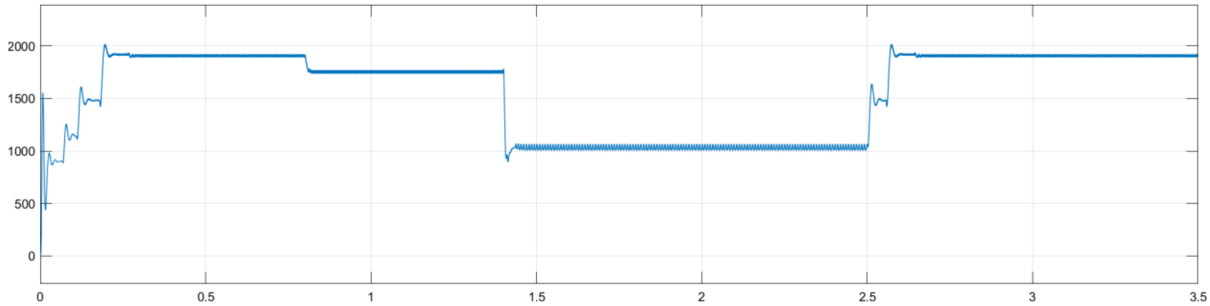


Figure.III.37 : Power Load Incremental Conductance

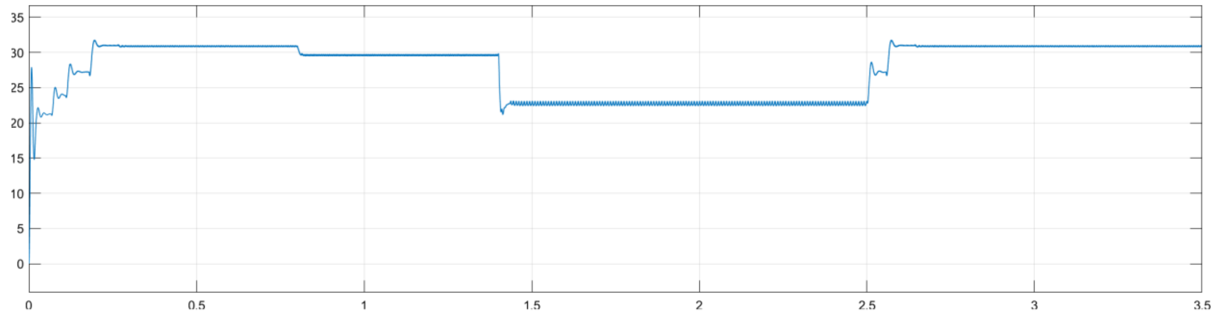


Figure.III.38 : Voltage Load Incremental Conductance

The power response in this figure shows that the system reaches the MPP with less oscillation compared to P&O. The convergence is faster and more stable, even under moderate irradiance variation.

The load power output efficiently follows the PV curve, showing minimal fluctuations. The response is smoother than that of P&O, indicating better control over the converter.

III.5.2 Observations

IncCond offers enhanced stability and accuracy compared to P&O. It significantly reduces power losses due to oscillations and adapts more effectively to changing irradiance. Nevertheless, it is more complex to implement as it requires calculation of derivatives and can suffer from implementation delays under rapid transients if not carefully tuned

III.6 Fuzzy logic

Fuzzy logic is a heuristic approach that uses a set of rules and membership functions to make decisions. Unlike P&O and IncCond, it does not require an accurate mathematical model of the PV system.

Figure.III.39: P&O and FLC Subsystem

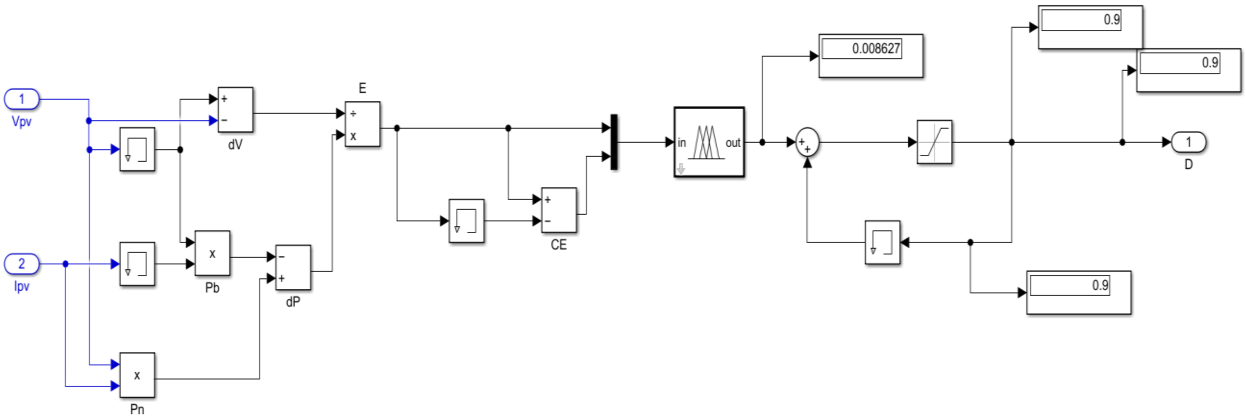


Figure.III.40: Fuzzy Logic Controller And P&O Subsystem

The diagram above is subsystem of P&O And FLC MPPT Algorithm based on Fuzzy logic Controller

This is a **Fuzzy Logic MPPT controller**, which:

- Uses changes in power and voltage to estimate system state.
- Applies fuzzy logic to make smart, adaptive decisions
- Updates the duty cycle to extract maximum power from the PV panel under varying conditions
- **Power Calculation:**
  - Pn = Vpv × Ipv → current power
  - Pb = Vpv(t-1) × Ipv(t-1) → previous power (via memory blocks)
  - dP = Pn - Pb → change in power
- **Voltage Change:**
  - dV = Vpv - Vpv(t-1) → change in voltage

- E = dP / dV

This error is stored and passed to calculate the **change in error (CE):**

- CE = E(t) - E(t-1)

III.6.1 Fuzzy Logic Controller :

- **Inputs**: E and CE
- The **Fuzzy Logic block** (middle of the diagram) uses predefined **membership functions** and **rules** to determine **the output duty cycle change.**

Inside the FLC Block (Fis):

