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A Photovoltaic System Maximum Power Point Tracking Techniques Comparison under Variable Atmospheric Condition

Mashal Khan
U.S.-Pakistan Center for Advanced Studies in Energy, University of Engineering and Technology, Peshawar, Pakistan

Atif Sardar Khan*
Department of Mechatronics, University of Engineering and Technology, Peshawar, Pakistan
*Corresponding author

Sadaf Sardar
Department of Mechatronics, University of Engineering and Technology, Peshawar, Pakistan

M. Iftikhar Khan
Department of Electrical, University of Engineering and Technology, Peshawar, Pakistan

Abstract
Photovoltaic (PV) systems are increasingly popular as a renewable energy source due to their ability to directly convert sunlight into electricity. However, despite their numerous advantages, PV systems are susceptible to the negative impacts of partial shading. This can significantly affect the operational efficiency and energy output of the systems. When a PV system is some part is under shading and other receive direct light is known as partial shading. This shading can be caused by nearby structures, vegetation, or other objects that block sunlight and cast shadows on the system. Shading reduces the electrical output of shaded cells, degrading the PV system performance. Temperature and the intensity of sunlight also effects the PV modules efficiency. To increase the PV systems performance an algorithm utilized is Maximum Power Point Tracking (MPPT). The MPPT algorithm track the panels' maximum power point (MPP), which signifies the power generation capability. Through its adaptive nature, the MPPT algorithm maximizes power extraction from solar panels by adapting to varying environmental conditions for enhanced efficiency. Perturb and Observe (P&O), Incremental Conductance (InC), and Fuzzy logic algorithm represent different types of MPPT algorithms designed to maximize the power output of a solar photovoltaic (PV) system. These algorithms employ various methods to determine the Maximum Power Point (MPP), aiming to optimize the electricity generation from the PV system. By continuously monitoring and adjusting the operating point, the MPPT algorithm has an important role to ensure the efficient operation of a PV system. Utilizing the appropriate MPPT algorithm can enhance the system's utilization of solar energy and improve its overall performance. Researchers often use MATLAB/SIMULINK software for modeling and analyzing PV systems, especially in the context of a 1 kW system under alternative environmental circumstances.

Keywords
Solar, Algorithm, Maximum Power Point, Efficient Algorithm, Perturb and Observe, Incremental Conductance, Fuzzy Logic

1. Introduction
The photovoltaic (PV) power system is commonly employed in residential and industrial settings, converting sunlight into electricity through solar cells. It use is increasing due to its generation capability of electricity [1-6]. One key benefit of PV power is its independence from fossil fuels, unlike traditional power plants that heavily rely on sources like hydrocarbons and nuclear energy. By harnessing natural sunlight, PV systems offer a cost-free and eco-friendly energy alternative compared to fossil fuels, helping to safeguard the environment [7].

Traditional power plants such as hydro, diesel, and nuclear facilities are dependent on burning fossil fuels like coal, leading to significant environmental damage through pollution, global warming, and acid rain. In contrast, PV systems harness solar energy from sunlight, offering a cleaner alternative having no outcomes such as acid rain and global warming.

One drawback of PV systems is the partial or full shading effect on its power generation. The PV system configuration, shading levels, and efficiency of the system can be greatly influenced by the inclusion of bypass diodes [8-9].

Shading from factors like buildings and trees can result in the decline of PV modules efficiency, leading to energy losses and impacting the reverse bias within the cells [8-9]. When sunlight is obstructed, the electrons in the PV cells are not excited, resulting in decreased power generation. High temperatures can also have a significant impact over the decline in efficiency caused by shading and overheating [7-9].

The reduced efficiency of PV modules caused by obstructions like buildings, trees, and shading can lead to decreased short circuit current (I_{sc}), open circuit voltage (V_{oc}), and maximum power (P_{max}) of the PV system. This reduction can potentially damage the entire PV system. PV modules and batteries are critical and expensive components of standalone solar PV systems. Connecting batteries directly to PV modules without protection can shorten the battery lifespan due to the risk of overcharging. To address this issue, utilizing charge controllers such as MPPT connected to PV modules helps protect batteries from overcharging, ensuring optimal performance and longevity of the system.

To ensure optimal efficiency and increase the electricity supplied to batteries, PV module operation at MPPT is important [11-12]. Furthermore, DC/DC converters are utilized for charging the batteries. or operate the load, with MPPT algorithms powering PV modules. Several MPPT methods are reported (i.e. fuzzy logic, perturb and observe (P&O), and incremental conductance (InC) methods) for better performance of the PV system [12-13].

PV (Photovoltaic) systems journey started back in the 19th century. In 1839, Alexandre-Edmond Becquerel, a French physicist, introduced the photovoltaic effect. This groundbreaking discovery revealed the capability of certain substances to convert light into electricity. However, during the mid-20th century the PV technology began its progression. A pivotal moment occurred in 1954 when at Bell Laboratories, the scientist fabricated a silicon-based solar cell, with 6 % efficiency [10]. This achievement marked the dawn of new era of PV technology. Over the ensuing decades, continuous innovations propelled PV technology forward, enhancing both efficiency and cost-effectiveness. Initially designed primarily for space applications like powering satellites and spacecraft, photovoltaic (PV) systems have become more accessible due to improvements in manufacturing techniques and materials, leading to a reduction in the cost of solar cells. Nowadays, PV systems are commercially available for its use in residential, commercial, and utility-scale installations, to harness clean and renewable energy from sunlight. In order to optimize the power collection from the PV system, it depends on the algorithms for maximum power point tracking (MPPT). The main focus of the MPPT algorithm is to optimize power generation by ensuring that the PV system captures the full potential power available from sunlight.

