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Design and Simulation of Solar PV System with MPPT using Perturb & Observe Method in MATLAB/Simulink

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Abstract — This paper presents the validation and implementation of a Maximum Power Point Tracking (MPPT) algorithm using the Perturb and Observe (P&O) technique for photovoltaic (PV) systems. Initially, the maximum power value is set to a reference level and is continuously updated by measuring the PV voltage and current at regular intervals. The instantaneous power is calculated and compared with the previously recorded maximum value. If the new power value is higher, it is updated as the new maximum power point. The algorithm continuously tracks the operating point to ensure maximum power extraction under varying environmental conditions. However, the conventional P&O method exhibits slight oscillations around the maximum power point. To reduce this effect, a minor modification in the step size adjustment has been incorporated, improving system stability and response. Furthermore, efficient power transfer is achieved by maintaining impedance matching between the source and load through appropriate control of the converter duty cycle. The complete system is modeled and simulated using MATLAB/Simulink, and the results demonstrate improved performance and stable power output.

Keywords: Maximum Power Point Tracking (MPPT); Perturb and Observe (P&O) Algorithm; Photovoltaic (PV) Systems; DC-DC Converter Control; MATLAB/Simulink Modeling; Renewable Energy Optimization

I. INTRODUCTION

An element of energy is the measure of the actual energy that is perceived by the visible energy load flowing in the region. Basically a measure of how a current upload is converted into an active product. The smaller the power factor of the system, the less effective it is economically. [1]

A. Solar PV System

A photovoltaic (PV) system consists of several essential components that work together to convert solar energy into usable electrical power. The primary component is the solar cell, which directly converts sunlight into direct current (DC) electricity using the photovoltaic effect. Multiple solar cells are connected to form a PV module, and several modules are further combined to create a PV array for higher power generation. The output from the PV array is then regulated using a DC-DC converter, which adjusts the voltage level according to system requirements. To ensure maximum power extraction under varying environmental conditions, an MPPT (Maximum Power Point Tracking) controller is employed, which continuously adjusts the operating point of the system. In many applications, an inverter is also used to convert DC power into alternating current (AC) for compatibility with household or grid-connected systems. Additionally, batteries may be included for energy storage in standalone or hybrid systems. Together, these components ensure efficient, reliable, and continuous operation of the PV system.[1][2]

1) Solar Cell (Photovoltaic System)

A solar cell, also known as a photovoltaic (PV) cell, is a device that directly converts solar energy into electrical energy using the photovoltaic effect. Photovoltaic cells are typically fabricated from semiconducting materials such as silicon, which generate electricity when exposed to sunlight. When light strikes the surface of the cell, energy in the form of photons is absorbed, 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,” meaning electrical potential. Since individual solar cells produce relatively low voltage and current, they are connected together to form modules and panels. Multiple modules are further combined to create a PV array, which can generate sufficient power for practical applications. Large PV arrays may consist of thousands of interconnected solar cells and can function as electric power generation systems.

These PV systems are widely used for supplying electrical energy to residential, commercial, and industrial applications. Smaller arrangements of solar cells are commonly referred to as solar panels, which are often installed on rooftops and terraces to supplement or replace conventional electricity sources.

The efficiency of photovoltaic cells is theoretically around 25%. However, the efficiency is affected by temperature, and it decreases as the temperature increases. Even a small rise in temperature can lead to a reduction in efficiency, which highlights the importance of thermal management in PV systems.[7]

2) Working of Solar Cell

A solar cell operates based on the photovoltaic effect and essentially consists of a p–n junction that generates an electromotive force (EMF) when exposed to sunlight. When light with energy greater than the bandgap of the semiconductor material falls on the solar cell, photons are absorbed, leading to the generation of electron-hole pairs.

In a typical solar cell structure, a thin layer of n-type silicon (n-Si) is formed on one side of a p-type silicon (p-Si) wafer using diffusion techniques. The p–n junction formed between these layers creates an internal electric field. A metal contact is applied on the backside of the p-Si layer, known as the back contact, while a metallic grid or finger electrodes are placed on the top surface of the n-Si layer, serving as the front contact.