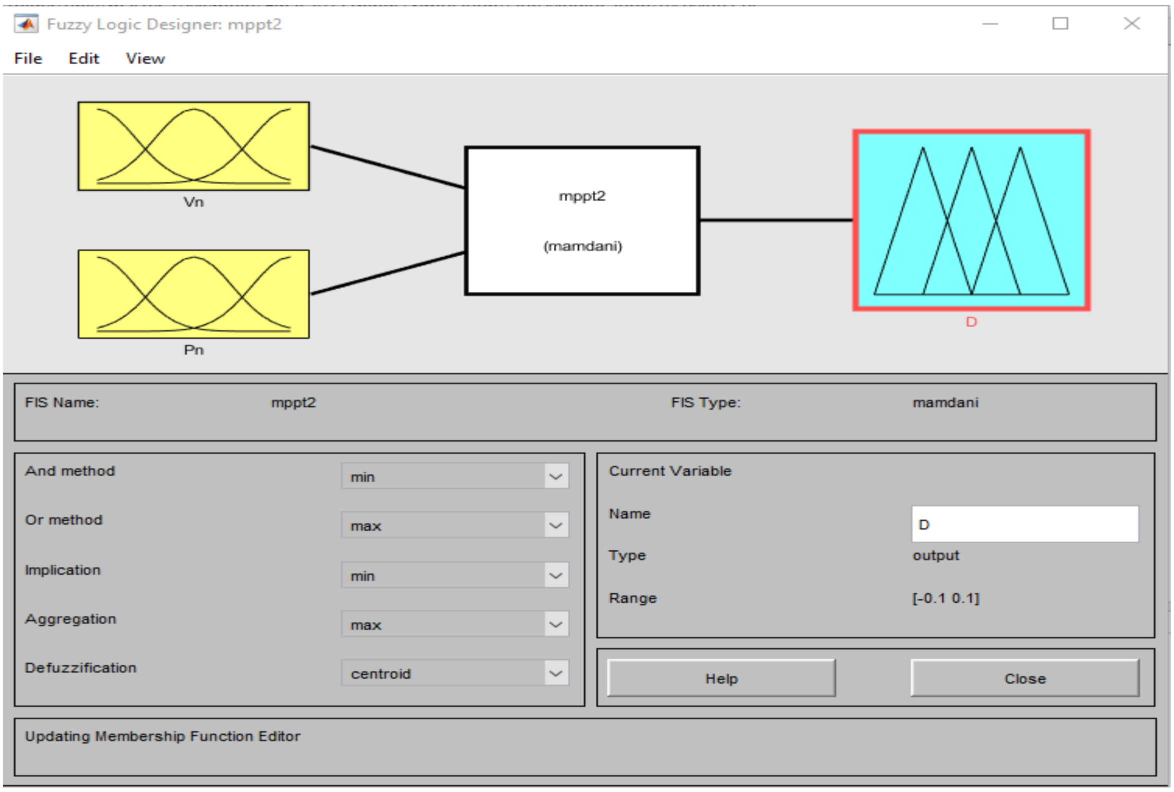


Figure.III.41: Fuzzy Logic Algorithm Block

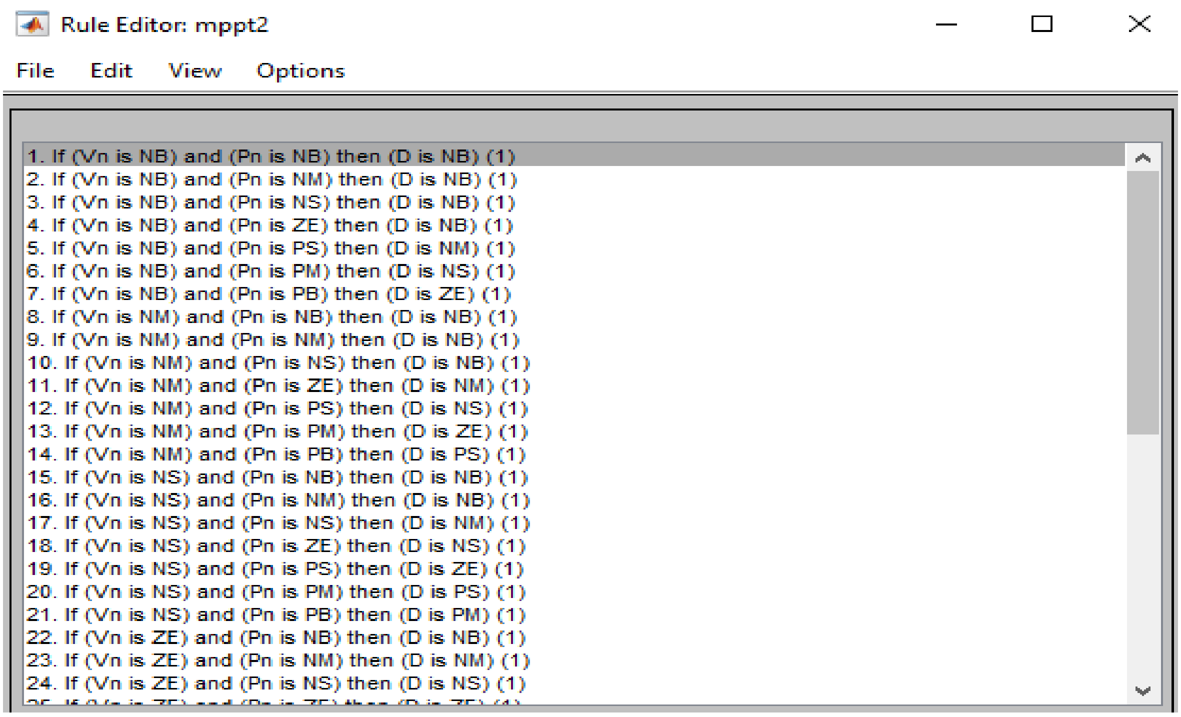


Figure.III.42: Rules FLC Part1

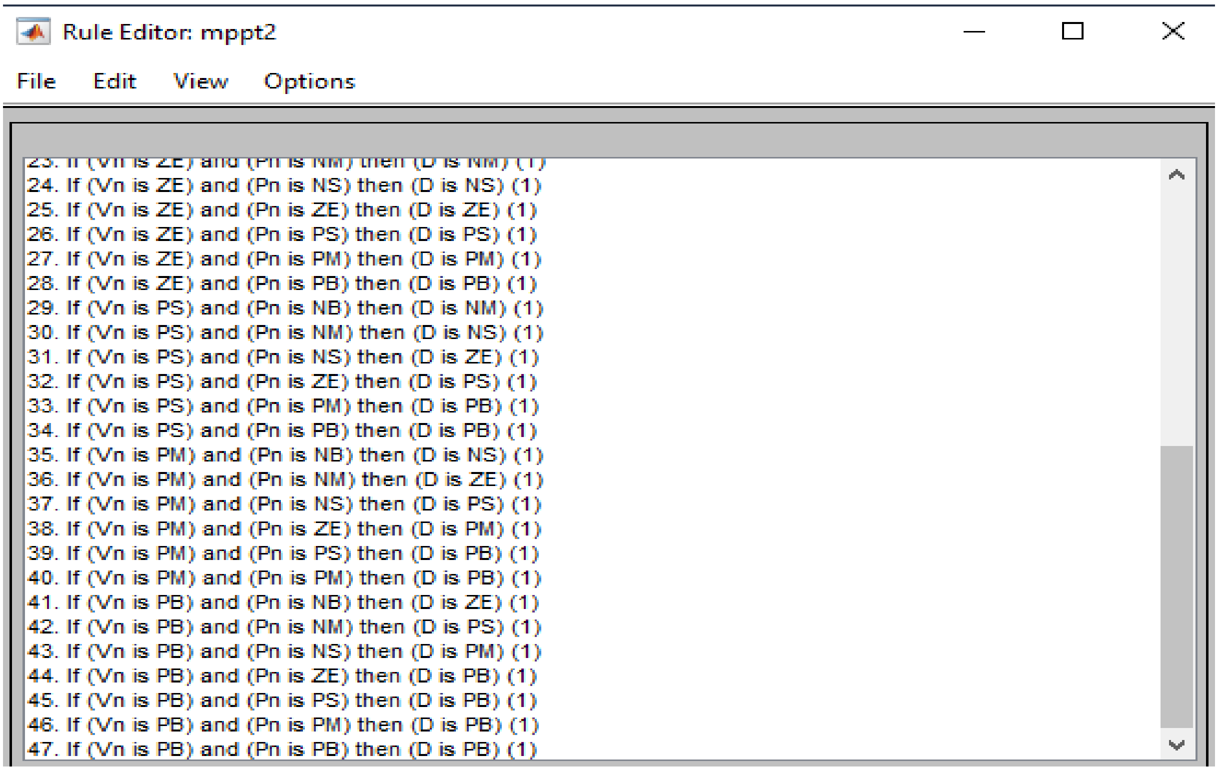


Figure.III.43: Rules FLC Part2