Solar photovoltaic (PV) systems are widely used in utility-scale installations to capture clean and renewable energy from sunlight. To ensure optimal power generation and efficiency, these systems rely on the MPPT algorithm. The major goal of MPPT algorithm is to maximize power output by enabling the PV system to capture the full potential power available from sunlight. The performance of the PV system depends on the irradiance and temperature. The power output of a solar panel is directly linked to the voltage and current at its terminals. However, the voltage and current relationship is nonlinear, making it essential in determining the Maximum Power Point (MPP) where the power output is at its peak. Over time, MPPT algorithms performance and efficiency have improved. Examples of previous techniques include the Incremental Conductance (InC) and Perturb and Observe (P&O) algorithms. The advancements in MPPT technology have significantly improved the power generation capabilities of solar PV systems [6-8]. To maintain the Maximum Power Point (MPP), algorithms like Incremental Conductance (InC) and Perturb and Observe (P&O) dynamically adjust the operating voltage while monitoring power output. By enhancing tracking accuracy and response time, advanced MPPT algorithms have been developed, utilizing mathematical models, control theory, and optimization methods to optimize performance and adaptability. The MPPT algorithm plays a vital role in renewable energy systems by continuously tweaking PV system parameters to track the MPP effectively. This optimization process enhances power generation, boosts system efficiency, and maximizes solar energy utilization.

The research conducted by Djalab and Merzouk [14] is based on the reliability and environmental benefits of PV system. However, PV system performance is dependent upon solar radiation, system temperature, and its conFiguration. Understanding the impact of shadows on solar panels is essential for optimizing their performance. This knowledge is similar to recognizing how clouds can obstruct sunlight, influencing the energy production of solar panels. By comprehending these shadow effects, individuals can effectively conFig their solar panels to maximize electricity generation for their households. For the increase in efficiency of a solar power system, understanding the impact of partial shading is crucial. This occurs when certain modules in a system receive different levels of sunlight, often due to nearby structures, shading, or even cloud cover. By considering how partial shading, temperature variations, and sunlight intensity affect the IV and PV characteristics curve of solar panels, you can optimize your system's performance for maximum energy generation.

Kachhiya & Patel (2011) [15] explored to work on the analytical model of the Photovoltaic module. It was observed that the PV panels IV and PV characteristics curve impacted by PV system temperature. The output of the maximum power point can vary by adjusting these parameters, as sunlight energy/irradiance and temperature play key roles. The study shows that a MPPT algorithm (incremental conductance) integrated to A DC-DC Boost converter is designed to optimize the output power.

Beriber et al. (2013) [16] reports a comparison of four tracking of power strategies in their study. These techniques include Perturb and Observe (P&O), Incremental Conductance (InC), a fuzzy logic-based tracking strategy, and a technique that measures a current of PV system. Among these strategies, the fuzzy logic-based tracking technique is the least familiar. The issue except for the fuzzy logic, in all other algorithm is during a steady state. The losses in PV system are caused by the variation in the operating point near the peak power point. The Perturb and Observe (P&O) and Incremental Conductance (InC) methods are highlighted in the study. The comparative analysis shows that the fuzzy logic outperforms other algorithms.

In their study, Salman and Zhouyang (2018) [17] focused on the challenges associated with solar cells, such as initial costs, low-conversion efficiency, and intermittent power generation. They emphasized the impact of fluctuations in solar insolation levels and temperature impact the solar cells performance, leading to fluctuations in the maximum power point (MPP). The researchers aimed to address these issues by developing a battery charge controller based on microcontroller implementing a maximum power point tracker (MPPT) can enhance the power output of the solar PV system based on prevailing insolation and temperature conditions. The researchers set out to tackle these challenges by optimizing the PV system current and temperature condition through a microcontroller based on maximum power point tracker (MPPT). Among several MPPT techniques, the perturb and observe (P&O) method was chosen for its superior performance. In this study, an MPPT charge controller will be developed using a DC/DC buck converter and a microcontroller. A working model of the MPPT charge controller performance was evaluated with a lead acid battery and a 200-watt solar panel. Results revealed that in contrast to traditional charge controller, the MPPT controller for the PV panel significantly enhanced the panel's overall efficiency.

2. Model and Characteristics of a PV System

In an ordinary photovoltaic (PV) cell conFiguration, there are three key elements the resistors connection, a current source and a diode. The solar panel produced a current can be determined by the formula in equation (1). [18]:

$$I_{pv} = I_R - I_{d1} - I_{pe} \qquad (1)$$

Where PV system output current be represented by I_{pv}. While, I_R is the saturation current, I_{pe} is the shunt current, and I_{d1} represents the diode current

Moreover, equation (2) is further expressed by expanding a diode current:

$$I_{d1} = I_{01}\left[exp\, q\frac{(v_{pv+i_{pv}R_{se}})}{nKT} - 1\right] \qquad (2)$$

Where, I_{01} denotes the reverse saturation current, R_{se} is a series resistance, n is the diode factor, K is the Boltzmann constant = 1.3805 x 10^{-23} J/K, T represents a cell temperature, q is the electron charge = 1.6 x 10^{-19} C

Equation (3) provides the basic representation of the current by a PV cell.

$$I_R = \frac{W}{W_0}(I_c + \lambda\,(T - T_0)) \qquad (3)$$

Where, I_c is the short circuit current denotation, with W_0 and W representing reference irradiance and nominal irradiance, T_0 and T symbolize temperature and nominal temperature, respectively, and λ represent short-circuit current of the temperature coefficient.

As, V = 0 for the short-circuited terminal the current increases with an increase in light intensity as in equation (4)

$$i_{pv} = I_R - I_{01}\left[e\, q\frac{(v_{pv+i_{pv}R_{se}})}{nKT} - 1\right] - \frac{(v_{pv+R_{sc}i_{pv}})}{R_{pe}} \qquad (4)$$

Hence, reverse saturation current can be written as in equation (5)

$$I_{01} = I_{01ref}\,(\frac{T}{T_0})^3 e^{\left[\frac{qE_G}{nK}\left(\frac{1}{T} - \frac{1}{T_0}\right)\right]} \qquad (5)$$

Where E_G represents the the energy band gap = 1.12 eV.

