

# Adaptive MPPT Control of Solar PV System Incremental Conductance Algorithm

Nitesh Kumar Dewangan<sup>1</sup> Kuldeep K Yadav<sup>2</sup>

<sup>1,2</sup>Department of Electrical Engineering (Power System)

<sup>1,2</sup>RSR RCET, Bhilai, India

**Abstract** — Solar photovoltaic (PV) systems have emerged as one of the most promising renewable energy sources due to their clean and sustainable nature. However, the output power of a PV system is highly dependent on environmental conditions such as solar irradiance and temperature. To ensure maximum energy extraction under varying operating conditions, an efficient Maximum Power Point Tracking (MPPT) technique is required. Conventional MPPT methods, including Perturb and Observe (P&O) and Incremental Conductance (INC), are widely used in PV applications. Although the P&O method offers simple implementation and fast response, it suffers from steady-state oscillations around the Maximum Power Point (MPP). On the other hand, the Incremental Conductance technique provides better accuracy but requires higher computational effort and may exhibit slower response under certain conditions. This paper proposes an Adaptive Hybrid MPPT Control Algorithm that combines the advantages of both P&O and Incremental Conductance methods. The proposed controller utilizes the fast tracking capability of the P&O algorithm during transient conditions and switches to the Incremental Conductance technique near the MPP to improve tracking accuracy and minimize power oscillations. The performance of the proposed system is evaluated using MATLAB/Simulink under different irradiance conditions. Simulation results demonstrate that the hybrid MPPT controller achieves faster convergence, improved stability, reduced oscillations, and higher tracking efficiency compared to conventional MPPT techniques. The proposed approach attains a tracking efficiency of approximately 98.8%, making it an effective solution for enhancing the performance and energy yield of solar PV systems operating under dynamic environmental conditions.

**Keywords:** Solar Photovoltaic System, Maximum Power Point Tracking (MPPT), Hybrid MPPT, Perturb and Observe (P&O), Incremental Conductance (INC), MATLAB/Simulink, Renewable Energy Systems.

## I. INTRODUCTION

The increasing demand for clean and sustainable energy has accelerated the development and deployment of renewable energy sources, among which solar photovoltaic (PV) systems have gained significant importance. Solar energy is abundant, environmentally friendly, and widely available; however, the efficiency of PV systems is strongly influenced by environmental factors such as solar irradiance and temperature. These continuously varying conditions lead to fluctuations in the output characteristics of the PV system, making it essential to operate the system at its Maximum Power Point (MPP) for maximum energy extraction.

To ensure optimal performance, Maximum Power Point Tracking (MPPT) techniques are employed in PV systems. Among the various MPPT methods, the Perturb and Observe (P&O) and Incremental Conductance (INC) algorithms are the most widely used. The P&O algorithm is

simple and easy to implement but suffers from steady-state oscillations around the MPP, which reduces system efficiency. In contrast, the Incremental Conductance method offers better accuracy and faster tracking under rapidly changing atmospheric conditions; however, it involves higher computational complexity.

To overcome the limitations of these conventional methods, a hybrid MPPT approach is proposed in this work by combining the advantages of both P&O and Incremental Conductance algorithms. Furthermore, an adaptive control mechanism is incorporated to dynamically adjust the step size based on system conditions. This helps in achieving faster convergence to the MPP during rapid changes while minimizing oscillations during steady-state operation.

The proposed adaptive hybrid MPPT controller is implemented using MATLAB/Simulink. The system consists of a solar PV array, a DC–DC boost converter, and an MPPT control unit. The controller continuously monitors the voltage and current of the PV system and adjusts the duty cycle of the converter to ensure maximum power extraction. The performance of the proposed method is evaluated under varying irradiance conditions, and the results demonstrate improved tracking efficiency, reduced oscillations, and enhanced overall system performance compared to conventional MPPT techniques.. [1]

### A. Solar PV System

A Solar Photovoltaic (PV) system is a renewable energy system that converts solar radiation directly into electrical energy by using photovoltaic cells. The basic principle of a PV system is based on the photovoltaic effect, in which semiconductor materials generate electric current when exposed to sunlight. Silicon is the most commonly used semiconductor material for manufacturing PV cells due to its suitable electrical properties and high efficiency.

A single PV cell produces a small amount of voltage and current; therefore, multiple cells are connected in series and parallel combinations to form a PV module. Several modules are further connected together to form a PV array capable of delivering the required power output. The output characteristics of a PV system mainly depend on environmental factors such as solar irradiance and temperature. An increase in solar irradiance increases the output current and generated power, whereas an increase in temperature decreases the output voltage and overall efficiency of the system.[1]

The electrical behavior of a PV system is generally represented by Current–Voltage (I–V) and Power–Voltage (P–V) characteristics.

A photovoltaic (PV) system is composed of several important components that work together to convert solar energy into usable electrical power. The fundamental component of the system is the solar cell, which converts sunlight directly into direct current (DC) electricity through the photovoltaic effect. Multiple solar cells are connected together to form a PV module, and several modules are

combined to create a PV array capable of generating higher power output.

The electrical output obtained from the PV array is regulated using a DC–DC converter, which controls and adjusts the voltage level according to system requirements. To maximize the power extraction from the PV system under varying irradiance and temperature conditions, a Maximum Power Point Tracking (MPPT) controller is employed. The MPPT controller continuously monitors the operating conditions and adjusts the duty cycle of the converter to ensure operation at the maximum power point.

In many practical applications, an inverter is used to convert the DC power generated by the PV array into alternating current (AC) power suitable for household loads or grid-connected systems. In standalone and hybrid PV systems, batteries are often incorporated for energy storage and backup power supply. Together, these components ensure efficient, reliable, and continuous operation of the photovoltaic system under different environmental conditions.

[2][3]

#### 1) Solar Cell (Photovoltaic System)

A solar cell, also known as a photovoltaic (PV) cell, is a device that converts solar energy directly into electrical energy through the photovoltaic effect. Photovoltaic cells are generally manufactured using semiconductor materials such as silicon, which generate electricity when exposed to sunlight. When solar radiation falls on the surface of the PV cell, photons are absorbed by the semiconductor material, resulting in the generation of free electrons and the flow of electric current.

The term “photovoltaic” is derived from two words: “photo,” meaning light, and “volt,” referring to electrical potential. Since a single solar cell produces only a small amount of voltage and current, multiple cells are connected together to form a PV module or solar panel. Several modules are further interconnected to create a PV array capable of producing higher power output for practical applications. Large PV arrays may contain thousands of interconnected solar cells and are widely used for electrical power generation.

Photovoltaic systems are extensively used in residential, commercial, and industrial applications for supplying clean and renewable electrical energy. Smaller PV

arrangements, commonly known as solar panels, are typically installed on rooftops and terraces to supplement or replace conventional electricity sources.

The efficiency of photovoltaic cells is theoretically around 25%; however, the actual efficiency depends on several environmental and operating conditions, particularly temperature. As the temperature of the PV cell increases, the output voltage and overall efficiency of the system decrease. Even a slight rise in temperature can significantly reduce the performance of the PV system, highlighting the importance of proper thermal management and cooling techniques in photovoltaic applications.[4]

#### 2) Working of Solar Cell

A solar cell operates on the principle of the photovoltaic effect and primarily consists of a p–n junction that generates an electromotive force (EMF) when exposed to sunlight. When solar radiation with energy greater than the bandgap of the semiconductor material falls on the surface of the solar cell, photons are absorbed by the semiconductor, resulting in the generation of electron–hole pairs.