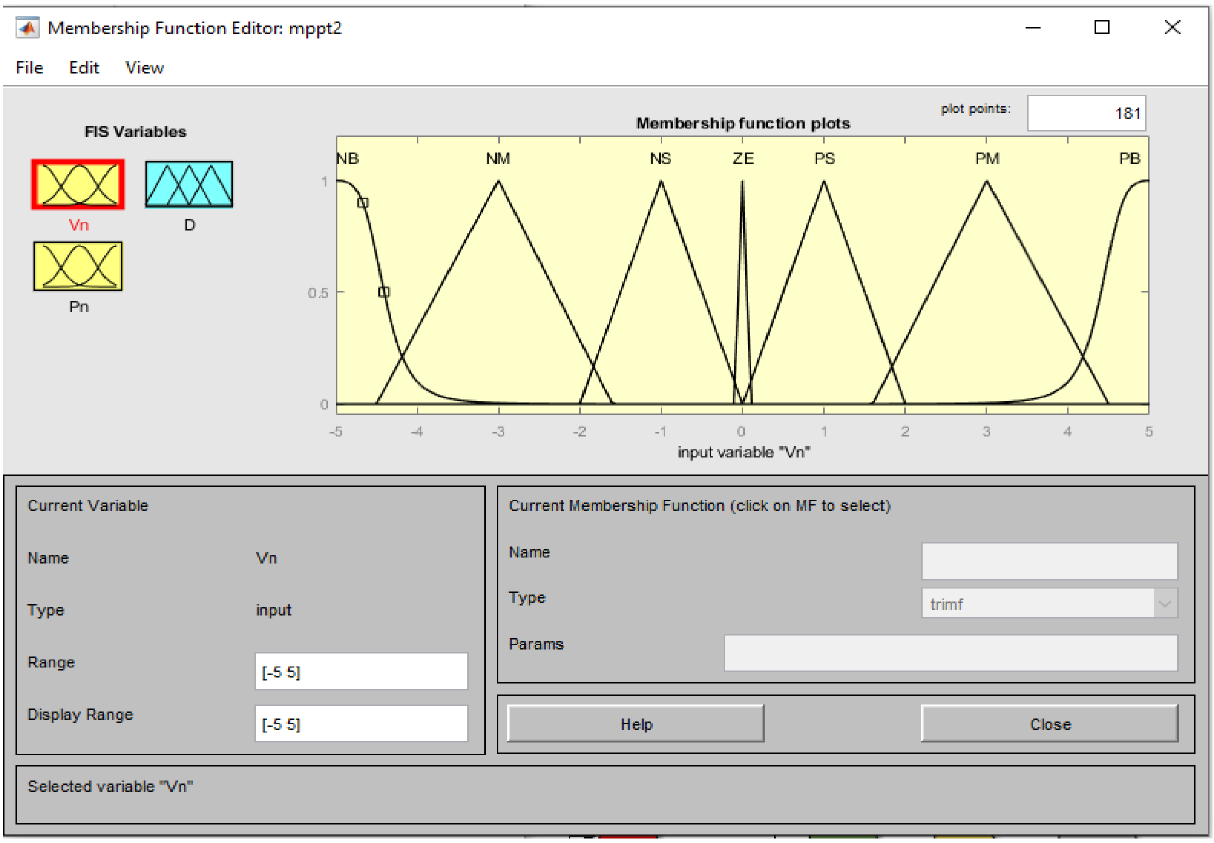


Figure.III.44: Variable Input Vn

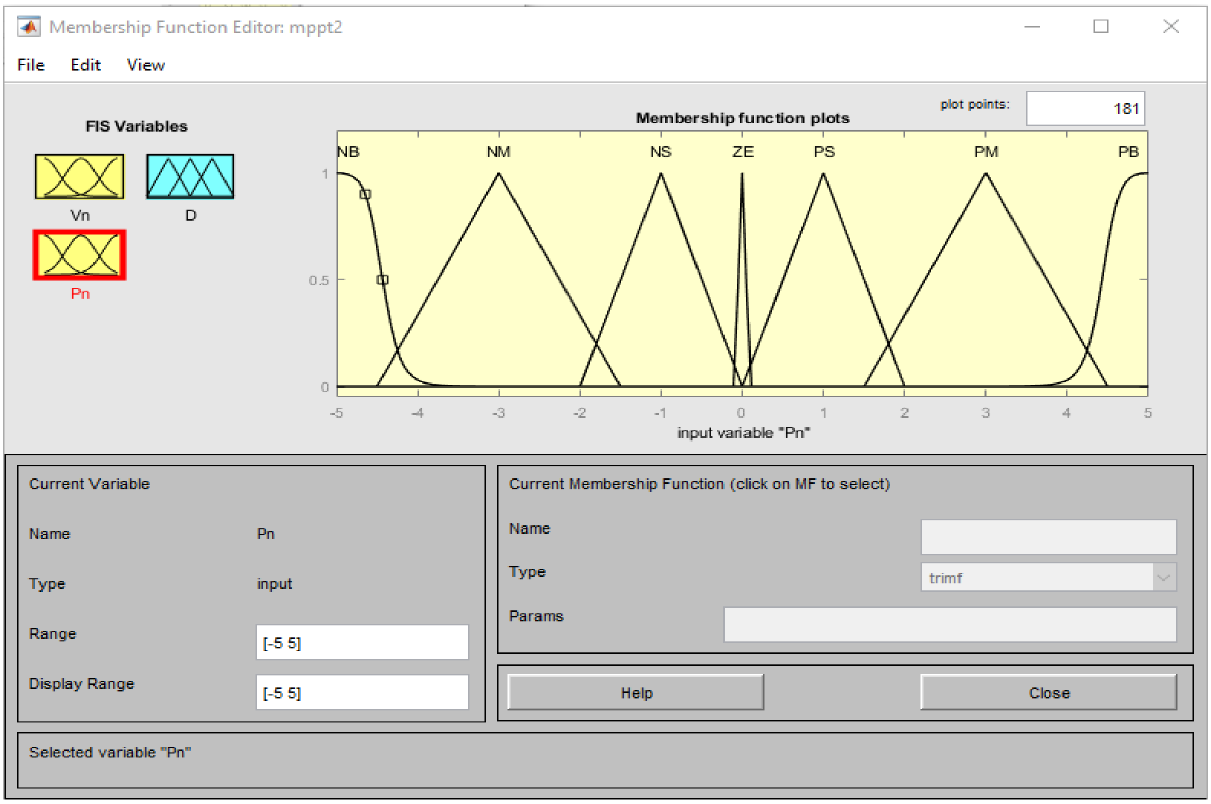


Figure.III.45: Variable Input Pn

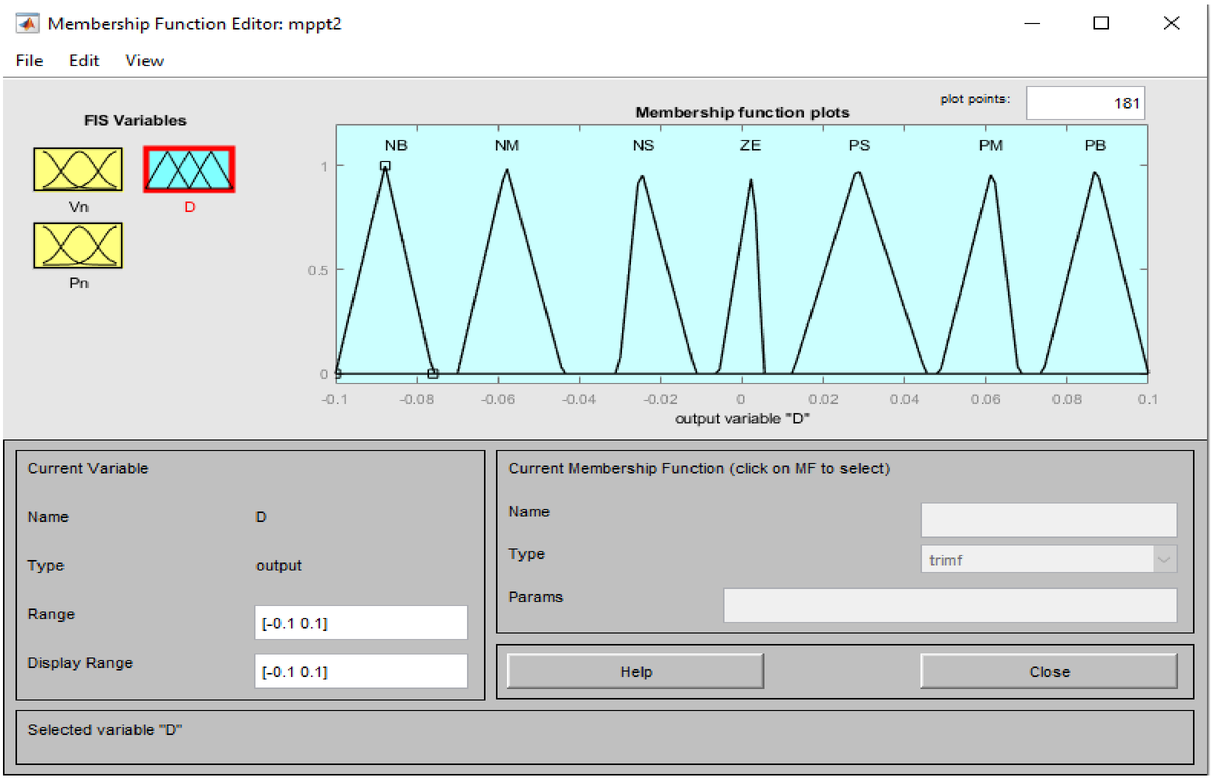


Figure.III.46: Variable Output D

III.6.2 Result of simulation :