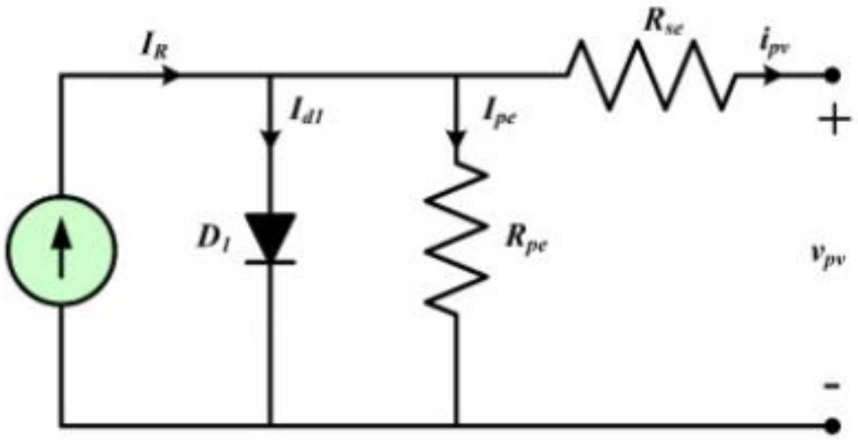

Fig. 1 Solar cell equivalent circuit

The 200 W solar panel rating is considered, where its specifications are provided in Table 1 below.

Table 1 PV Module Specification

Parameter	**Notation**	**Value**
Power	W	200
Voltage	Voc	33
Maximum voltage	Vmp	26
Current	Isc	8
Maximum current	Imp	7.6
Cells per module	N_{cell}	54

MATLAB software is utilized to model the specific information of a 200 W rated solar panel module. This leads to a detailed discussion on the solar PV model. In Fig 1, the PV system includes inputs for irradiance (Ir) and temperature (T), alongside positive and negative terminals for connecting with other components. The "m" designation represents the measurement port where voltage, current, irradiance, temperature, and diode current can be measured.

In the context of a solar PV module, with one parallel string and two series-connected modules per string, the resistor value can be calculated using the formula, $R = V/I$. By running the simulation, the current is determined to be I = 7.6 A, the voltage V = 26.4 V, and the power approx. 200 W, as depicted in Fig 3**.**

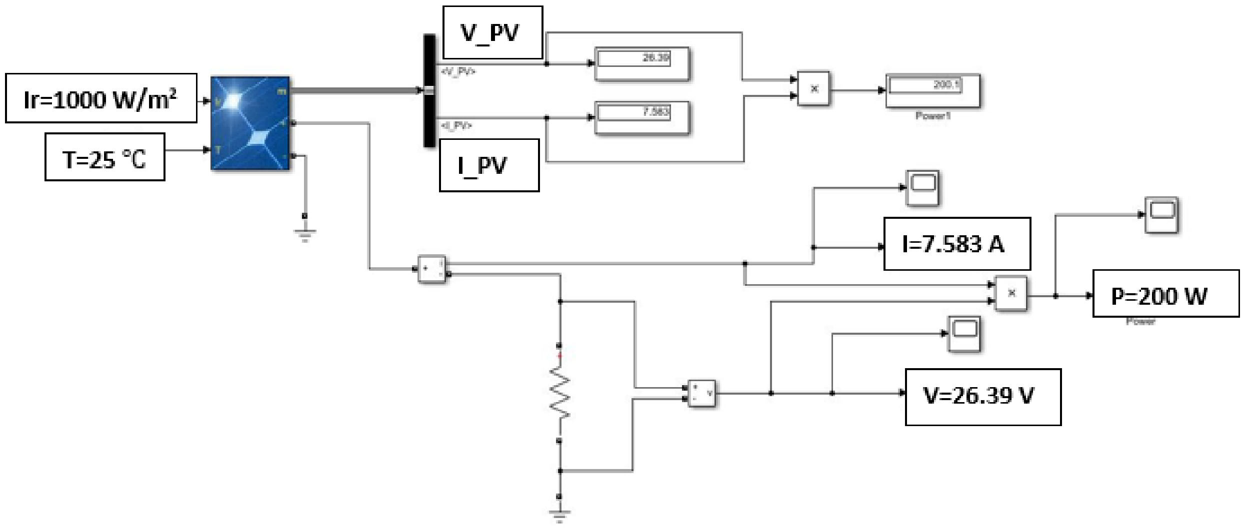

Fig. 2 Implemented PV system Simulink model

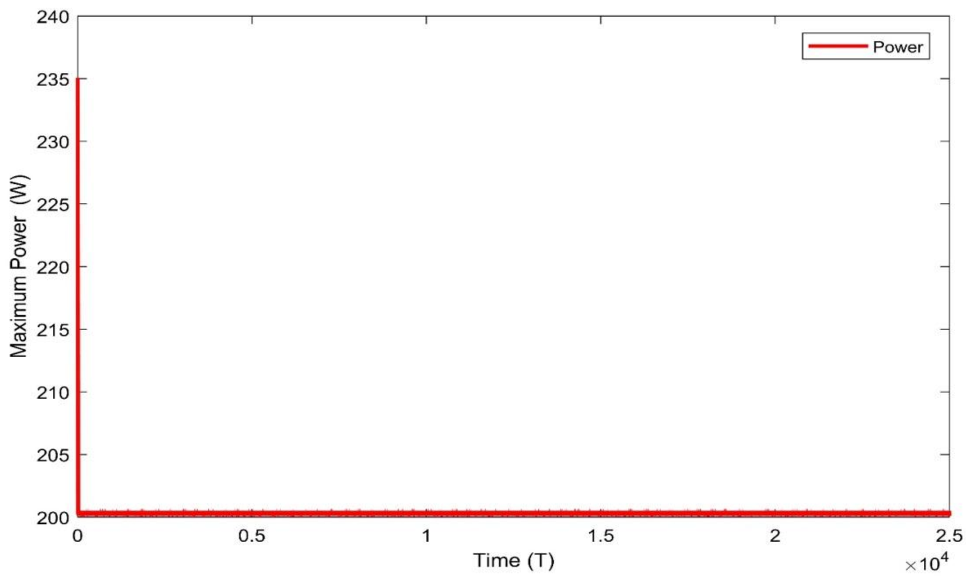

Fig. 3 PV Module Maximum Power

2.1 Solar System Standard Test Condition

A photovoltaic (PV) system design comprising of 6 modules, having a parallel two strings with 3 modules in each string, with series connection. MATLAB Simulink is used to carry out the model simulation focusing on the Kyocera Solar KC200GT modules under standard test condition (STC) for solar systems, as illustrated in Fig 4.