In a typical solar cell structure, a thin layer of n-type silicon (n-Si) is formed over a p-type silicon (p-Si) wafer through diffusion techniques, thereby creating a p–n junction. This junction develops an internal electric field that plays a crucial role in the operation of the cell. A metal contact is provided on the backside of the p-type layer, known as the back contact, while metallic grid lines or finger electrodes are placed on the top surface of the n-type layer, which act as the front contact.

To maximize light absorption and improve current generation, the surface area of the solar cell junction is maintained as large as possible. When sunlight strikes the solar cell, three important processes take place simultaneously: generation of electron–hole pairs, separation of charge carriers due to the internal electric field, and collection of these carriers at the respective contacts. The movement of electrons and holes towards opposite terminals produces an electromotive force (EMF), resulting in the flow of electric current through the external circuit.

Thus, the operation of a solar cell can be understood as the combined process of generation, separation, and collection of charge carriers, which enables the direct conversion of solar energy into electrical energy efficiently.[5]

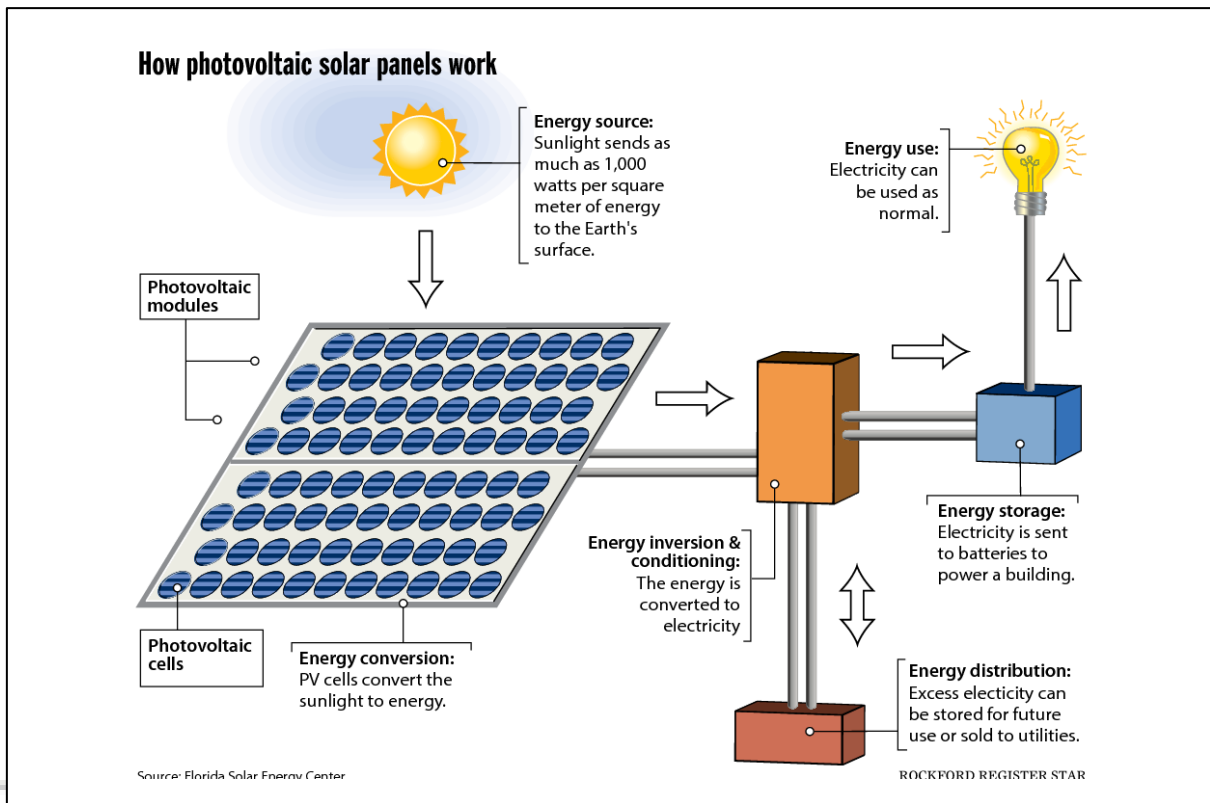


Fig. 1.1: working of solar

### 3) I-V Characteristics of a Solar Cell

A solar cell, also known as a photovoltaic (PV) cell, is the fundamental unit of a solar energy generation system that directly converts light energy into electrical energy without any intermediate conversion process. The operation of a solar cell is based on the photovoltaic effect, in which electrical power is generated when sunlight falls on a semiconductor material.

A solar cell is essentially a semiconductor device formed by a p-n junction created by joining p-type and n-type semiconductor materials. The p-type region contains a high concentration of holes, whereas the n-type region contains a high concentration of electrons. When these two regions are joined together, electrons from the n-type side diffuse toward the p-type side, while holes from the p-type side move toward the n-type side. This diffusion process results in the formation of a depletion region and an internal electric field across the junction, which is essential for the operation of the solar cell.

When sunlight strikes the surface of the solar cell, photons having energy greater than the bandgap energy of the semiconductor material are absorbed. This absorption generates electron-hole (e-h) pairs within the semiconductor material. Due to the presence of the internal electric field in the depletion region, these charge carriers are separated automatically: electrons move toward the n-type region, while holes move toward the p-type region. This separation of charge carriers creates a potential difference across the solar cell.

A typical photovoltaic cell consists of a negative front contact and a positive back contact, with the p-n junction positioned between them. When the two terminals are connected through an external circuit, electric current

flows from the positive terminal to the negative terminal, thereby delivering electrical power to the connected load.

In silicon-based solar cells, the bandgap energy at room temperature is approximately 1.1 eV, while the diffusion potential generally ranges between 0.5 V and 0.7 V. These characteristics form the basic theoretical foundation and working principle of a photovoltaic solar cell.

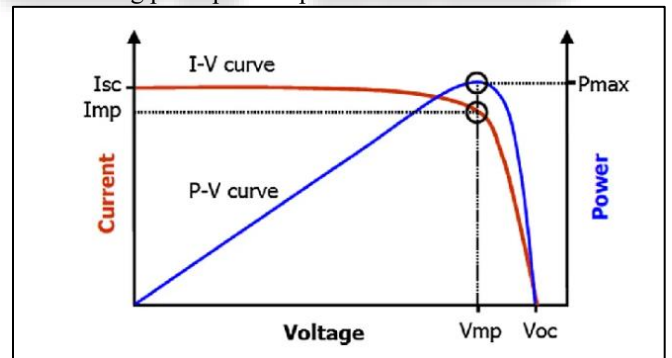


Fig. 1.2: working of solar iv curve

### B. The mathematical modeling of a photovoltaic (PV) system

The mathematical modeling of a photovoltaic (PV) system is commonly based on the single diode model, which effectively represents the electrical behavior of a solar cell. The output current of the PV cell is expressed by the following equation:

$$I = I_{ph} - I_0 \left[ e^{\frac{V+IR_s}{nV_t}} - 1 \right] - \frac{V + IR_s}{R_{sh}}$$

where  $I_0$  = "dark saturation current" or diode leakage current in absence of light

$q$  = electronic charge

$V$  = applied voltage across the terminals of the diode

$n$  = ideality factor  
 $k$  = Boltzmann's constant  
 $T$  = temperature  
 $I_L$  = light generated current.