- ➢ <u>**Note**</u> :Simulation Time in Seconds
- **Fixed 1000 irradiance 25° Temperture**

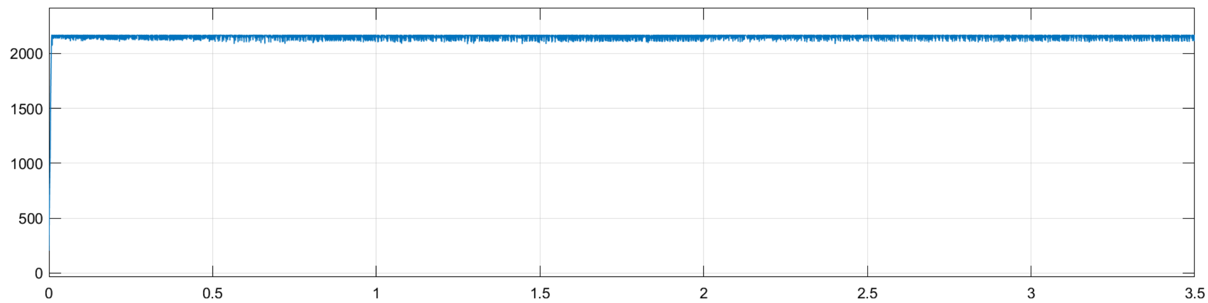


Figure.III.47 : Power PV Perturb and Observe And Fuzzy logic

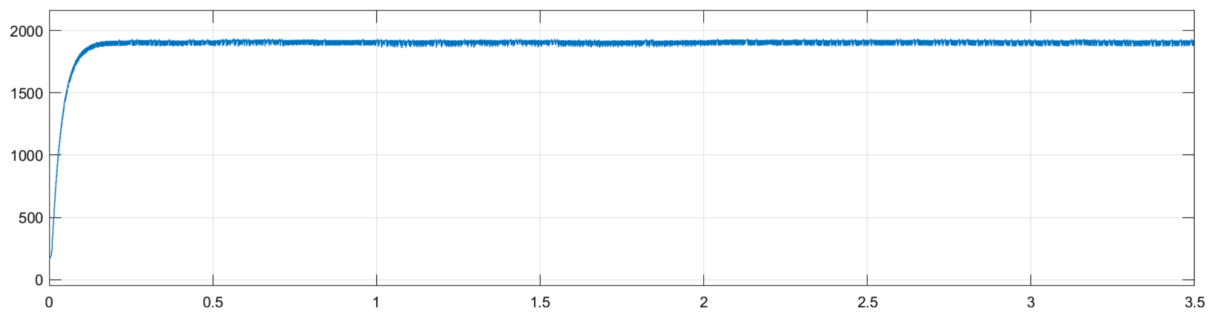


Figure.III.48 : Power Load Perturb and Observe And Fuzzy logic

- **Fixed Temperture 25°C and variable irradiance**

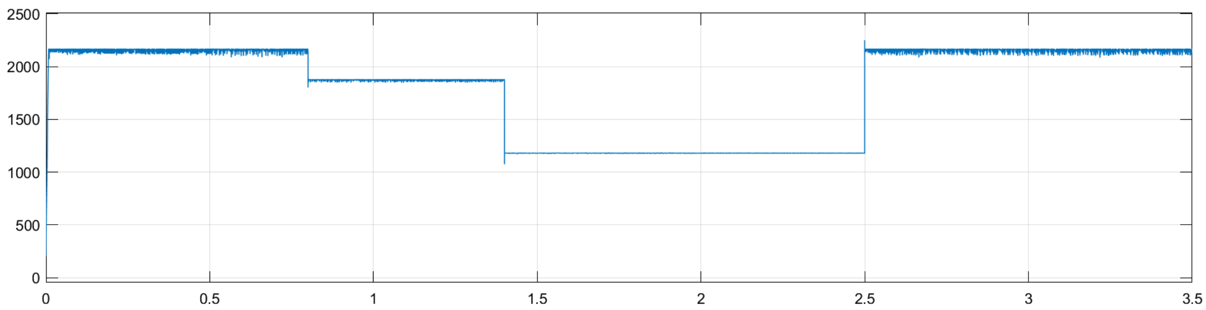


Figure.III.49 : Power PV Perturb and Observe And Fuzzy logic

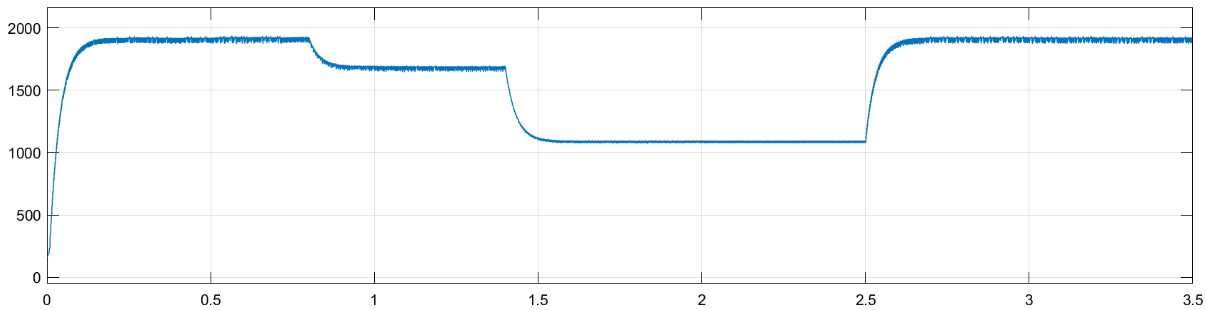


Figure.III.50 : Power Load Perturb and Observe And Fuzzy logic

The FLC tracks the MPP effectively across irradiance changes (1000 → 850 → 500 → 1000 W/m²). It reacts quickly at each step, with smooth transitions and minimal overshoot. When irradiance returns to 1000 W/m², the controller re-stabilizes near the original MPP with almost no delay.

Load power closely follows the PV power, showing efficient energy transfer and low ripple. The controller maintains stable output even during rapid irradiance changes.

III.6.3 Observations

FLC offers fast, smooth, and stable tracking under both irradiance and slight temperature changes. Its rule-based logic handles nonlinearity well, with minimal oscillations. The main challenge is designing the fuzzy rules, but the performance justifies it.