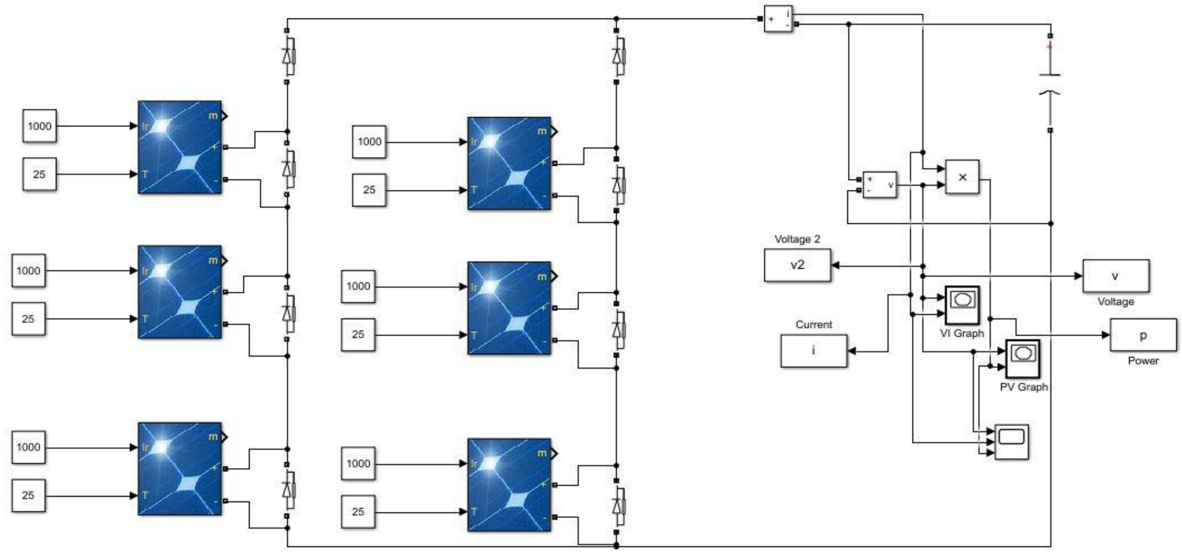

Fig. 4 Model of the Implemented PV system Simulink Model

The PV module utilized in this study, Kyocera Solar KC200GT, is detailed in table 2. Under the STC the IV and PV characteristics are simulated. The power generation capability of 6-module PV system (6 × 200 = 1200 W) reveals a current of 16.4 A (short-circuit) and voltage of Voc (open circuit) of 78.3 V. These characteristics are illustrated in Fig 5. Under 1000 W/m^2, the peak current of 16.42 A is attained at standard temperature, resulting in a maximum power output close to 1200 W at that moment.

Table 2 PV Module Specifications

PV KC200GT Characteristics	Notation	Rated Values
Power	W	200
Voltage	Voc	33
Maximum Voltage	Vmp	26
Cells per module	$Ncell$	54
Current	Isc	8.2
Maximum Current	Imp	7.6
Temperature coefficient of short-circuit current ($\%/deg.C$)	Isc	0.06
Temperature coefficient of open-circuit voltage ($\%/deg.C$)	Voc	-0.35502

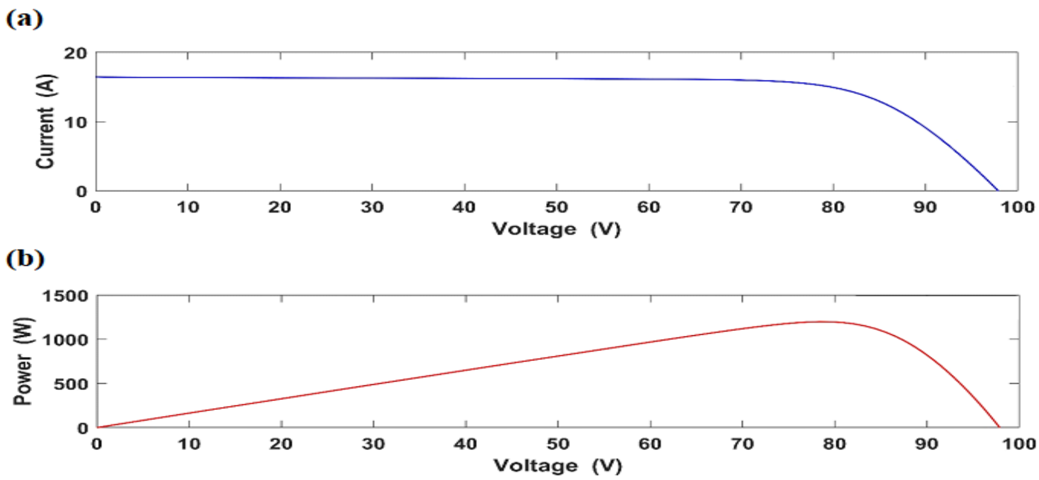

Fig. 5 Under STC condition: (a) IV and (b) PV characteristic of PV system

2.2 Partial Shading Effect on Solar Module

In a solar panel system, shading occurs when specific parts of the solar module are either partially or completely obscured, while other regions receive direct sunlight. This shading effect can be triggered by various elements like nearby trees, buildings, or even dust buildup on the surface of the module. To mitigate the negative impact of shading on solar panels, bypass diodes play a critical role. These electronic components are connected in parallel to individual solar cells or groups of cells within the module. When certain sections of a solar module are shaded and do not receive direct sunlight creates resistance which resulted a decline in the total power of the system. Bypass diodes provide a solution by offering a new pathway for the electric current to evade the cells under shade, empowering the unshaded cells to continue generating electricity. The feature is crucial in maintaining the efficiency of solar panels. The use of bypass diodes prevents shaded areas from diminishing the overall performance of the module, enabling it to generate maximum power even when subjected to partial shading. Without bypass diodes, shaded sections would considerably reduce the module's output, ultimately decreasing the total energy production. Bypass diodes play an important role in ensuring optimal performance and enhancing the power output of solar panels, especially in situations where partial shading is inevitable. A visual representation in Fig 6 illustrates the impact on the IV and PV curves when shaded conditions occur. When shading impacts a photovoltaic (PV) module, the output IV and PV curve reveal a decrease in the total power generation.