To enhance the absorption of incident light and increase the generated current, the surface area of the junction is kept large. When sunlight strikes the cell, three main processes occur: generation of electron-hole pairs, separation of these charge carriers due to the internal electric field, and collection of carriers at the respective contacts. These processes together result in the generation of an electromotive force (EMF) and the flow of electric current in an external circuit.[10]

The overall working of the solar cell can thus be understood as the combined effect of generation, separation, and collection of charge carriers, which enables the direct conversion of solar energy into electrical energy.

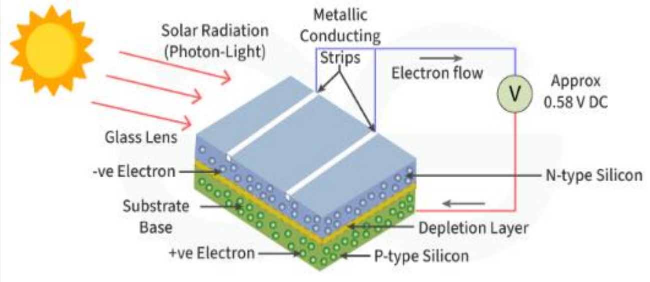


Fig. 1.1: working of solar

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

A solar cell is the basic unit of a solar energy generation system, in which electrical energy is directly extracted from light energy without any intermediate conversion process. The operation of a solar cell is based on the photovoltaic effect; therefore, it is also known as a photovoltaic (PV) cell. 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 has a high concentration of holes, whereas the n-type region has a high concentration of electrons.

At the junction, electrons from the n-type region tend to diffuse toward the p-side, while holes from the p-type region move toward the n-side. This movement results in the formation of an electric field across the junction and creates a depletion region. The electric field plays a crucial role in the operation of the solar cell.

When sunlight falls on the solar cell, photons with energy greater than the bandgap of the semiconductor are absorbed, leading to the generation of electron-hole (e–h) pairs. These charge carriers are then separated by the internal electric field present in the depletion region. Electrons are driven toward the n-side, and holes move toward the p-side, resulting in the development of a potential difference across the cell.

Typically, a photovoltaic cell consists of a negative front contact and a positive back contact, with the p–n junction located between them. When these two terminals are connected through an external circuit, current begins to flow from the positive terminal to the negative terminal, thereby producing electrical power.

For silicon-based solar cells, the bandgap energy at room temperature is approximately 1.1 eV, and the diffusion potential ranges from 0.5 to 0.7 V. This forms the basic working principle and theoretical foundation of a solar cell.

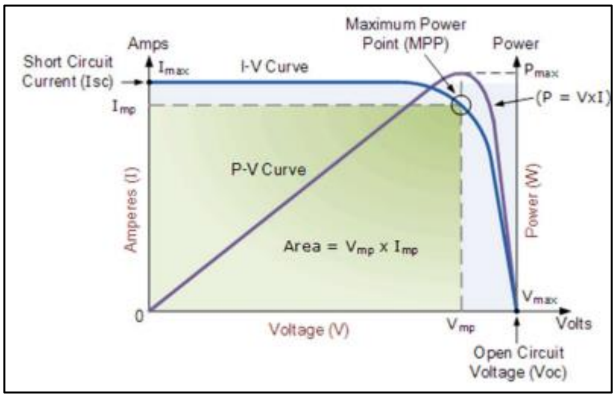


Fig. 1.2: working of solar iv curve

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 I0 = "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
IL = light generated current.

This equation describes the non-linear relationship between the output current and voltage of the PV cell. In this expression, Iph represents the photo-generated current, which is directly dependent on solar irradiance, while I0 is the diode saturation current, influenced by temperature. The term Rs denotes the series resistance, accounting for internal losses, and Rsh represents the shunt resistance, indicating leakage currents within the cell. The parameter Vt is the thermal voltage, and n is the diode ideality factor.[6]

The equation combines the effects of generated current, diode behavior, and resistive losses to accurately model the performance of the PV system. Due to its exponential nature, the current-voltage (I–V) characteristics of the PV cell are highly non-linear. This model is widely used to derive both I–V and power-voltage (P–V) curves, which are essential for analyzing system performance and identifying the Maximum Power Point (MPP).