III.7 PSO

PSO is a population-based metaheuristic inspired by the social behavior of bird flocking. It explores the solution space using particles that update their positions based on their own experience and that of their neighbors to find the global optimum

Figure.III.51: MatlabFunction PSO Algorithm

- The **MatlabFunction** Block contains Our MPPT algorithm Code of PSO

Two inputs Vpv & Ipv with one Output it's the DutyCycle To control the PWM

III.7.1 Result of simulation :

- **Note: Simulation time in Seconds**
- **Fixed 1000 irradiance 25° Temperture (Not Modified PSO)**

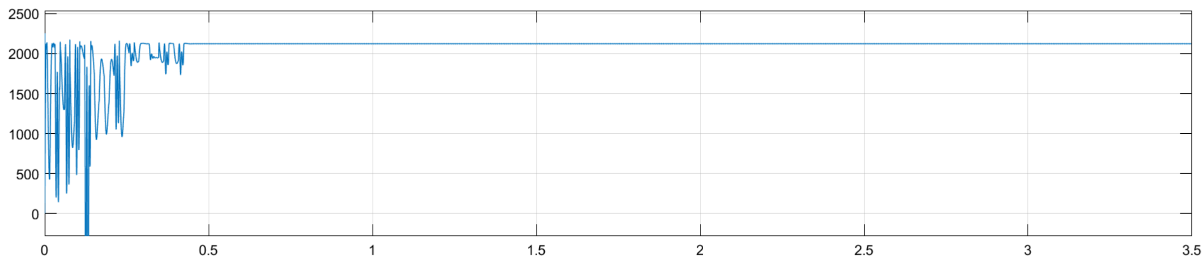


Figure.III.52 : Power PV Particle Swarm Optimization

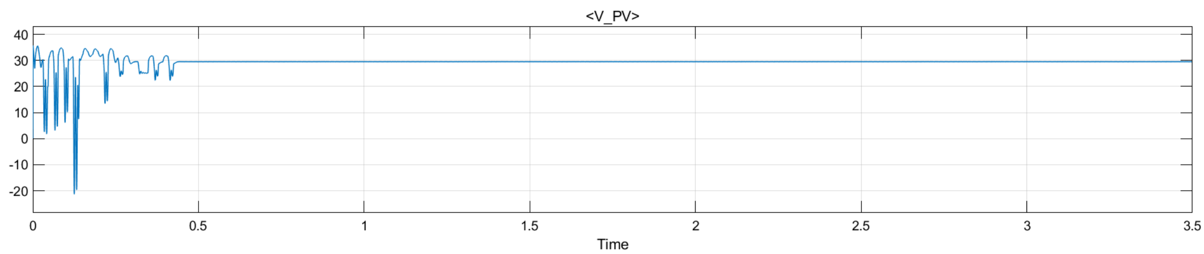


Figure.III.53 : Voltage PV Particle Swarm Optimization

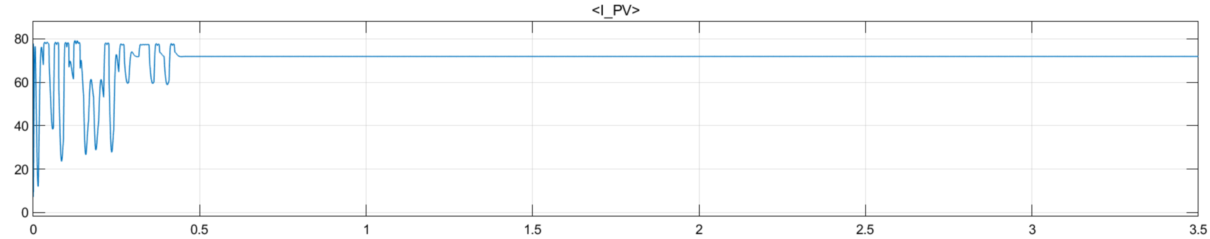


Figure.III.54 : Current PV Particle Swarm Optimization

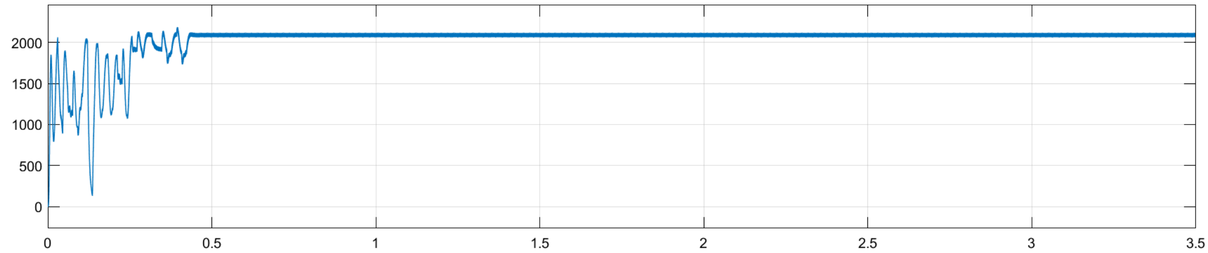


Figure.III.55 : Power Load Particle Swarm Optimization

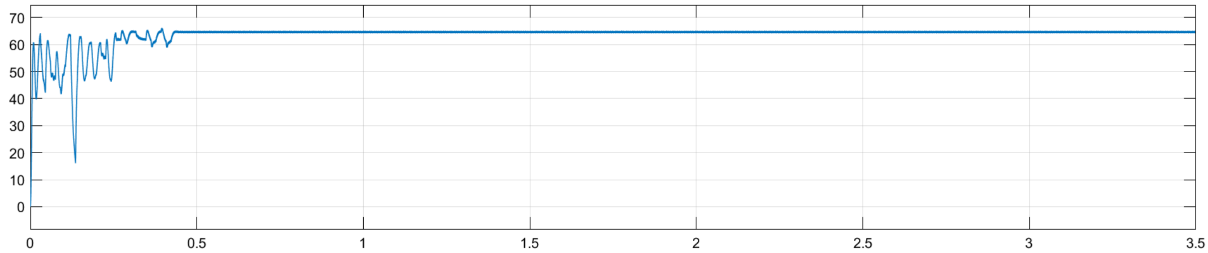


Figure.III.56: Voltage Load Particle Swarm Optimization

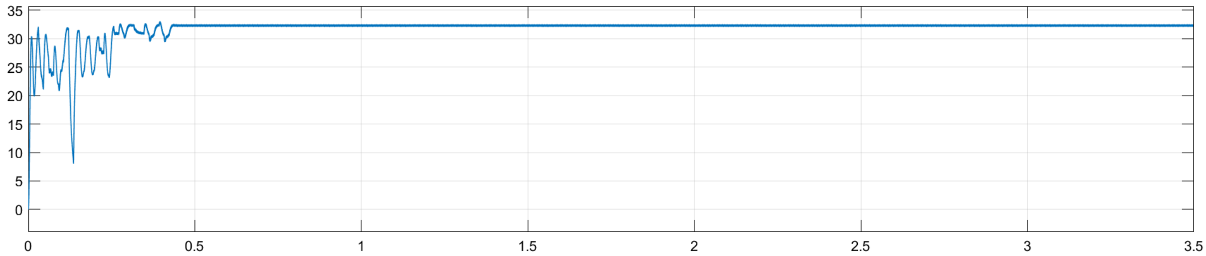


Figure.III.57 : Current Load Particle Swarm Optimization

- **Fixed 1000 irradiance 25° Temperture (Modified PSO)**