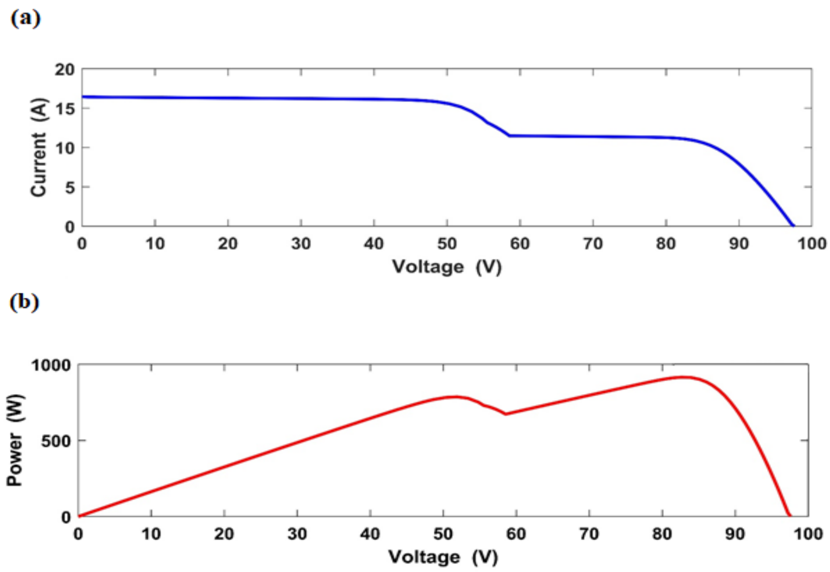

Fig. 6 Under Partial shading condition: (a) IV and (b) PV Characteristic of photovoltaic system

2.3 The Effect of Temperature and Sunlight Intensity on Solar Modules

A solar cell is basically a device made up of semiconductor material that converts solar energy into electricity. In this context, Iph denotes the current generated by light in the solar cell, R_{sh} and R_s indicate the internal resistance in series and in parallel with the battery, respectively. The equation for the solar cell I - V characteristics is as follows

The equation for the I-V characteristics of the solar cell is as follows:

$$I = I_{ph} - I_{sat}\left[\exp\left(\frac{q(V+IR_s)}{AKT}\right) - 1\right] - \frac{V+IR}{R_{sh}} \qquad (6)$$

In equation (6), A represents the ideal solar cell parameter with a value of 1. The symbols for Boltzmann constant (1.3806 x 10^{-23} J/K) is K, q for the electric charge (1.6 x 10^{-19} C), and T for the reference temperature of the solar cells. I_{ph} and I_{sat} represent the currents generated by light sources and reverse saturation currents of solar cells, respectively. Depending on the operations the photovoltaic system P-V curves can have different shapes, as the efficiency of solar panels is impacted by the surrounding temperature and the intensity of sunlight. Under varying temperatures as depicted in Fig 7 (a) and Fig 7 (b) shows the I-V characteristic curve and P-V, respectively, of solar modules. Analysis of the curve reveals that with an increase in ambient temperature, there is a notable decrease in the voltage (open-circuit) of solar modules, while the current (short-circuit) shows minimal variation. This information can guide us in deciding when to make use of solar modules and when to refrain from doing so under high-temperature conditions, as it impacts the output power levels.

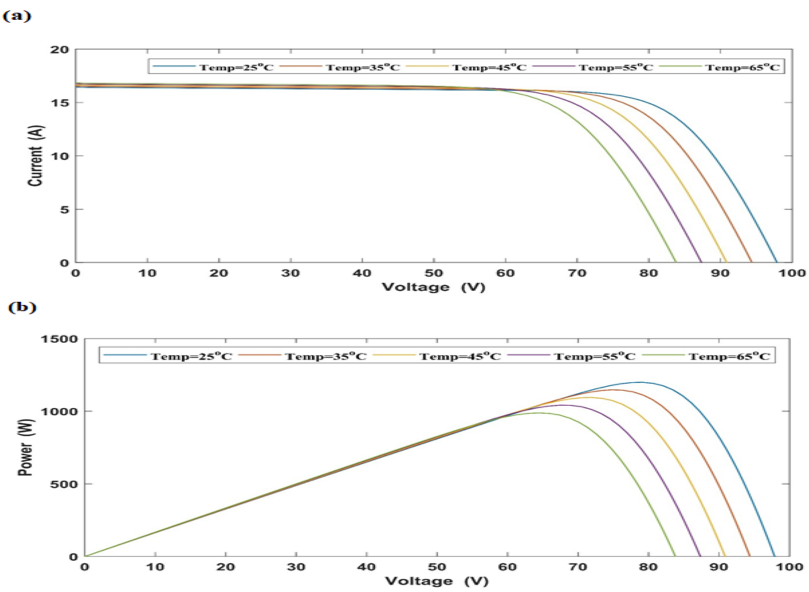

Fig. 7 Different temperature of solar modules: (a) IV curves, and (b) PV characteristic curves

Furthermore, the PV module characteristic curve can vary with the variation in light intensity on the module. The solar modules I-V and P-V characteristic curves are depicted in Fig 8 (a) and Fig 8 (b), respectively, under fixed temperature conditions and varying levels of sunshine intensity. By examining these curves, we can predict how changes in sunshine intensity will affect the output power of the solar modules, determining whether it will increase or decrease accordingly.