This equation represents the mathematical model of a photovoltaic (PV) cell and describes the non-linear relationship between its output current and output voltage. The photo-generated current ( $I_{ph}$ ) is primarily dependent on the level of solar irradiance incident on the PV cell, whereas the diode saturation current ( $I_0$ ) is strongly influenced by temperature variations. The series resistance ( $R_s$ ) accounts for internal conduction losses within the cell, while the shunt resistance ( $R_{sh}$ ) represents leakage current paths that affect the overall performance of the PV module. Furthermore,  $V_t$  denotes the thermal voltage, and  $n$  represents the diode ideality factor, which characterizes the behavior of the semiconductor junction.

The mathematical model incorporates the combined effects of photo-generated current, diode characteristics, and resistive losses to accurately represent the electrical behavior of a PV cell. Due to the presence of the exponential diode term, the current-voltage ( $I$ - $V$ ) characteristics exhibit highly non-linear behavior. Consequently, the output power of the PV system also varies non-linearly with voltage, resulting in distinct power-voltage ( $P$ - $V$ ) characteristics.

The  $I$ - $V$  and  $P$ - $V$  curves obtained from this model are widely used to evaluate PV system performance under different operating conditions. These characteristics provide valuable information regarding the operating region of the PV module and facilitate the identification of the Maximum Power Point (MPP), where the maximum electrical power can be extracted from the solar panel.

In MATLAB/Simulink, this mathematical model serves as the foundation for photovoltaic system simulation and analysis. It enables the investigation of PV performance under varying environmental conditions such as changes in solar irradiance and temperature. Moreover, the model plays a crucial role in the development and implementation of Maximum Power Point Tracking (MPPT) techniques, which continuously adjust the operating point of the PV system to achieve maximum energy extraction and improve overall system efficiency.[15][10]

### C. MPPT Controller

#### 1) MPPT Control Strategy

Maximum Power Point Tracking (MPPT) is an essential control technique employed in photovoltaic (PV) systems to maximize the extraction of electrical power from solar panels under varying environmental conditions. The output characteristics of a PV system are highly dependent on solar irradiance, temperature, and load variations. Since these factors continuously change throughout the day, the operating point of the PV array also shifts, making it necessary to continuously track the Maximum Power Point (MPP).

The Maximum Power Point (MPP) is a unique operating point on the current-voltage ( $I$ - $V$ ) and power-voltage ( $P$ - $V$ ) characteristic curves of a photovoltaic module where the product of voltage and current is maximum. At this point, the PV system delivers its highest possible output power and operates with maximum efficiency. However, due to fluctuations in irradiance and temperature, the location of

the MPP changes continuously, requiring an adaptive control mechanism to maintain optimal operation.

MPPT algorithms are designed to identify and track this optimal operating point by continuously monitoring the voltage and current generated by the PV array. Based on these measurements, the controller adjusts the duty cycle of a DC-DC converter to regulate the operating voltage of the PV system. By modifying the electrical impedance seen by the PV array, the controller ensures that the system remains close to the peak point of the  $P$ - $V$  characteristic curve.

The primary objective of an MPPT controller is to maximize energy harvesting from solar panels and improve the overall efficiency of the photovoltaic system. Without MPPT, the PV array may operate away from the maximum power point, resulting in reduced power output and lower energy conversion efficiency. Therefore, MPPT plays a crucial role in enhancing the performance and reliability of solar energy systems.

In modern photovoltaic applications, MPPT algorithms are integrated into solar charge controllers, grid-connected inverters, and standalone PV systems. These algorithms dynamically respond to changing atmospheric conditions and continuously adjust the operating parameters to ensure maximum power extraction. As a result, MPPT significantly improves system efficiency, increases energy yield, and enhances the overall utilization of solar energy resources.[16]

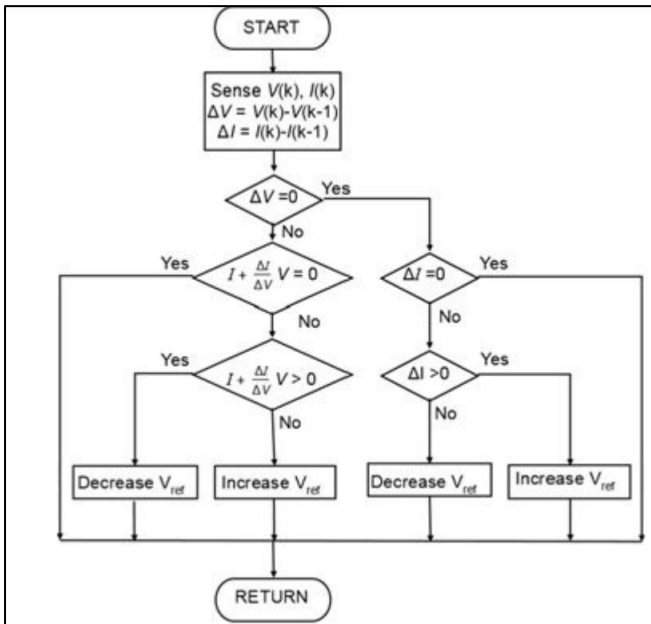
#### 2) The three most common MPPT algorithms are:

Perturbation and observation (P&O): This algorithm perturbs the operating voltage to ensure maximum power. While there are several advanced and more optimized variants of this algorithm, a basic P&O MPPT algorithm is shown below.[2]

#### 3) Incremental Conductance (INC) Algorithm Theory

The Incremental Conductance (INC) algorithm is one of the most widely used Maximum Power Point Tracking (MPPT) techniques in photovoltaic (PV) systems. Its main purpose is to continuously track the Maximum Power Point (MPP) of a solar panel under changing environmental conditions such as solar irradiance and temperature. The INC method provides better tracking accuracy and faster response compared to the conventional Perturb and Observe (P&O) method.

The operating principle of the Incremental Conductance algorithm is based on the slope of the Power-Voltage ( $P$ - $V$ ) characteristic curve of a PV module. At the maximum power point, the slope of the power curve becomes zero. On the left side of the MPP, the slope is positive, while on the right side it becomes negative. Therefore, the INC algorithm determines the position of the operating point by comparing the incremental conductance ( $\Delta I/\Delta V$ ) with the instantaneous conductance ( $-I/V$ ) [17]



The Fractional Open-Circuit Voltage (FOCV) method is a simple and cost-effective Maximum Power Point Tracking (MPPT) technique used in photovoltaic (PV) systems. The method is based on the principle that the maximum power point voltage ( $V_{mpp}$ ) is approximately proportional to the open-circuit voltage ( $V_{oc}$ ) ( $V_{oc}$ ) of the solar panel. This relationship is generally expressed as:  $V_{mpp} \approx k \times V_{oc}$  [18]

#### D. Solar Irradiance (G) & Photovoltaic Temperature (T)

##### 1) Solar Irradiance

Solar irradiance refers to the amount of solar radiation incident on a surface per unit area and is commonly measured in watts per square meter ( $W/m^2$ ). It indicates the instantaneous intensity of sunlight falling on a photovoltaic (PV) module. Mathematically, irradiance is expressed as power density, which is defined as the ratio of power to area.

A distinction should be made between irradiance and irradiation. Irradiance represents the instantaneous solar power received per unit area, whereas irradiation refers to the total amount of solar energy received over a certain period of time.

Solar irradiance plays a vital role in determining the performance of photovoltaic cells. As the irradiance level increases, the number of photons striking the PV cell surface also increases. This results in greater generation of electron-hole pairs within the semiconductor material. Consequently, the short-circuit current of the PV cell increases almost linearly with irradiance, causing the current-voltage (I-V) characteristics to shift upward and enhancing the overall power output of the PV system.