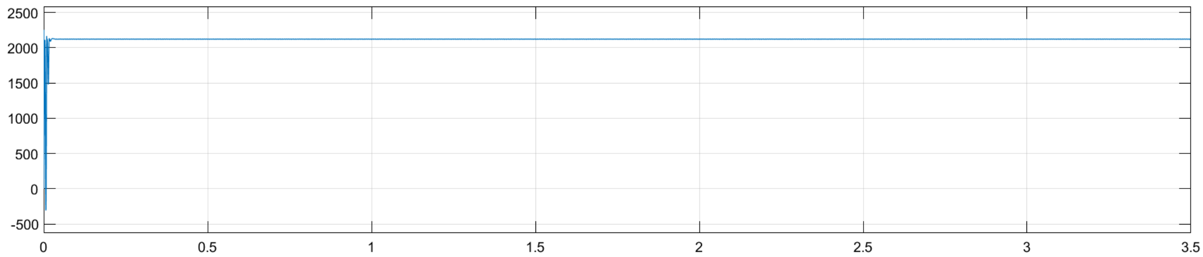


Figure.III.58 : Power PV Particle Swarm Optimization

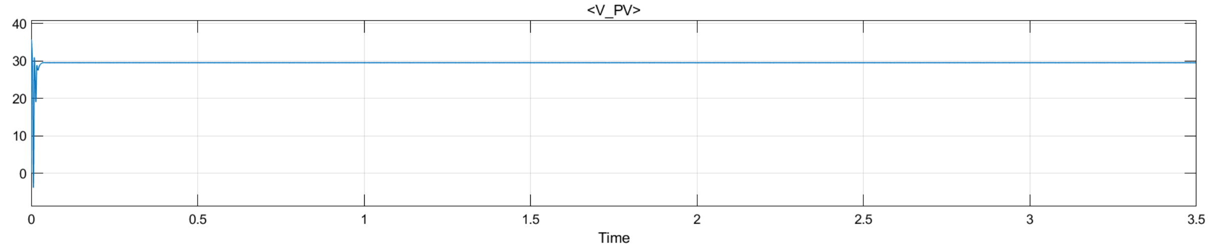


Figure.III.59 : Voltage PV Particle Swarm Optimization

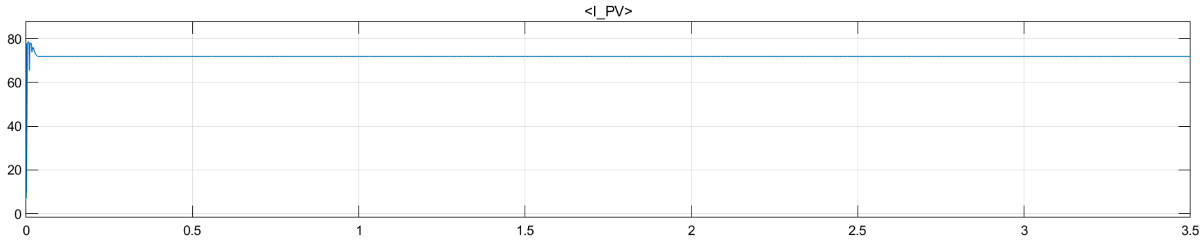


Figure.III.60 : Current PV Particle Swarm Optimization

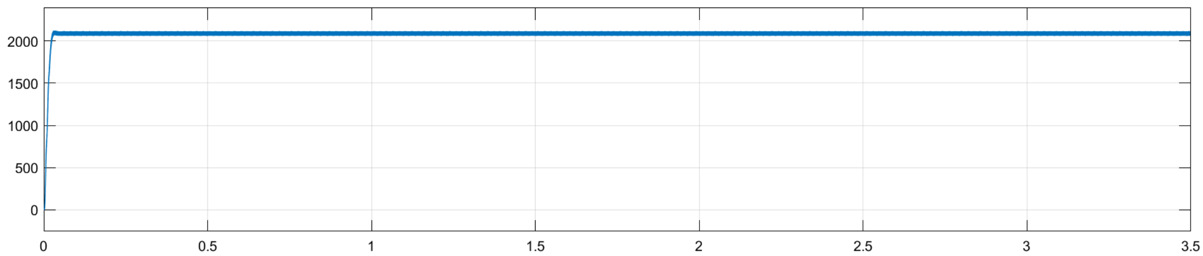


Figure.III.61 : Power Load Particle Swarm Optimization

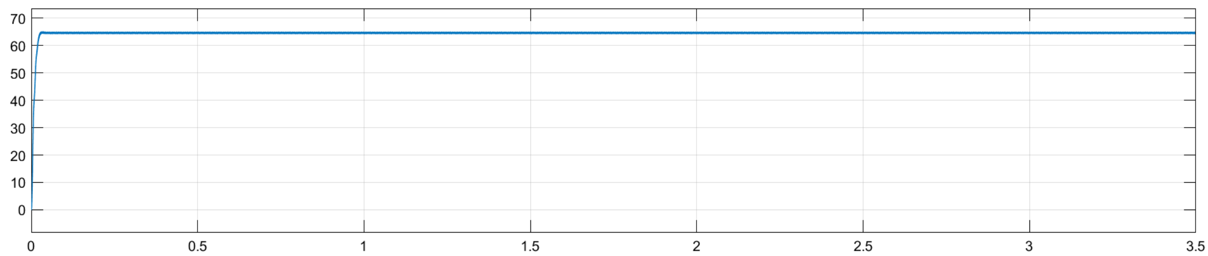


Figure.III.62 : Voltage Load Particle Swarm Optimization

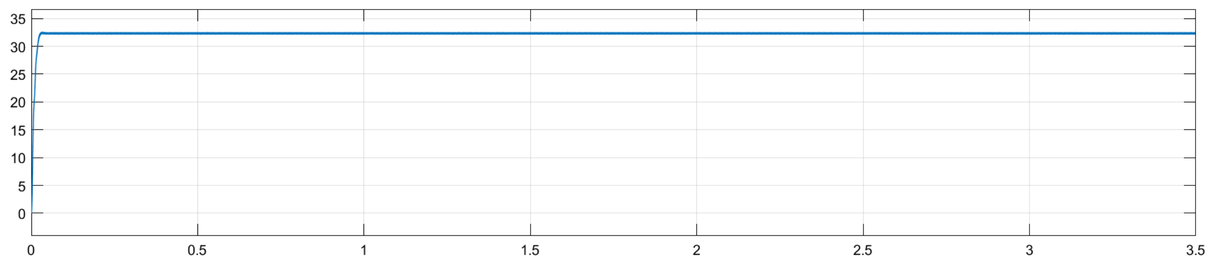


Figure.III.63 : Current Load Particle Swarm Optimization

Comment :

Under a constant irradiance of 1000 W/m² and fixed temperature, the Modified PSO algorithm demonstrates a noticeably faster response in reaching the Maximum Power Point compared to the Non-Modified PSO. The power, voltage, and current curves of the Modified PSO show a quicker stabilization with minimal overshoot, indicating efficient convergence. In contrast, the Non-Modified PSO exhibits slower tracking with more oscillations before settling. This highlights the advantage of the Modified approach in terms of response speed and tracking precision under stable environmental conditions.