In MATLAB/Simulink, this mathematical model forms the basis of PV system simulation, allowing accurate analysis under varying environmental conditions such as irradiance and temperature. It also plays a vital role in the implementation of MPPT algorithms, which rely on these characteristics to maximize power extraction.[10]

C. *Solar Irradiance (G) & Photovoltaic Temperature (T)*

1) *Solar Irradiance*

Solar irradiance is defined as the power of solar radiation incident on a surface per unit area, and it is typically measured in watts per square meter (W/m²). It represents the instantaneous intensity of sunlight falling on the photovoltaic (PV) module. Mathematically, irradiance can be expressed as power density, i.e., the ratio of power to area. It is important to distinguish between irradiance and irradiation: irradiance refers to instantaneous power per unit area, whereas irradiation represents the total solar energy received over a period of time.

Solar irradiance has a direct impact on the performance of PV cells. As irradiance increases, the number of photons incident on the cell also increases, leading to higher generation of electron-hole pairs. Consequently, the short-circuit current of the PV cell increases almost linearly with irradiance, resulting in an upward shift of the current-voltage (I–V) curve and an increase in overall power output.[9][10]

D. Combined Mathematical Modeling (PV Performance)

The performance of a photovoltaic (PV) system is influenced by environmental factors such as solar irradiance and temperature, which affect the I–V and P–V characteristics. These relationships are commonly modeled using the single diode model.

The photo-generated current ((Iph) is directly proportional to solar irradiance and also depends on temperature. It can be expressed as:

$$I_{ph} = [I_{sc} + K_i(T - T_{ref})] \times \frac{G}{G_{ref}}$$

where IscI_ is the short-circuit current, Ki is the temperature coefficient of current, T is the operating temperature, TrefT is the reference temperature, G is the irradiance, and Gref is the reference irradiance.

The diode saturation current (I0) is strongly dependent on temperature and is given by:

$$I_0 = I_{rs}\left(\frac{T}{T_{ref}}\right)^3 \exp\left[\frac{qE_g}{nk}\left(\frac{1}{T_{ref}} - \frac{1}{T}\right)\right]$$

where IrsI_ is the reverse saturation current, Eg is the bandgap energy, q is the electron charge, k is Boltzmann's constant, and n is the diode ideality factor.

The output voltage of the PV system is also affected by temperature and can be approximated using:

$$V = V_{oc} - K_v(T - T_{ref})$$

Where Voc the open-circuit voltage and Kv is the temperature coefficient of voltage.

These equations collectively describe the dependence of PV system performance on environmental conditions and are widely used for accurate modeling and simulation in MATLAB/Simulink.

1) Standard Test Conditions (STC)

For standardization and comparison, photovoltaic modules are tested under Standard Test Conditions (STC), which include an irradiance of 1000 W/m², a cell temperature of 25°C (298 K), and an air mass of 1.5 (AM 1.5 spectrum).

2) 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/m² to 1000 W/m²), 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.

3) Effect of Irradiance and Temperature on Solar PV Characteristics

a) Mathematical Modeling of Solar Cell

The solar cell is modeled using the single-diode model, which accurately represents the electrical behavior of a photovoltaic (PV) cell. The output current of the solar cell is given by:

Equation (1): Solar Cell Current Equation

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

This equation shows the nonlinear relationship between current and voltage and is used in MATLAB to generate I–V and P–V curves.

The photo-generated current depends on irradiance and temperature:

Photo-Generated Current

$$I_{ph} = [I_{sc} + K_i(T - T_{ref})]\,\frac{G}{G_{ref}}$$

This indicates that the generated current increases linearly with solar irradiance. The reverse saturation current, which is temperature dependent, is expressed as:

The open-circuit voltage is given by:

$$V_{oc} = \frac{nkT}{q}\ln\left(\frac{I_{ph}}{I_0} + 1\right)$$

II. LITERATURE REVIEW

Literature Review Table

S.no	Title	Candidate details	Drawback/ soltuion
1	Modelling and Simulation of Perturb and Observe MPPT Algorithm Based on The PI Controller for Photovoltaic System[2]	Ahlam Mohamad Shakoor Petroleum and Energy Technical College of Engineering Sulaimani Polytechnic University Sulaimani, Iraq Ahlam.shakoor@spu.edu.iq	.