Hence, higher solar irradiance generally improves the efficiency and energy generation capability of photovoltaic systems.[9][10]

##### 2) Photovoltaic Cell Temperature

Photovoltaic cell temperature refers to the operating temperature of a PV module surface and is generally measured in degrees Celsius ( $^{\circ}C$ ) or Kelvin (K). The temperature of a solar cell mainly depends on environmental conditions such as ambient temperature and solar irradiance.

Temperature has a considerable influence on the electrical performance of photovoltaic systems. As the cell temperature increases, the open-circuit voltage of the PV cell decreases significantly, which reduces the maximum power output of the system. Consequently, the power-voltage (P-V) characteristic curve shifts downward.

Although the output current of the PV cell increases slightly with temperature, the reduction in voltage is much greater than the increase in current. Therefore, the overall efficiency and performance of the photovoltaic system decrease as the temperature rises.

Hence, proper thermal management is important for maintaining the efficiency and reliable operation of PV systems under varying environmental conditions. [9][10]

##### 3) Standard Test Conditions (STC)

For standardization and comparison, photovoltaic modules are tested under Standard Test Conditions (STC), which include an irradiance of  $1000 W/m^2$ , a cell temperature of  $25^{\circ}C$  (298 K), and an air mass of 1.5 (AM 1.5 spectrum).

##### 4) Variation of Solar Irradiance

The effect of solar irradiance on the current-voltage (I-V) and power-voltage (P-V) characteristics of a photovoltaic (PV) system is significant. When the temperature is kept constant and irradiance is varied over a range (such as  $200 W/m^2$  to  $1000 W/m^2$ ), noticeable changes are observed in the system performance. As the irradiance increases, the output current of the PV system increases almost linearly due to the higher number of incident photons generating more electron-hole pairs.

This increase in current results in an upward shift of the I-V curve, while the open-circuit voltage shows only a slight increase. Consequently, the maximum power output also increases with irradiance, leading to an upward shift of the P-V curve. Thus, higher solar irradiance directly enhances the power generation capability of the PV system.

##### - Effect of Solar Irradiance

The effect of solar irradiance on the I-V and P-V characteristics is analyzed by keeping the temperature constant at  $25^{\circ}C$  and varying irradiance from  $200 W/m^2$  to  $1000 W/m^2$ .

## II. LITERATURE REVIEW

### A. Incremental Conductance (INC) MPPT Algorithm

The Incremental Conductance (INC) algorithm improves the tracking performance by comparing incremental conductance ( $dI/dV$ ) with instantaneous conductance ( $I/V$ ). The algorithm determines whether the operating point is to the left or right of the maximum power point and adjusts the voltage accordingly. Unlike the P&O method, the INC algorithm can stop perturbation once the MPP is reached, thereby reducing oscillations.[17]

#### Advantages

- Higher tracking accuracy than P&O
- Reduced oscillations near MPP
- Better performance under rapidly changing irradiance
- Faster convergence toward maximum power point

#### Limitations

- More complex than P&O
- Requires additional computations

- Higher implementation cost
- Performance depends on selected step size

## B. Perturb and Observe MPPT Algorithm for Solar PV Systems-Modeling and Simulation [1]

### 1) Theory / Existing Work

The research work focuses on the design and simulation of a photovoltaic (PV) system integrated with a Maximum Power Point Tracking (MPPT) controller using the Perturb and Observe (P&O) algorithm. The study emphasizes the importance of MPPT techniques in maximizing power extraction from solar PV systems under varying irradiance and temperature conditions. The complete system, including the PV array, DC-DC converter, and MPPT control logic, is modeled and simulated in MATLAB/Simulink to evaluate its performance.

### 2) Advantages of the Existing Work

The main advantage of this work is the use of the P&O algorithm, which is simple, easy to implement, and widely used for MPPT applications. It effectively tracks the maximum power point under normal operating conditions and improves the overall efficiency of the PV system compared to systems without MPPT control.

### 3) Problem / Limitation

One of the major limitations of the conventional P&O algorithm is the continuous oscillation around the Maximum Power Point (MPP). These oscillations lead to fluctuations in output power and reduce the overall efficiency of the system. This issue mainly arises due to the use of a fixed perturbation step size, which prevents the operating point from settling exactly at the MPP.

### 4) Proposed Improvement / Future Work

To overcome this limitation, step size optimization can be introduced. Instead of using a fixed step size, a variable or adaptive step size approach can be implemented. This method reduces oscillations around the MPP and improves the tracking accuracy and response speed of the system. As a result, the PV system can achieve better stability and higher efficiency under varying environmental conditions.

## C. MATLAB-Based Simulation

### 1) Overview of the Existing Work

The study titled "Design and Simulation of a Photovoltaic System with MPPT Control using P&O Algorithm" by Amit Malviya and Burla Sridhar focuses on the implementation of a photovoltaic (PV) system integrated with a Maximum Power Point Tracking (MPPT) controller using the Perturb and Observe (P&O) algorithm. The system is designed and simulated to improve power extraction efficiency under varying environmental conditions. The P&O algorithm is used to continuously monitor and adjust the operating point of the PV system in order to achieve maximum power output.[1][5]

### 2) Advantages of the Existing Method

The main advantage of this approach is the simplicity of the P&O algorithm. It is easy to implement and requires less computational effort compared to other advanced MPPT techniques. The method provides acceptable performance under steady-state conditions and is widely used in PV system simulations using MATLAB/Simulink.

### 3) Limitations of the Existing Method

Despite its advantages, the conventional P&O algorithm suffers from oscillations around the maximum power point (MPP). These oscillations result in continuous power fluctuations, which reduce the overall efficiency of the system. This issue mainly occurs due to the use of a fixed perturbation step size, which prevents the system from stabilizing at the exact maximum power point.

### 4) Proposed Improvement

To overcome this limitation, step size optimization can be introduced in the P&O algorithm. Instead of using a fixed perturbation step size, a variable or adaptive step size approach can be implemented. This helps in reducing oscillations near the MPP and improves both the tracking accuracy and overall efficiency of the PV system.

## D. solar irradiance and temperature

Several researchers have investigated the impact of environmental conditions, particularly solar irradiance and temperature, on the performance of photovoltaic (PV) cells.

According to, a photovoltaic cell is a semiconductor device that converts solar energy into electrical energy through the photovoltaic effect. The performance of a solar cell mainly depends on solar irradiance and ambient temperature, which directly influence output current, voltage, and power.

The study presented in utilizes a single-diode model for representing the PV cell, which is widely used due to its simplicity and accuracy. This model includes a current source, diode, series resistance, and shunt resistance, enabling accurate prediction of I-V and P-V characteristics under varying environmental conditions.

From previous research, it has been observed that:

- Solar irradiance has a direct impact on current generation. As irradiance increases, the short-circuit current increases linearly due to higher photon absorption.
- Temperature mainly affects voltage. An increase in temperature causes a rise in reverse saturation current, which reduces the open-circuit voltage and overall efficiency.

The results discussed in (see Figures 3–6, page 3–4) show that:

- Increasing irradiance significantly enhances both current and power output.
- Increasing temperature results in a noticeable drop in voltage and maximum power.

Furthermore, the combined effect of irradiance and temperature (Figures 7 and 8, page 4) indicates that maximum power is achieved under high irradiance and low temperature conditions. This confirms that temperature acts as a negative factor in solar cell performance, while irradiance acts as a positive factor.