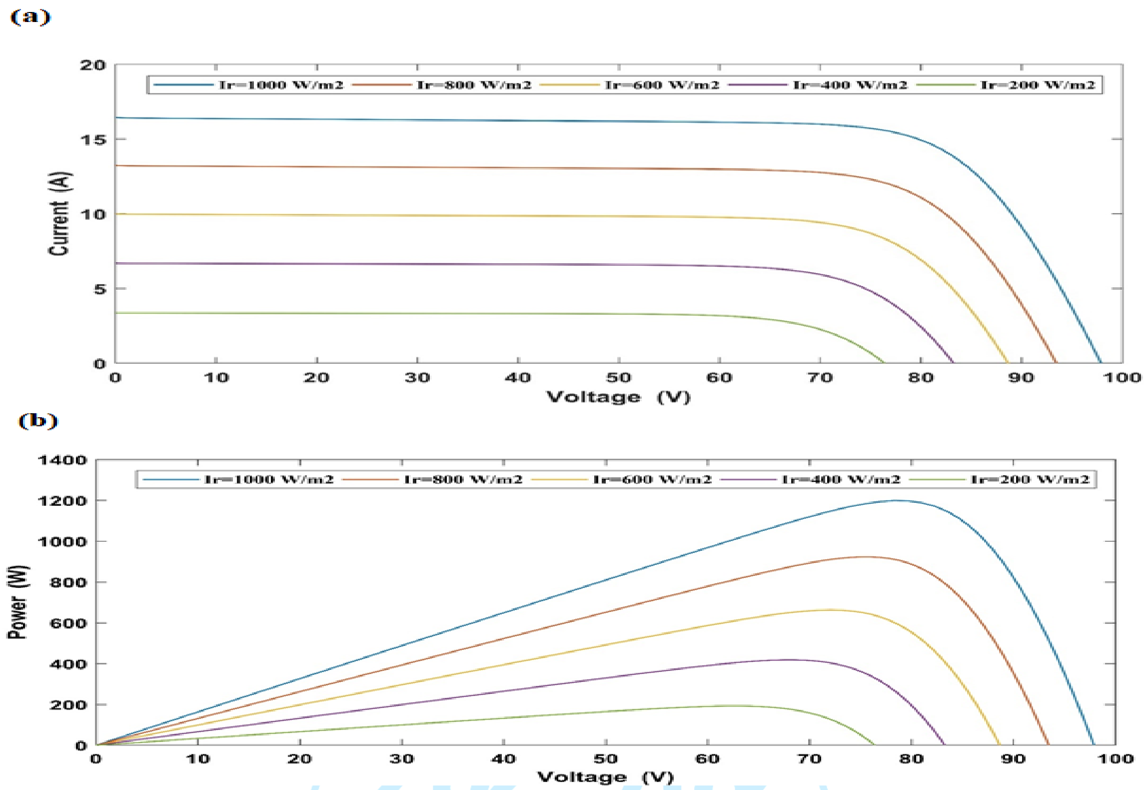

Fig. 8 Different intensity of solar modules: (a) IV curves, and (b) PV characteristic curves

2.4 Maximum Power Point Tracking

The MPPT measures the voltage (V_k) and current(I_k) . It then calculates the power (p_k) to compares it with the prior value $(p_k - 1)$ to find the difference, known as Δpk. A Δpk of zero signifies that the PV cell is operating at the maximum power point (MPP). On basis of the polarity of Δp_k and ΔV_k, adjustments are made to the command voltage for regulating the converter duty cycle (δ). The PV cells operational point is adjusted towards the Maximum Power Point (MPP), enhancing power output. The methodology is demonstrated in the flowchart presented in Fig 10. With the information provided above, we are able to create and simulate the circuit. The schematic diagram is depicted in Fig 9.