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.	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]
3	Design and Simulation of a Photovoltaic System with MPPT Control using P&O Algorithm	Mr. Amit Malviya1 , Mr. Burla Sridhar2 1Student, Electrical & Electronics, Oriental Institute Of Science And Technology 2Assistant Professor, Electrical & Electronics, Oriental Institute Of Science And Technology	Oscillation around Maximum Power Point The conventional Perturb and Observe (P&O) algorithm produces continuous oscillations around the maximum power point, which reduces the overall efficiency of the system.[1][5]

III. METHODOLOGY

A. *System Description*

The proposed photovoltaic (PV) system is designed to extract maximum available power using a Maximum Power Point Tracking (MPPT) technique based on the Perturb and Observe (P&O) algorithm. The overall system consists of three main components: a solar PV array, a DC–DC boost converter, and an MPPT controller.

The PV array converts solar irradiance into electrical energy, while the boost converter regulates the output voltage and enables control of the operating point. The MPPT controller continuously monitors the system parameters and adjusts the duty cycle of the converter to ensure that the PV system operates at or near the maximum power point (MPP). Similar system configurations have been widely adopted in PV modeling and simulation studies due to their simplicity and effectiveness.

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. *Implementation of P&O MPPT Algorithm*

The Perturb and Observe algorithm is implemented to track the maximum power point of the PV system. The algorithm operates by introducing small perturbations in the operating voltage and observing the resulting change in output power.

At each sampling instant, the voltage and current of the PV system are measured, and the corresponding power is calculated. The current power is compared with the previous power value to determine whether the operating point is moving toward or away from the MPP. Based on this comparison, the direction of perturbation is maintained or reversed. This iterative process continues throughout the operation of the system, ensuring continuous tracking of the maximum power point.

D. *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.

E. *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.

F. *P&O MPPT Algorithm Implementation*

The Perturb and Observe algorithm is implemented to track the maximum power point. The steps involved are:

1) Measure PV voltage (V) and current (I)
2) Calculate power (P = V × I)
3) Compare current power with previous power
4) Adjust duty cycle accordingly:
    - If power increases → continue in same direction
    - If power decreases → reverse direction

This process is repeated continuously to maintain operation near the MPP.

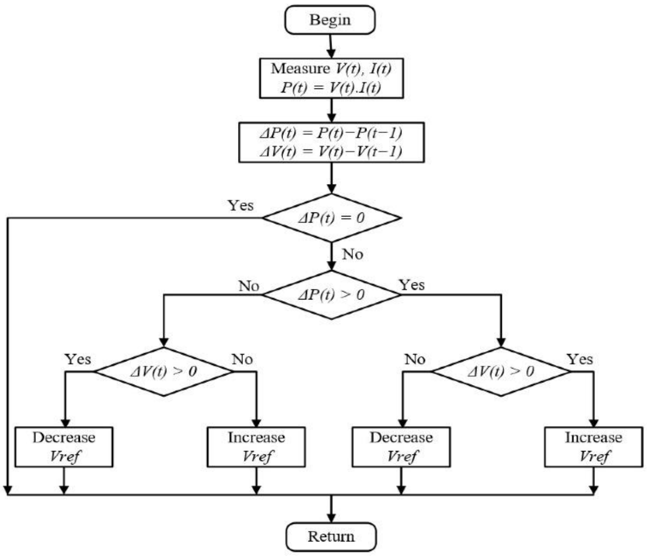


Fig. 3.1: flow chart of P&O method working

This flowchart explains the working of the Perturb and Observe (P&O) MPPT algorithm used in photovoltaic (PV) systems. The process begins by measuring the instantaneous voltage (V(t)) and current (I(t)) of the solar panel. Using these values, the output power is calculated as (P(t) = V(t) \times I(t)). The algorithm then compares the present power with the previous power to determine the change in power (\Delta P(t)) and change in voltage (\Delta V(t)). If (\Delta P(t) = 0), it indicates that the system is already operating near the maximum power point (MPP), so no adjustment is required.