The study concludes that accurate modeling of PV systems using MATLAB/Simulink helps in predicting real-time performance and is useful for optimizing solar energy systems under different environmental conditions.[9][10][7]

## E. The Perturb and Observe (P&O)

The Perturb and Observe (P&O) algorithm is one of the most widely used Maximum Power Point Tracking (MPPT)

techniques for photovoltaic (PV) systems due to its simplicity, ease of implementation, and low computational requirements. The main objective of the P&O algorithm is to continuously track and maintain the operating point of the PV system at the maximum power point (MPP), where the solar panel delivers maximum possible power under varying environmental conditions such as irradiance and temperature. The algorithm operates by introducing a small perturbation in the operating voltage or duty cycle of the DC–DC converter and observing the resulting change in output power. If the power increases after the perturbation, the algorithm continues to move in the same direction, indicating that the system is approaching the MPP. On the other hand, if the power decreases, the direction of perturbation is reversed, which helps in redirecting the operating point toward the MPP.

This process is repeated continuously, allowing the system to track the maximum power point dynamically. However, the P&O algorithm has certain inherent limitations. It cannot settle exactly at the MPP and instead causes oscillations around it in steady-state conditions, resulting in power losses. Moreover, the algorithm may fail under rapidly changing atmospheric conditions because it assumes that any

variation in power is caused only by its perturbation, which may not always be true. There is also a trade-off between tracking speed and accuracy, as a larger perturbation step size improves response speed but increases oscillations, whereas a smaller step size reduces oscillations but slows down the tracking process. Despite these limitations, the P&O algorithm remains widely used due to its robustness, low cost, and ease of implementation, and several improved versions such as variable step size and adaptive P&O techniques have been developed to enhance its performance.[12]

1) *Limitations of P&O Algorithm*

Despite its advantages, the P&O algorithm has certain limitations. One of the major drawbacks is that it causes oscillations around the maximum power point in steady-state conditions, leading to power losses. Additionally, under rapidly changing atmospheric conditions, the algorithm may produce incorrect tracking results because it assumes that any change in power is caused only by its perturbation. There is also a trade-off between tracking speed and accuracy, as a larger step size improves response speed but increases oscillations, whereas a smaller step size reduces oscillations but slows down the tracking process.

F. Literature Review Table

s.no	Title	Candidate details	Drawback/ solution
1	Perturb and Observe MPPT Algorithm for Solar PV Systems- Modeling and Simulation[2]	Jacob James Nedumgatt, Jayakrishnan K. B., Umashankar S., Vijayakumar D., School of Electrical Engineering VIT University Vellore, India. jacob_jned@yahoo.com, jayakrishnankb007@gmail.com, shankarums@gmail.com, vijayakumar.d@vit.ac.in.	2. Fixed Step Size Limitation The use of a fixed perturbation step size leads to a compromise between tracking speed and accuracy, resulting in either slow response or increased oscillations.[1]
2	Incremental Conductance Algorithm for PV System[17]	Prashant N. Donge a , Gaurav Karlekar b a PG Scholar, Department of Electrical engg., Ballarpur Institute of Technology, Bamni, Tah-Ballarpur Dist-Chandrapur 442701, India, b Assistant professor, Department of Electrical engg., Ballarpur Institute of Technology, Bamni, Tah-Ballarpur Dist-Chandrapur 442701, IndiaScience And Technology	In photovoltaic (PV) systems, the output power of the solar panel continuously varies with changes in solar irradiance and temperature. In conventional PV systems operating without Maximum Power Point Tracking (MPPT), the operating point of the PV array does not remain at the maximum power point (MPP). As a result, the system fails to extract the maximum available power from the solar panel, leading to reduced efficiency and significant power loss under varying environmental conditions. The absence of

In photovoltaic (PV) systems, the output power of the solar panel continuously varies with changes in solar irradiance and temperature. In conventional PV systems operating without Maximum Power Point Tracking (MPPT), the operating point of the PV array does not remain at the maximum power point (MPP). As a result, the system fails to extract the maximum available power from the solar panel, leading to reduced efficiency and significant power loss under varying environmental conditions. The absence of MPPT also results in poor dynamic response, unstable operating conditions, and inefficient utilization of solar energy.

To overcome these limitations, Maximum Power Point Tracking (MPPT) techniques are employed in photovoltaic systems to continuously track the maximum power point and improve the overall efficiency of the system. Among various MPPT techniques, the Incremental Conductance (INC) algorithm is widely used because of its higher tracking accuracy and better performance under rapidly changing irradiance conditions. The INC algorithm operates by comparing the incremental conductance ( $dI/dV$ ) with the instantaneous conductance ( $I/V$ ) to determine the position of the operating point relative to the maximum power point. Once the MPP is reached, the controller adjusts the

operating voltage accordingly and minimizes unnecessary perturbations.

Although the Incremental Conductance method performs better than the conventional Perturb and Observe (P&O) technique, it still suffers from certain limitations such as oscillations around the maximum power point, fixed step-size issues, and increased computational complexity. A large step size improves tracking speed but increases oscillation, whereas a small step size reduces oscillation but slows down the tracking response.

Therefore, in order to improve the tracking performance and reduce steady-state oscillations, an adaptive hybrid MPPT technique based on Incremental Conductance and P&O algorithms is proposed in this work. The proposed method utilizes adaptive variable step-size control to achieve faster convergence, improved stability, and higher efficiency under varying environmental conditions.[17]

### III. METHODOLOGY

Following methods are used in this project

#### A. System Description

In this work, an adaptive variable step-size Incremental Conductance (INC) based Maximum Power Point Tracking (MPPT) technique is proposed to improve the performance of the photovoltaic (PV) system under varying environmental conditions. The conventional Incremental Conductance algorithm is widely used because of its higher tracking accuracy and better response compared to traditional MPPT techniques. However, the conventional INC method generally uses a fixed step size, which leads to steady-state oscillations around the maximum power point (MPP) and reduced tracking performance during rapid changes in solar irradiance and temperature.

In the conventional INC algorithm, a large step size provides faster tracking speed but increases oscillations and power loss near the maximum power point. Conversely, a small step size reduces oscillations and improves stability, but slows down the convergence speed and increases the settling time of the system. Therefore, selecting an appropriate fixed step size becomes a major challenge in conventional MPPT control.

To overcome these limitations, an adaptive variable step-size control strategy is incorporated into the Incremental Conductance algorithm. In the proposed method, the perturbation step size is automatically adjusted according to the operating condition of the PV system. When the operating point is far from the maximum power point, a larger step size is applied to achieve faster tracking. As the operating point approaches the maximum power point, the step size is automatically reduced to minimize oscillations and improve steady-state stability.

The proposed adaptive INC controller continuously monitors the PV voltage and current and dynamically adjusts the operating voltage of the PV array to ensure maximum power extraction under varying atmospheric conditions. The complete photovoltaic system consisting of a PV array, DC-DC converter, MPPT controller, and load is modeled and simulated using MATLAB/Simulink.

The performance of the proposed adaptive Incremental Conductance MPPT technique is evaluated in

terms of tracking speed, oscillation reduction, output power, and overall system efficiency. The proposed method is expected to provide improved dynamic response, reduced power loss, and enhanced stability compared to the conventional fixed step-size INC algorithm.[17]

The Incremental Conductance (INC) method is one of the most widely used Maximum Power Point Tracking (MPPT) techniques for photovoltaic (PV) systems because of its higher tracking accuracy and improved performance under varying environmental conditions. The method is based on the principle that the slope of the power-voltage (P-V) curve of a PV array becomes zero at the maximum power point (MPP), positive on the left side of the MPP, and negative on the right side of the MPP.