- **Variable irradiance Fixed 25° Temperture (Not Modified PSO)**

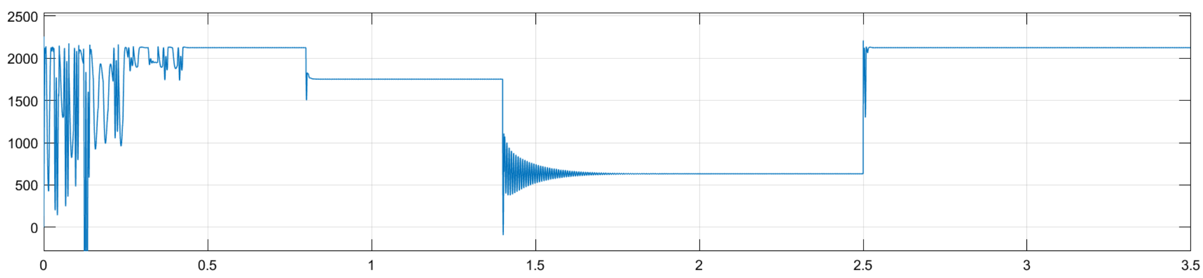


Figure.III.64 : Power PV Particle Swarm Optimization

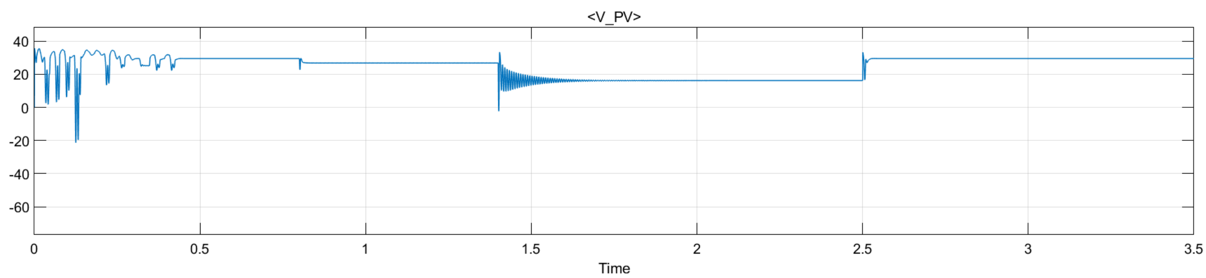


Figure.III.65 : Voltage PV Particle Swarm Optimization

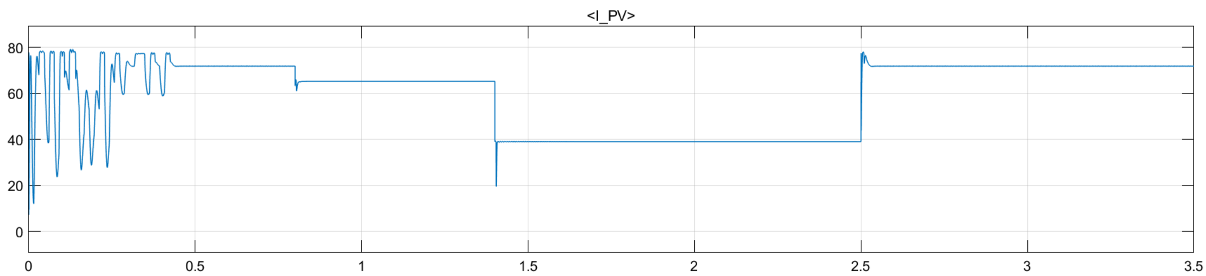


Figure.III.66 : Current PV Particle Swarm Optimization

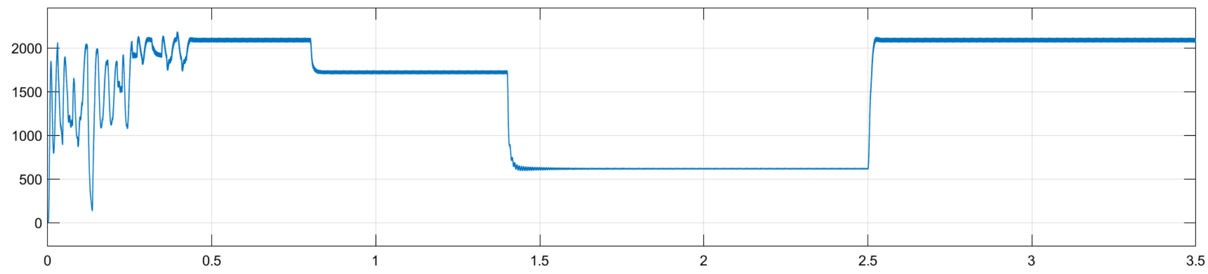


Figure.III.67 : Power Load Particle Swarm Optimization

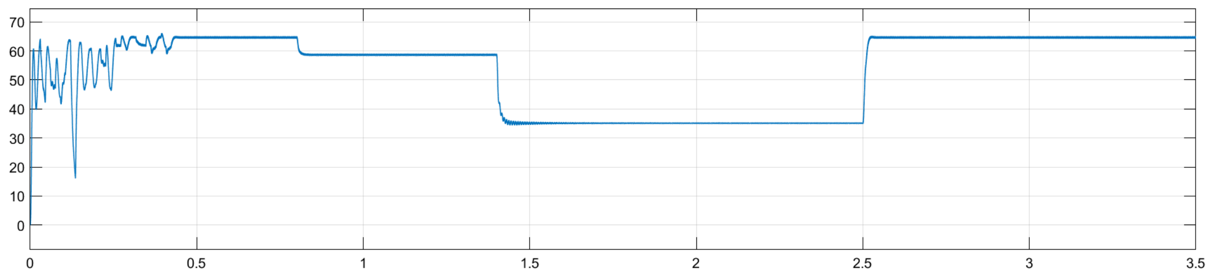


Figure.III.68 : Voltage Load Particle Swarm Optimization

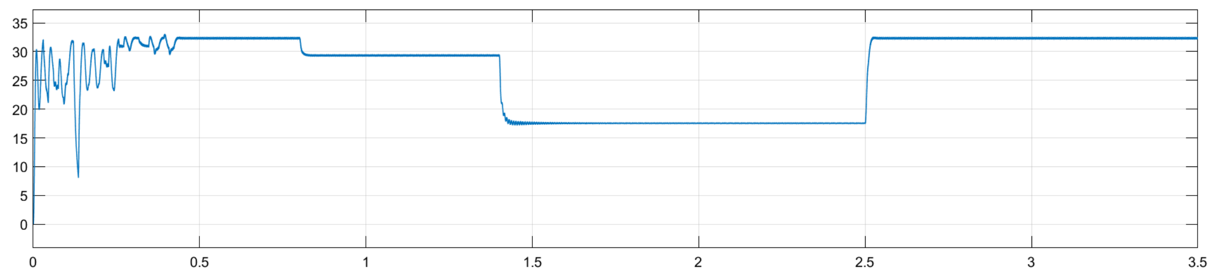


Figure.III.69: Current Load Particle Swarm Optimization

- **Variable irradiance Fixed 25° Temperture (Modified PSO)**

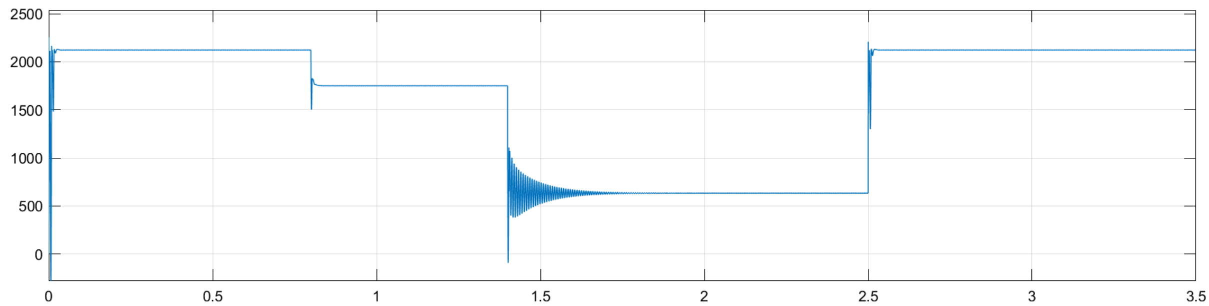


Figure.III.70: Power PV Particle Swarm Optimization

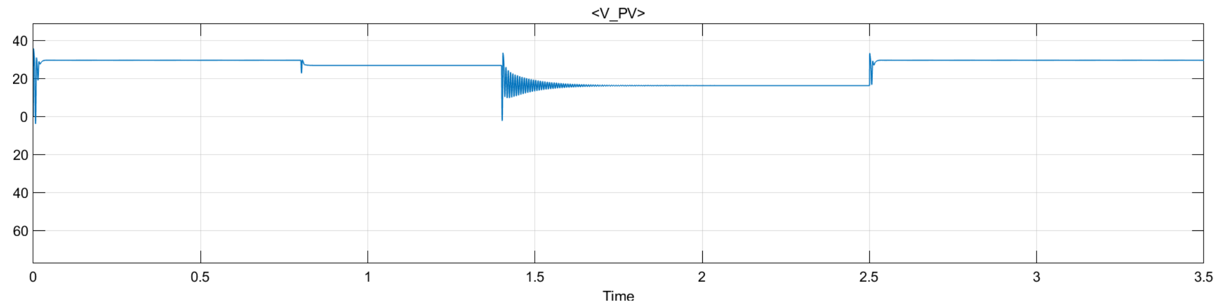


Figure.III.71 : Voltage PV Particle Swarm Optimization

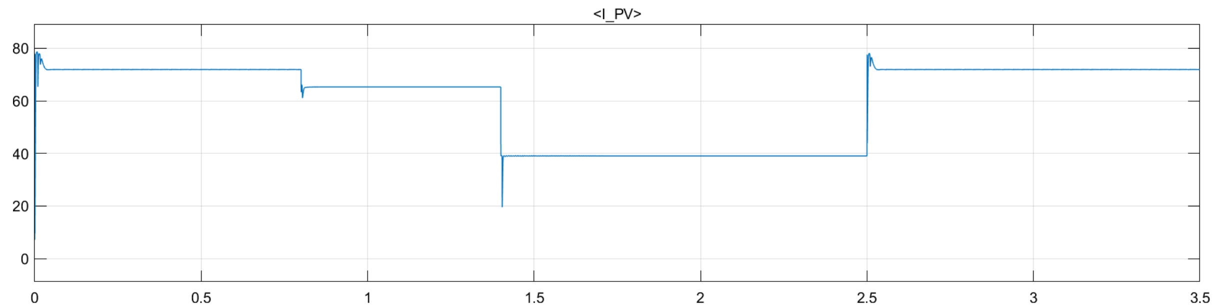


Figure.III.72 : Current PV Particle Swarm Optimization

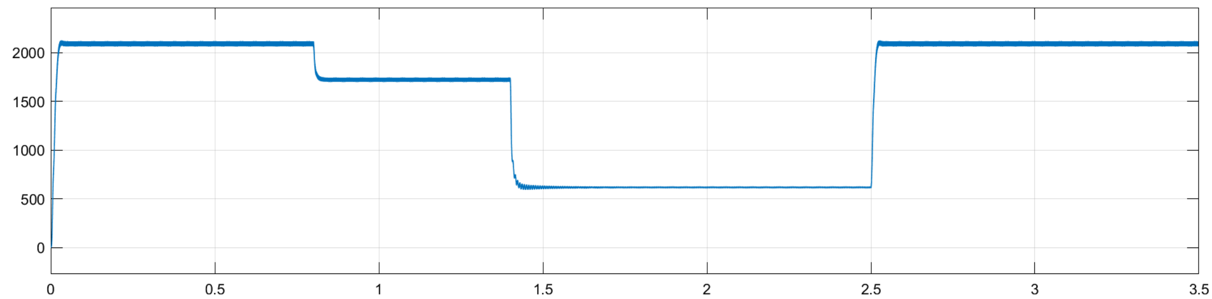


Figure.III.73: Power Load Particle Swarm Optimization

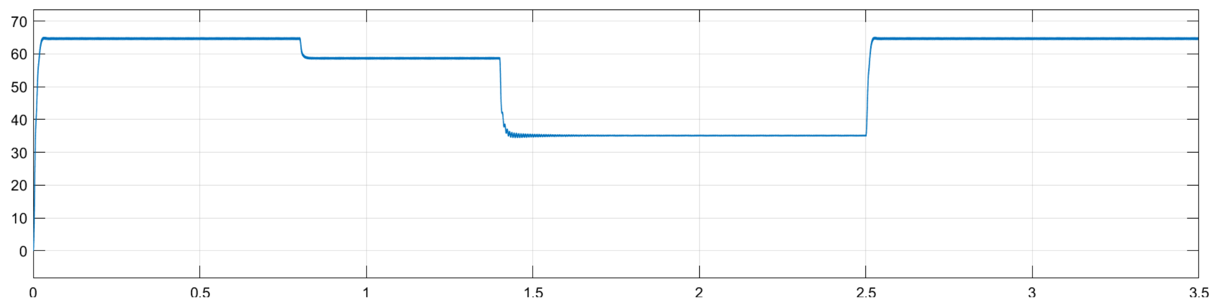


Figure.III.74: Voltage Load Particle Swarm Optimization

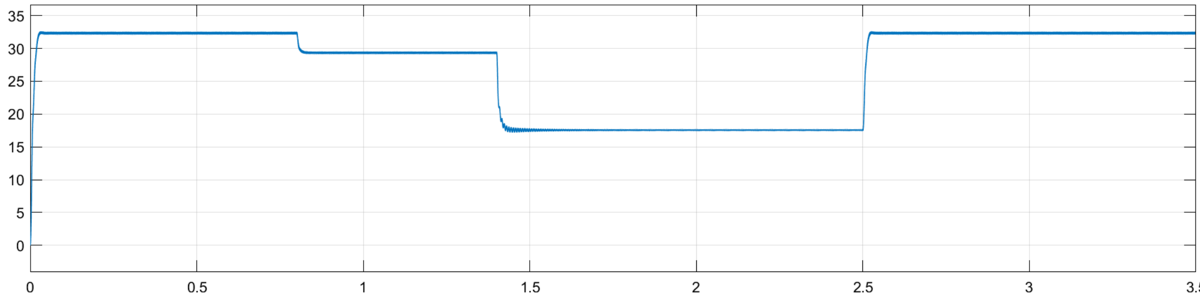


Figure.III.75 : Current Load Particle Swarm Optimization

III.7.2 Observations

The simulation results clearly demonstrate the improved performance of the Modified PSO algorithm over the Non-Modified version. Specifically, the Modified PSO exhibits a significantly faster convergence to the Maximum Power Point, minimizing the response time. Additionally, it achieves this with reduced oscillation and more stable output under both constant and varying environmental conditions. This enhanced behavior is particularly valuable in real-time PV systems where rapid adaptation to changes in irradiance and temperature is critical for maximizing energy extraction.

III.8 Comparative Analysis of MPPT Techniques :

Table.III.1 : Comparison between MPPT Techniques.**[23],[24]**

Method	Speed	Accuracy at MPP	Oscillations	Adaptability	Computationl Cost
P&O	Moderate	Moderate	High	Low	Low
Increamental Conductance	Fast	High	Low-Medium	Medium	Medium
Fuzzy Logic	Very Fast	High	Very Low	High	High
PSO	Fast	Very High	Negligible	Very High	Very High

III.9 Conclusion

In this chapter, we presented and analyzed the simulation results of four distinct MPPT techniques: P&O, Incremental Conductance, Fuzzy Logic, and Particle Swarm Optimization. Each method was evaluated based on its ability to track the maximum power point under varying solar irradiance and temperature.

From the simulations, it is evident that traditional methods like P&O and IncCond offer reasonable performance for stable conditions, but they struggle under rapid environmental changes. Intelligent and bio-inspired techniques, such as Fuzzy Logic and PSO, significantly enhance tracking efficiency and robustness.