If the power has changed, the algorithm checks whether (\Delta P(t)) is positive or negative. When (\Delta P(t) > 0), it means the recent change has moved the operating point closer to the MPP. In this case, the algorithm continues to adjust the reference voltage (V_{ref}) in the same direction as before. Specifically, if (\Delta V(t) > 0), the voltage is increased further, and if (\Delta V(t) < 0), the voltage is decreased further. On the other hand, if (\Delta P(t) < 0), it means the system has moved away from the MPP, so the direction of adjustment is reversed. That is, if (\Delta V(t) > 0), the reference voltage is decreased, and if (\Delta V(t) < 0), the reference voltage is increased. This continuous process of perturbing and observing allows the system to track the maximum power point dynamically, although it may cause small oscillations around the MPP in steady-state conditions.[12][11]

IV. SIMULATION AND ANALYSIS

Work 1 MATLAB Simulink model of solar PV system with MPPT. The images below shown us how to change the value of mppt algorythem. We choce method of P&O.

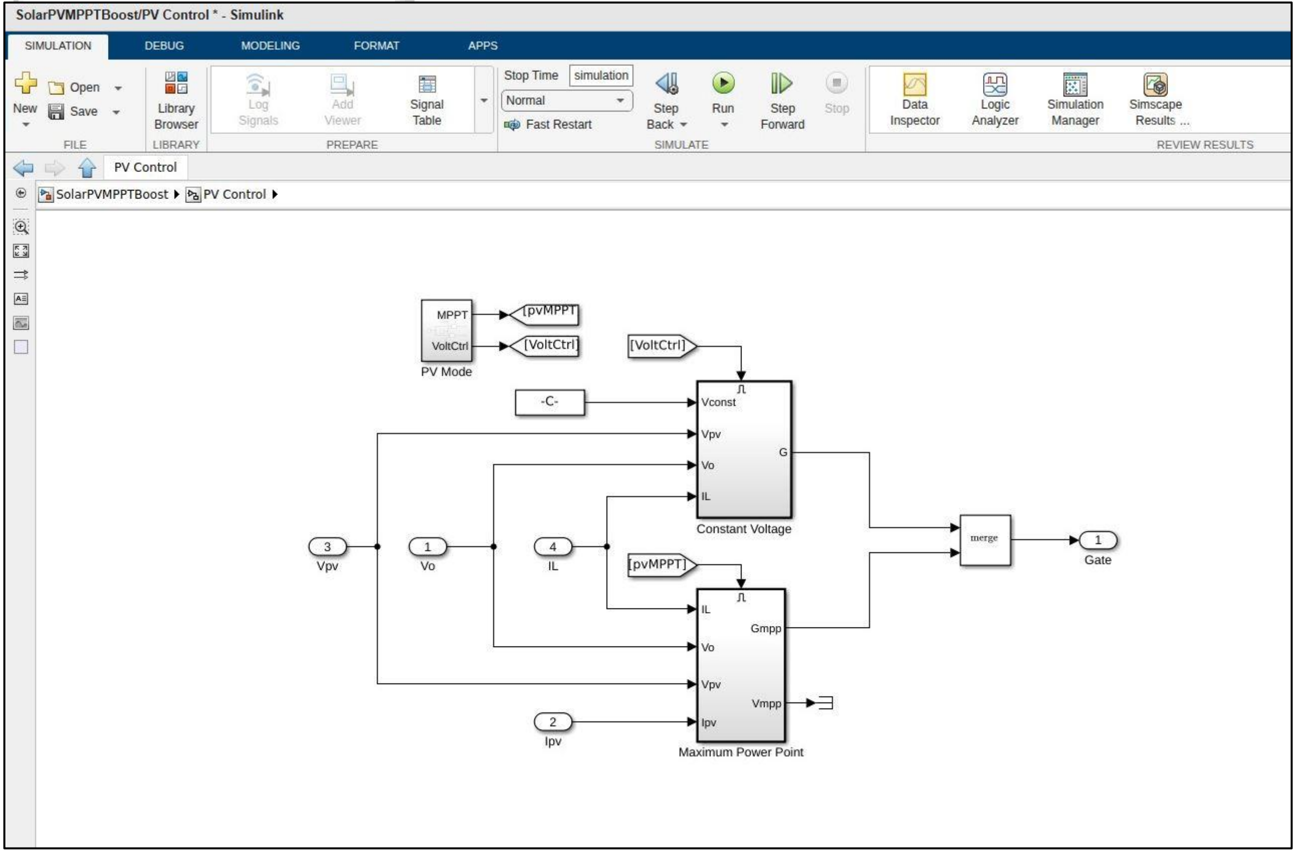


Fig. 4.1: MATLAB Simulink model of solar PV system with MPPT

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/m² to 1000 W/m².