The mathematical condition for the Incremental Conductance method is expressed as:

$$dV/dP=0 \text{ at MPP}$$

Since the output power of the PV module is given by:

$$P=IV$$

Differentiating the power equation with respect to voltage gives:

$$dP/dV=I+V dI/dV$$

At the maximum power point:

$$dI/dv = -I/V$$

If

- $dI/dV > -I/V$ , the operating point lies on the left side of the MPP.
- $dI/dV < -I/V$ , the operating point lies on the right side of the MPP.
- $dI/dV = -I/V$ , the operating point is exactly at the maximum power point.

#### B. Mathematical Modeling of PV System

The PV system is modeled using the single-diode equivalent circuit, which provides a good balance between accuracy and simplicity. The model consists of a current source representing the photo-generated current, a diode, and series and shunt resistances.

The output current of the PV module is dependent on solar irradiance, temperature, and terminal voltage. The nonlinear relationship between current and voltage results in characteristic I-V and P-V curves, which vary with environmental conditions. These characteristics are essential for identifying the maximum power point and are commonly used in PV system analysis and simulation.

#### C. MATLAB/Simulink Model Development

The entire PV system is modeled and simulated using MATLAB/Simulink. The simulation model includes a PV array block, a DC-DC boost converter, a PWM generator, and an MPPT controller implemented using a MATLAB function block.

Measurement blocks are used to obtain voltage, current, and power values, while scope blocks are used to visualize system performance. The model is tested under different irradiance and temperature conditions to evaluate the effectiveness of the MPPT algorithm. MATLAB/Simulink provides a flexible platform for analyzing the dynamic behavior of PV systems and validating control strategies.

D. Simulation Procedure and Performance Evaluation

The simulation is carried out by varying environmental parameters such as solar irradiance and temperature to observe their effect on the PV system. The MPPT controller adjusts the duty cycle of the converter in response to these changes to maintain operation at the maximum power point. The performance of the system is evaluated based on key parameters such as output power, voltage, current, and tracking efficiency. The effectiveness of the MPPT algorithm is verified by analyzing the I–V and P–V characteristics and observing the ability of the system to track the MPP under different operating conditions.

IV. SIMULATION AND ANALYSIS

The Simulink model shown above represents the implementation of the Incremental Conductance (INC) MPPT algorithm for a Solar Photovoltaic (PV) system integrated with a boost converter. In this subsystem, the photovoltaic voltage ( $V_{pv}$ ) and current ( $I_{pv}$ ) are continuously sensed and provided as inputs to the MPPT controller. The

delay block stores the previous values of voltage and current, enabling the controller to calculate the incremental changes in voltage ( $\Delta V$ ) and current ( $\Delta I$ ).

The Incremental Conductance algorithm works on the principle that the slope of the power-voltage (P–V) curve becomes zero at the Maximum Power Point (MPP). The controller compares the incremental conductance ( $\Delta I/\Delta V$ ) with the instantaneous conductance ( $I/V$ ) to determine whether the operating point is to the left or right side of the MPP. Based on this comparison, the controller generates either increment ( $V_{inc}$ ) or decrement ( $V_{dec}$ ) control signals to adjust the reference voltage ( $V_{mpp}$ ).

The switch and merge blocks shown in the subsystem are responsible for selecting the appropriate control action according to the controller conditions. If the operating point is below the Maximum Power Point, the controller increases the reference voltage, whereas if the operating point moves beyond the MPP, the controller decreases the reference voltage. When the MPP condition is satisfied, the operating voltage remains constant.

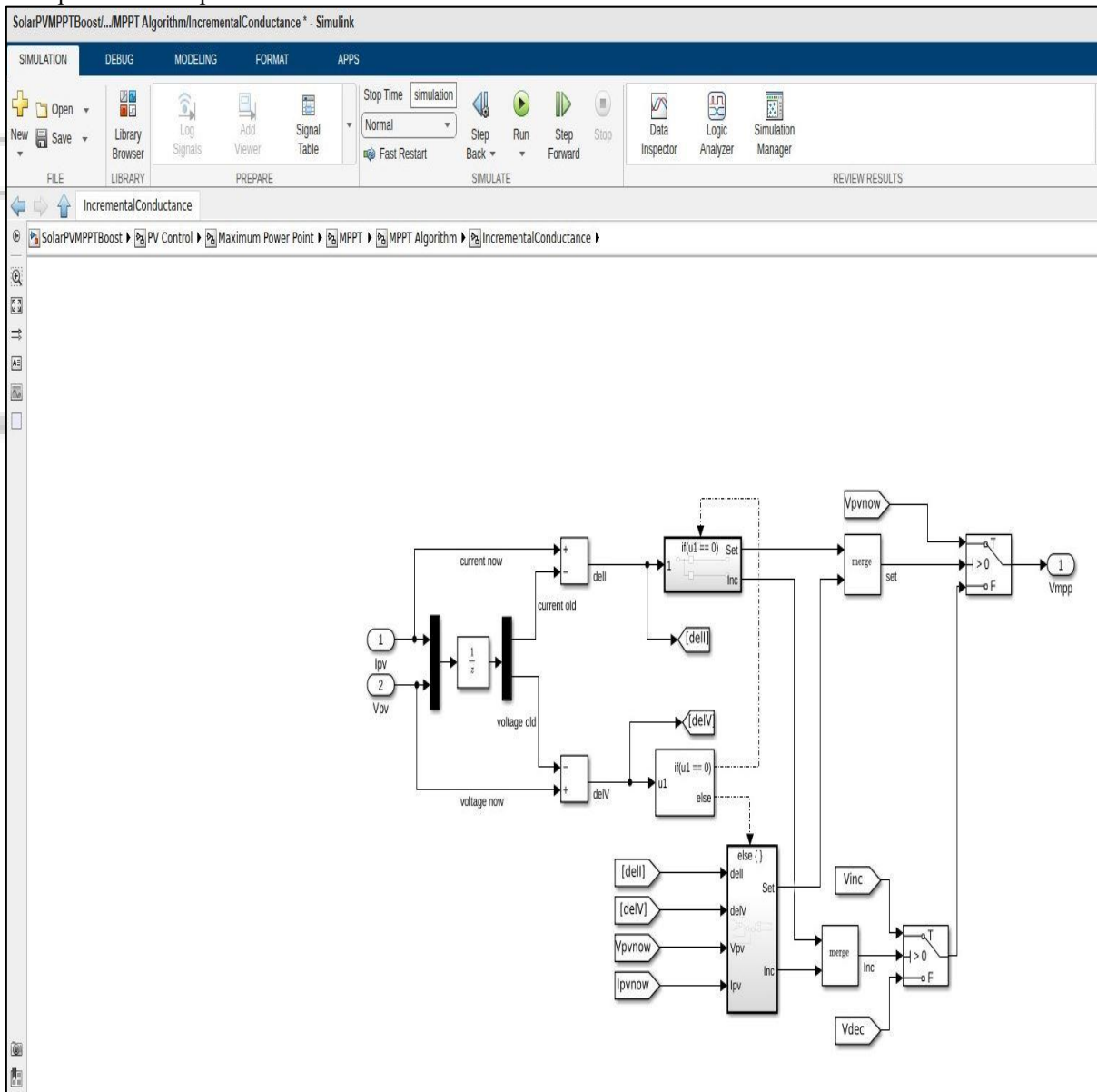


Fig. 4.1: Simulation diagram with MPPT

Finally, the generated reference voltage ( $V_{mpp}$ ) is supplied to the PWM controller of the boost converter. The PWM controller adjusts the duty cycle of the converter switch, thereby regulating the PV operating voltage and ensuring maximum power extraction from the solar panel under

varying irradiance and temperature conditions. The Incremental Conductance method provides fast tracking response, higher accuracy, and reduced steady-state oscillations compared to conventional MPPT techniques.