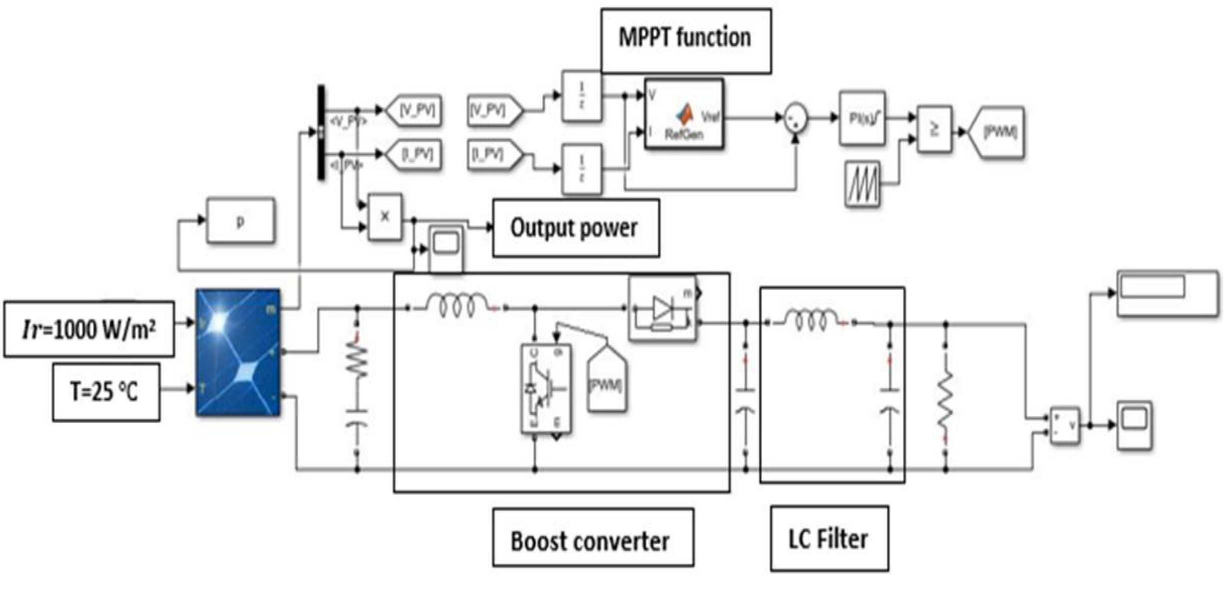

Fig. 9 Implemented MPPT Simulink Model

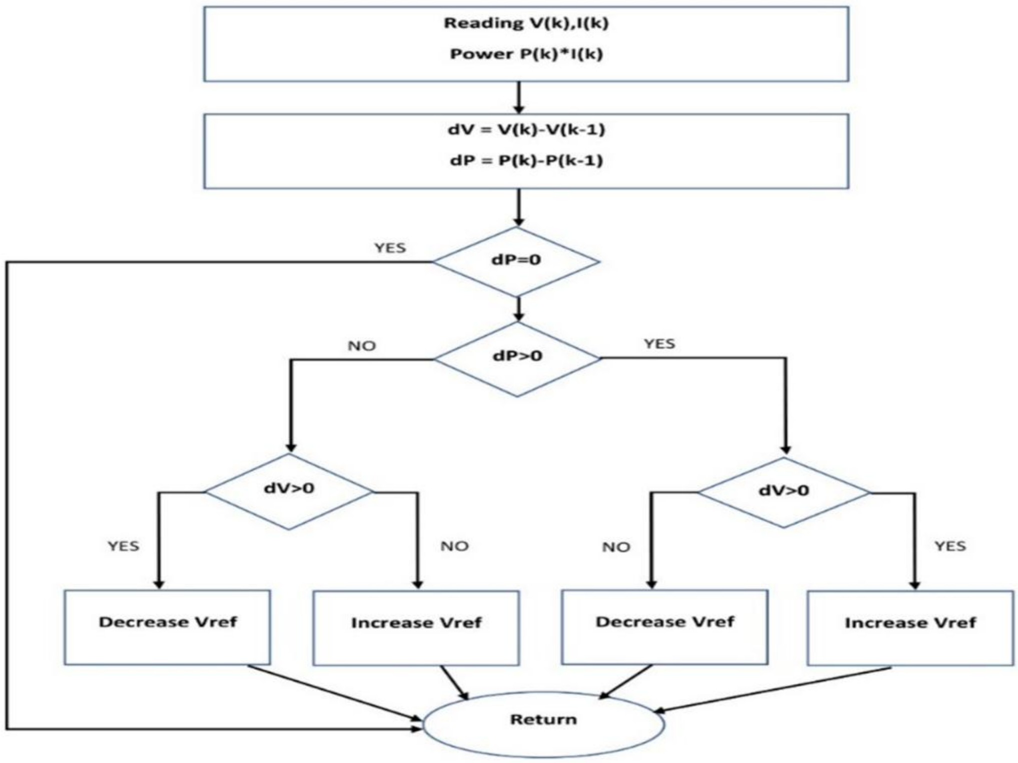

Fig. 10 Flowchart of the MPPT

When sunlight falls on PV cells, the resulting output power is impacted by the generated voltage and current. The Maximum Power Point (MPP) signifies the peak power production point of the solar panel. However, changes in temperature and sunlight intensity lead to fluctuations in the Maximum Power Point (MPP) during the course of the day. Fig 11 illustrates the power output characteristics of Maximum Power Point Tracking (MPPT). MPPT techniques strive to enhance the solar power systems efficiency that can lead to increased energy efficiency and reduced electricity costs for both residential and commercial use. In a research study, four distinct MPPT algorithms were extensively examined through MATLAB simulations.

In the context of enhancing solar power system efficiency, it is important to consider different conditions such as solar irradiance (Ir) in W/m^2 and temperature (T) in $°C$. For instance, when the solar irradiance is 1000 W/m^2 and then drops to 800 W/m^2 and subsequently decreases to 600 W/m^2, the resulting Maximum Power Point Tracking (MPPT) output power also changes accordingly. Another crucial factor is the temperature variation, where transitioning from 25 $°C$ to 35 $°C$ and finally reaching 45 $°C$ will have a negative impact over the output MPPT power and hence decreasing it. Therefore, the combined impact of these conditions on the output power is depicted in Fig 11.

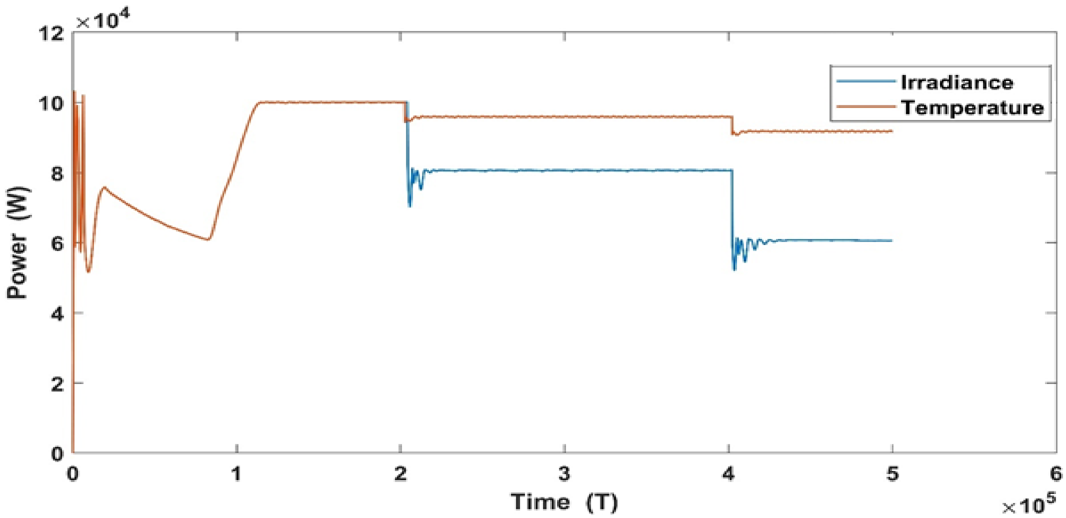

Fig. 11 Impact of variation in temperature and irradiance over the output power of MPPT

3. Maximum Power Point Tracking Algorithms

MPPT is a technique utilized in PV inverters to dynamically modify the impedance of the solar array, ensuring that the PV system operates at its optimal power point amid fluctuations in factors such as solar irradiance, temperature, and load.

3.1 Perturb and Observe Algorithm

The perturbation and observation approach is employed for its user-friendly nature. This method involves PV cells output voltage adjusting to steer the system towards its maximum power point using the P&O algorithm. Implementation of the algorithm (i.e. P&O) in MATLAB Simulation can be visualized through a flow chart, depicted in Fig 12. The P&O algorithm involves adjusting the PV cells output voltage to find the direction that maximizes power. The increment in power results in the adjustment of voltage; conversely, the decrease in power, reverses the adjustment direction. The process is repeated until the power maximum point is achieved, after which the system stabilizes around the MPP.