Figure 5.1: I–V Characteristics at Different Irradiance

I–V characteristics of the solar PV module at constant temperature (25°C) under varying irradiance levels (200 W/m² to 1000 W/m²). The curves show that the short-circuit current (Isc) increases linearly with irradiance, while the open-circuit voltage (Voc) shows only a slight increase.

Figure 5.2: P–V Characteristics at Different Irradiance

P–V characteristics of the solar PV module at constant temperature (25°C) for varying irradiance levels. The maximum power point (MPP) increases significantly with increasing irradiance.

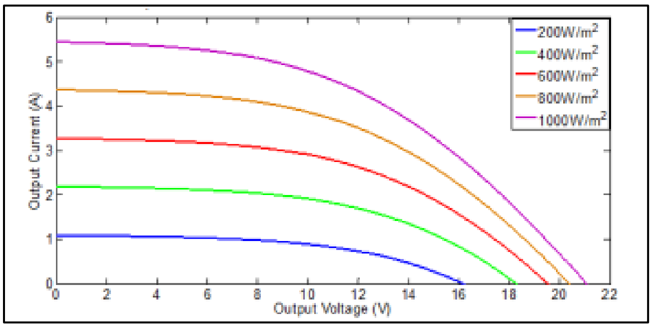


Fig. 5.1: I-V Output Characteristics of solar cell at different irradiance.

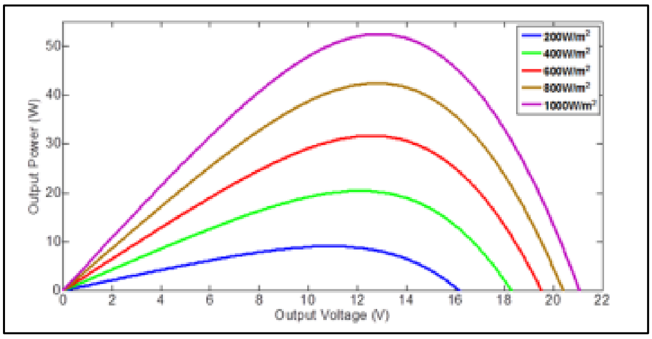


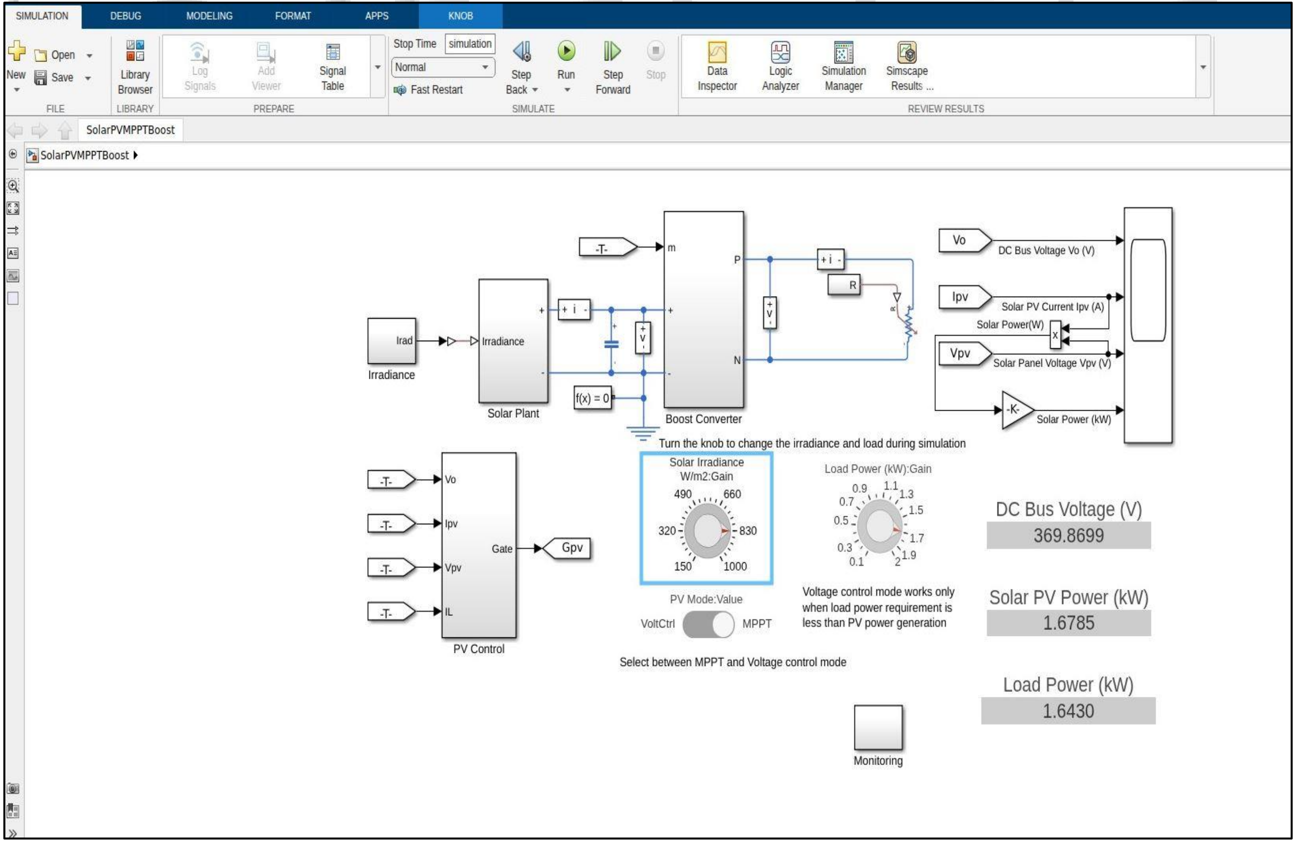
Fig. 5.2: P-V Output Characteristics of solar cell at different irradiance