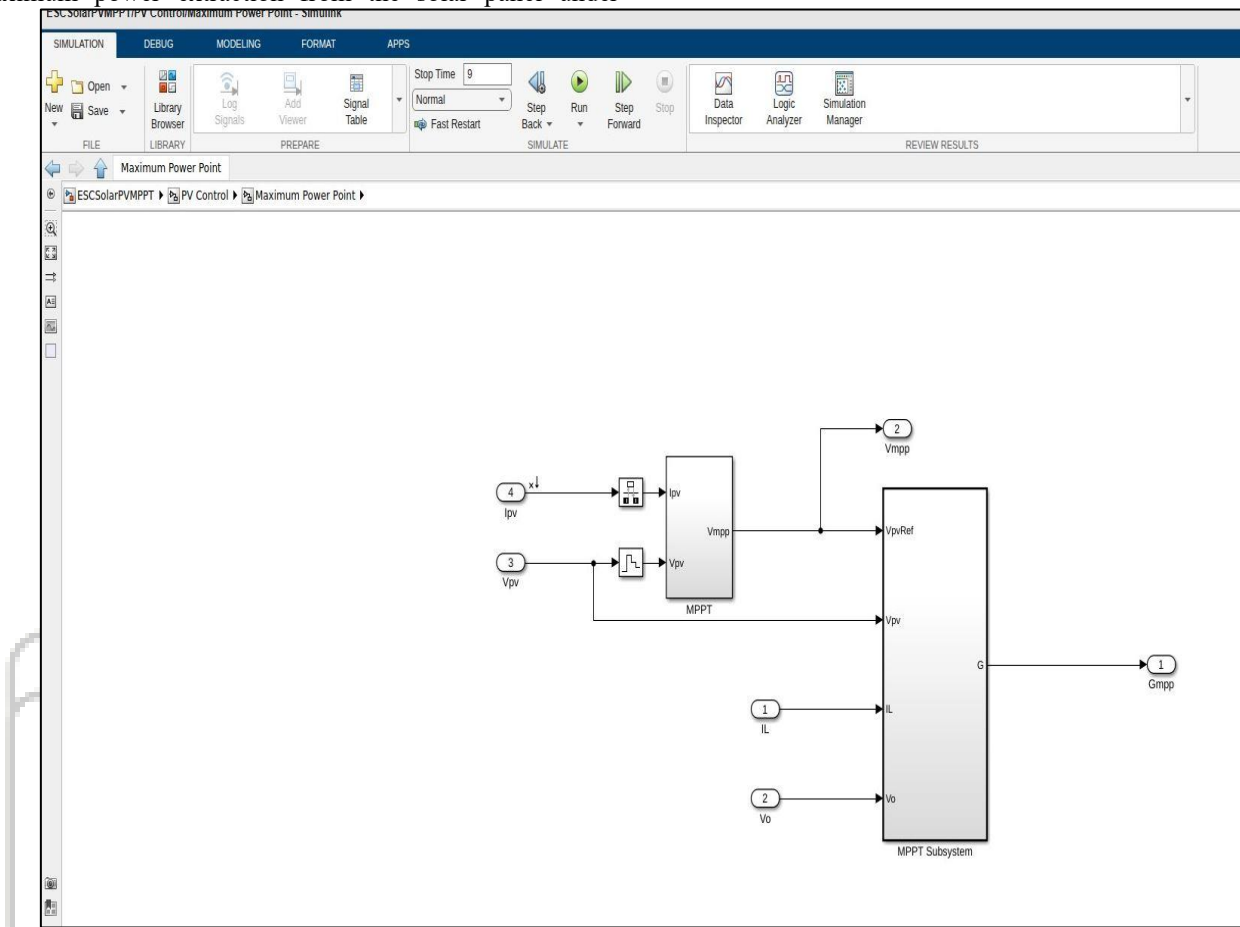


Fig. 4.2: simulation diagram box where put the I&C method algorithm

## V. RESULTS AND DISCUSSION

### A. Effect of Perturbation Step Size on MPPT Performance

In this study, the performance of the Perturb and Observe (P&O) MPPT algorithm has been analyzed by varying the perturbation step size in the MATLAB/Simulink environment. It is observed that the choice of step size significantly influences the dynamic behavior of the system. When a larger perturbation step size is applied, the system is able to reach the vicinity of the maximum power point (MPP) more quickly. However, this rapid response is accompanied by noticeable oscillations around the MPP, which leads to fluctuations in output power and reduces overall efficiency.

On the other hand, when a smaller step size is used, the oscillations around the MPP are minimized, resulting in a more stable output. Nevertheless, the system takes a longer time to reach the MPP, especially under changing environmental conditions such as variations in irradiance and temperature. Therefore, it can be concluded that there exists a trade-off between tracking speed and stability, and the selection of an appropriate step size is crucial for achieving optimal MPPT performance.

The effect of solar irradiance on the I–V and P–V characteristics is analyzed by keeping the temperature

constant at 25°C and varying irradiance from 200 W/m<sup>2</sup> to 1000 W/m<sup>2</sup>.

### B. Result Observation Table

Parameter	Conventional P&O	Hybrid P&O + INC
Tracking Speed	Moderate	High
Settling Time	Higher	Lower
MPP Accuracy	Good	Excellent
Oscillations Near MPP	High	Low
Dynamic Response	Moderate	Fast
Tracking Efficiency	95–97%	98–99%

### C. Performance Comparison of PV System with and without MPPT

A comparative performance analysis of the photovoltaic (PV) system was conducted to assess the effectiveness of the Maximum Power Point Tracking (MPPT) technique. In the conventional PV system without MPPT control, the operating point does not consistently coincide with the Maximum Power Point (MPP). Consequently, the system is unable to

utilize the available solar energy efficiently, resulting in reduced power output and lower overall efficiency.

To overcome this limitation, the Perturb and Observe (P&O) MPPT algorithm was integrated into the PV system. The MPPT controller continuously monitors the PV voltage and current and adjusts the duty cycle of the DC-DC converter to maintain operation near the Maximum Power Point. This adaptive control mechanism enables the PV system to respond effectively to variations in solar irradiance and temperature.

The simulation results indicate that the implementation of the MPPT algorithm significantly enhances the output power of the PV system. The controller rapidly tracks the optimal operating point and minimizes power losses associated with environmental changes. As a result, the PV system achieves improved energy harvesting capability and higher conversion efficiency.

The comparative analysis clearly demonstrates that the incorporation of MPPT technology substantially improves the performance, reliability, and energy utilization of the solar PV system. Therefore, MPPT plays a vital role in maximizing power extraction and ensuring efficient operation of photovoltaic energy conversion systems under varying atmospheric conditions.