Among all methods, PSO stands out as the most promising, offering fast convergence, minimal oscillations, and excellent adaptability. Despite its initial computational burden, once optimized, it has the potential to be integrated into real-time systems with modern embedded platforms.

This comparative study highlights the importance of selecting the MPPT strategy based on application-specific requirements such as system cost, expected environmental variability, and computational resources. The results justify the integration of hybrid or adaptive intelligent controllers for future work to combine the strengths of multiple methods.

General Conclusion

General Conclusion

Photovoltaic energy is among the most important renewable energy sources for electricity generation. However, its output power is directly influenced by environmental conditions such as solar irradiance and temperature. Therefore, optimizing the energy production of a PV system requires the implementation of intelligent control strategies capable of adapting to these variations.

This thesis aimed to improve the performance of a residential grid-connected photovoltaic system by investigating and simulating various Maximum Power Point Tracking techniques. The main objective was to analyze and compare the effectiveness of different control algorithms in tracking the maximum power point under changing environmental conditions.

The thesis is organized into three chapters,

The first chapter provided an overview of photovoltaic energy, including the structure and operation of PV cells, types of PV systems, and the main components involved. We also discussed the advantages and limitations of solar energy.

The second chapter focused on MPPT techniques and power conversion. We presented both classical and intelligent MPPT methods, including Perturb and Observe, Incremental Conductance, Fuzzy Logic, and the metaheuristic Particle Swarm Optimization algorithm. In addition, we discussed the role of DC-DC and DC-AC converters, with particular attention to their function in energy conversion and integration with the electrical grid.

In the third chapter, we simulated the operation of the photovoltaic system using the different MPPT techniques mentioned. The results showed that intelligent methods such as Fuzzy Logic and PSO provided better tracking accuracy, faster convergence, and lower oscillations compared to traditional techniques like P&O and IC. Among them, the modified PSO algorithm demonstrated the best performance in terms of speed and stability. The system maintained high efficiency and low Total Harmonic Distortion, even under dynamic conditions such as irradiance variation and partial shading.

In conclusion, the comparative analysis highlighted the superiority of intelligent MPPT algorithms, especially PSO, for optimizing the performance of residential PV systems connected to the grid.

[1] : Book Title: *Basic Photovoltaic Principles and Methods,*

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