Explanation

High irradiance → Higher current and power

High temperature → Lower voltage and efficiency

Thus, best performance occurs at high irradiance and low temperature.



Stop Time: simulation

Normal

Turn the knob to change the irradiance and load during simulation

Voltage control mode works only when load power requirement is less than PV power generation

Select between MPPT and Voltage control mode

DC Bus Voltage (V)
369.8699

Solar PV Power (kW)
1.6785

Load Power (kW)
1.6430

Fig. 5.3: MATLAB imegs of during irradiance levels (200 W/m² to 1000 W/m²).

VI. CONCLUSIONS AND FUTURE SCOPE

A. Conclusions

This project, “Design and Simulation of Solar PV System with MPPT using Perturb & Observe Method in MATLAB/Simulink,” successfully demonstrates the modeling, analysis, and performance evaluation of a solar photovoltaic (PV) system integrated with a Maximum Power Point Tracking (MPPT) controller using the Perturb and Observe (P&O) algorithm.

The MATLAB/Simulink model effectively represents the behavior of the solar PV system under varying environmental conditions such as changes in solar irradiance and temperature. From the simulation results, it is observed that solar irradiance directly affects the output current and power of the PV system, while temperature mainly influences the output voltage. These variations significantly impact the operating point of the solar panel, making MPPT essential for extracting maximum available power.

The project can also be upgraded by replacing the fixed-step P&O algorithm with an adaptive step-size P&O method, which can offer a better balance between tracking speed and accuracy. This would help overcome one of the major limitations of the conventional P&O technique.

Further scope includes the integration of battery energy storage systems (BESS) to ensure uninterrupted power supply and improve energy utilization during low irradiance or nighttime conditions. Such integration would make the system more suitable for standalone and hybrid renewable energy applications.

B. Future Scope

The project titled “Design and Simulation of Solar PV System with MPPT using Perturb & Observe Method in MATLAB/Simulink” provides a strong foundation for understanding photovoltaic system modeling and maximum power point tracking techniques. Although the present work focuses on the implementation of the conventional P&O algorithm in a simulated MATLAB/Simulink environment, there are several opportunities for future enhancement and practical expansion.

In future work, the proposed system can be extended by implementing advanced MPPT techniques such as Incremental Conductance (INC), Fuzzy Logic Control, Artificial Neural Networks (ANN), or hybrid optimization methods. These methods can improve tracking speed, reduce steady-state oscillations around the maximum power point, and enhance system efficiency under rapidly changing atmospheric conditions.

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