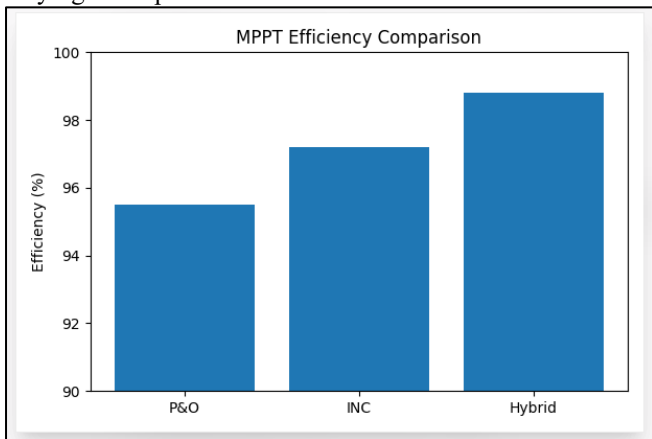


Fig. 5.1: result graph comparison

## VI. CONCLUSIONS AND FUTURE SCOPE

### A. Conclusions

The simulation results obtained from MATLAB/Simulink demonstrate that the proposed adaptive Incremental Conductance MPPT technique provides improved tracking speed, reduced steady-state oscillations, enhanced stability, and better maximum power extraction under varying irradiance and temperature conditions. Therefore, the proposed method improves the overall efficiency and dynamic performance of the photovoltaic system compared to the conventional fixed step-size INC algorithm.

### B. Future Scope

The proposed adaptive Incremental Conductance MPPT technique can be further extended and improved for future research and practical implementation. Advanced intelligent control techniques such as Fuzzy Logic Control, Artificial Neural Networks (ANN), and Machine Learning algorithms may be integrated with the MPPT controller to achieve higher

tracking accuracy and better adaptive performance under highly dynamic environmental conditions.

## REFERENCES

- [1] Fiza, S., "A Brief Introduction about Solar Photovoltaic," *International Journal of Engineering Research in Electronics and Communication Engineering (IJERECE)*, Vol. 9, Issue 4S, April 2023. Author: Ms. Samreen Fiza, Assistant Professor, Department of Electronics and Communication Engineering, Presidency University, Bangalore, India.
- [2] Perturb and Observe MPPT Algorithm for Solar PV Systems-Modeling and Simulation. Jacob James Nedumgatt, Jayakrishnan K. B., Umashankar S., Vijayakumar D., School of Electrical Engineering VIT University Vellore, India. jacob\_jned@yahoo.com, jayakrishnankb007@gmail.com shankarums@gmail.com, vijayakumar.d@vit.ac.in.
- [3] Modelling and Simulation of Perturb and Observe MPPT Algorithm Based on The PI Controller for Photovoltaic System. Ahlam Mohamad Shakoor Hersh Hasan Taha Petroleum and Energy Kirkuk Refinery Department Technical College of Engineering North Refineries Company Sulaimani Polytechnic University Ministry of Oil Sulaimani, Iraq Salah Al-Din, Iraq Ahlam.shakoor@spu.edu.iq herieshhassan@gmail.com Volume 7 - Issue 2- December 2022 DOI: 10.24017/Science.2022.2.6 Article history: Received: 19/06/2022 Accepted: 20/11/2022
- [4] ADVANCEMENTS IN SOLAR CELL TECHNOLOGIES AND THEIR MULTIFACETED APPLICATIONS IN A SUSTAINABLE FUTURE May 2025 *International Journal of Progressive Research in Engineering Management and Science*5(5):683-691 DOI: 10.58257/IJPREMS41252
- [5] ORIGAMI BASED FOLDING TECHNIQUES FOR SOLAR PANEL APPLICATIONS S. Yogesh, M. Yogalakshmi, M. Abishek, R. Ari Prasath Student, Department of Electrical and Electronics Engineering SRM Valliammai Engineering College, Kattankulatur, Tamil Nadu. India Dr. G. Madhusudan Assistant Professor, Department of Electrical and Electronics Engineering SRM Valliammai Engineering College, Kattankulatur, Tamil Nadu. India
- [6] Title: Modeling and Simulation of Photovoltaic System using MATLAB/Simulink Authors: Huan-Liang Tsai, Ci-Siang Tu, Yi-Jie Su Journal: *International Journal of Computer and Electrical Engineering* Link: <https://www.ijert.org/modeling-and-simulation-of-photovoltaic-system-using-matlab-simulink>
- [7] [https://www.niser.ac.in/sps/assets/files/msc-phd/I-V\\_characteristics\\_of\\_solar\\_cell](https://www.niser.ac.in/sps/assets/files/msc-phd/I-V_characteristics_of_solar_cell).
- [8] Investigation the effect of the temperature and irradiance on the output parameters of solar cell Ali Natheer Tuaimah 2 Shaker A. A. AL-Saidi 1Department of Physics- Collage of Science-University of Thi-Qar, Iraq. 2Department of Physics- College of Education of Pure Sciences- University of Thi-Qar, Iraq. Website:

- jsci.utq.edu.iq Email: jsci@utq.edu.iq Volume 7,  
Number 1, June 2019
- [9] The irradiance and temperature dependent mathematical model for estimation of photovoltaic panel performances M. Barukc'ic' <sup>†</sup>, V. C'orkluka, K. Mikloševic' Faculty of Electrical Engineering of Osijek, J.J. Strossmayer University of Osijek, Kneza Trpimira 2B, 31 000 Osijek, Croatia
- [10] Optimization of Perturb and Observe Maximum Power Point Tracking Method Nicola Femia, Member, IEEE, Giovanni Petrone, Giovanni Spagnuolo, Member, IEEE, and Massimo Vitelli IEEE TRANSACTIONS ON POWER ELECTRONICS, VOL. 20, NO. 4, JULY 2005
- [11] DESIGN AND SIMULATION OF A DC – DC BOOST CONVERTER T. A. Aika \*; F. O. Agbontaen  
†Department of Electrical/Electronic Engineering, University of Benin, Benin City \*  
ayemhenre.aika@uniben.edu
- [12] Modelling and Simulation of DC-DC Boost Converter and Inverter for PV System Mohamed Aqeel Shafeek\*1, Hariprasad Yogaraju1, Jasspeed Singh1 and Lingeswarran Thanaventhiran1 1 Manipal International University, MIU Boulevard, Putra Nilai, 71800, Negeri Sembilan, Malaysia Malaysian Journal of Science and Advanced Technology journal homepage: <https://mjsat.com.my/>
- [13] <https://in.mathworks.com/help/sps/ug/solar-pv-system-maximum-power-point-tracking-using-boost-converter.html>
- [14] MPPT Methods for Solar PV Systems: A Critical Review Based on Tracking Nature May 2019 IET Renewable Power Generation13(10)  
DOI: 10.1049/ietrpg.2018.5946 Amit Kumer Podder Naruttam Kumar Roy Hemanshu Roy Pota
- [15] Incremental Conductance Algorithm for PV System Prashant N. Donge a , Gaurav Karlekar b a PG Scholar, Department of Electrical engg., Ballarpur Institute of Technology, Bamni, Tah-Ballarpur Dist- Chandrapur 442701, India, b Assistant professor, Department of Electrical engg., Ballarpur Institute of Technology, Bamni, Tah-Ballarpur Dist- Chandrapur 442701, India, International Journal of Research Publication and Reviews Journal homepage: [www.ijrpr.com](http://www.ijrpr.com) ISSN 2582-7421
- [16] A fractional open circuit voltage based maximum power point tracker for photovoltaic arrays November 2010 1:V1-247 - V1-250 DOI: 10.1109/ICSTE.2010.5608868 Jawad Ahmad