The two crucial factors to take into account are Sun irradiance (I_r) and temperature (T). When the irradiance is 1000 W/m^2 and then decreased to 800 W/m^2 and further down to 600 W/m^2, it influences the current, voltage, and maximum output power. Similarly, changing the temperature from 25 ℃ to 35 ℃ and then to 45 ℃ results in a slight decline in the power as the temperature rises, as indicated in Fig 13.

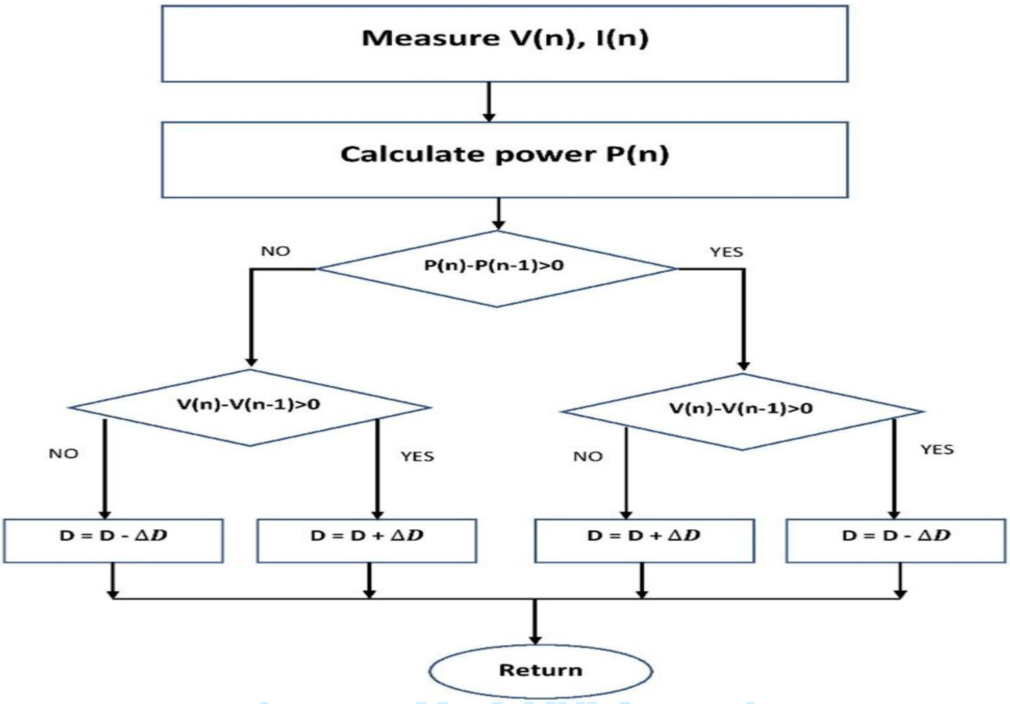

Fig. 12 P&O algorithm flowchart [11]

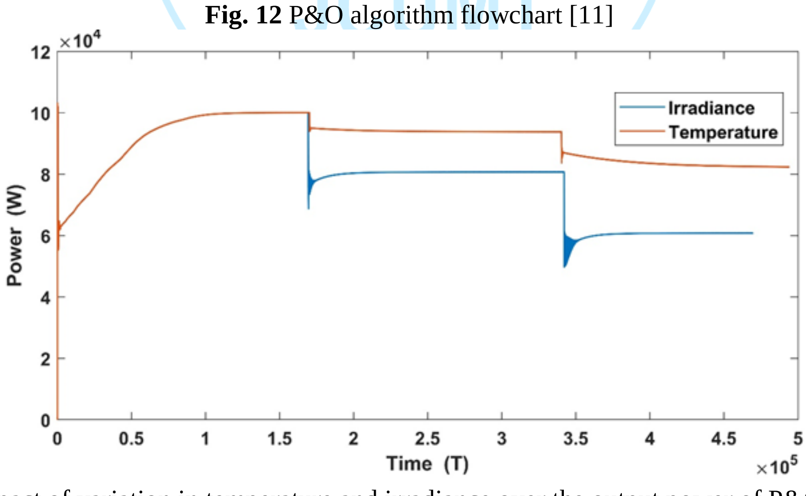

Fig. 13 Impact of variation in temperature and irradiance over the output power of P&O algorithm

3.2 Incremental Conductance Algorithm

Photovoltaic MPPT systems harness the power of the sun through the use of the Incremental Conductance algorithm, ensuring optimal operation of the PV system at its peak power production level. The implementation of the Incremental Conductance (InC) algorithm in MATLAB Simulation is illustrated in Fig 14, aiding in optimizing the PV system efficiency.

This algorithm is essential for optimizing the Photovoltaic (PV) system efficiency of maintaining the PV system operating at its maximum power point (MPP) during peak power production. The utilization of this algorithm comprises a series of steps:

1. Take regular readings of the PV system's voltage (V) and current (I).
2. Measure an instantaneous power (P) by multiplying V and I.
3. Identify the incremental conductance (dP/dV) by calculating the power variance over the voltage differentiation (P/V).

4. Compare the incremental conductance with zero. If it equals zero, the position of the system is already at the Maximum Power Point (MPP). The operational point is to the left of the MPP, if a value is positive while a negative value indicates it is to the right of the MPP.
5. In practical application, the algorithm involves the DC-DC converter duty cycle adjustment on the basis of the incremental conductance value. If the incremental conductance is positive, indicating Maximum Power Point (MPP) operational point is to the left, the duty cycle is decreased. Conversely, if the incremental conductance is negative, showing that the MPP operational point to the right, the duty cycle is increased. This adjustment allows the matching of the load voltage to the voltage of the DC-DC converter and photovoltaic (PV), optimizing the system for peak power production. The resulting output power alignment can be visualized as demonstrated in Fig 15.

The PV system performance is significantly impacted by two key factors: sun irradiance (Ir), in W/m^2 and temperature (T) in $°C$. The light intensity initially is 1000 W/m^2 to 800 W/m^2 and subsequently decreased to 600 W/m^2, variations in current, voltage, and maximum output power can be identified. Likewise, the temperature from 25 °C is increased to 35 °C and finally 45 °C is attained resulting a decrease in output power, as depicted in Fig 15. These findings emphasize the importance of adjusting system parameters to adapt to external environmental changes for optimal power generation.

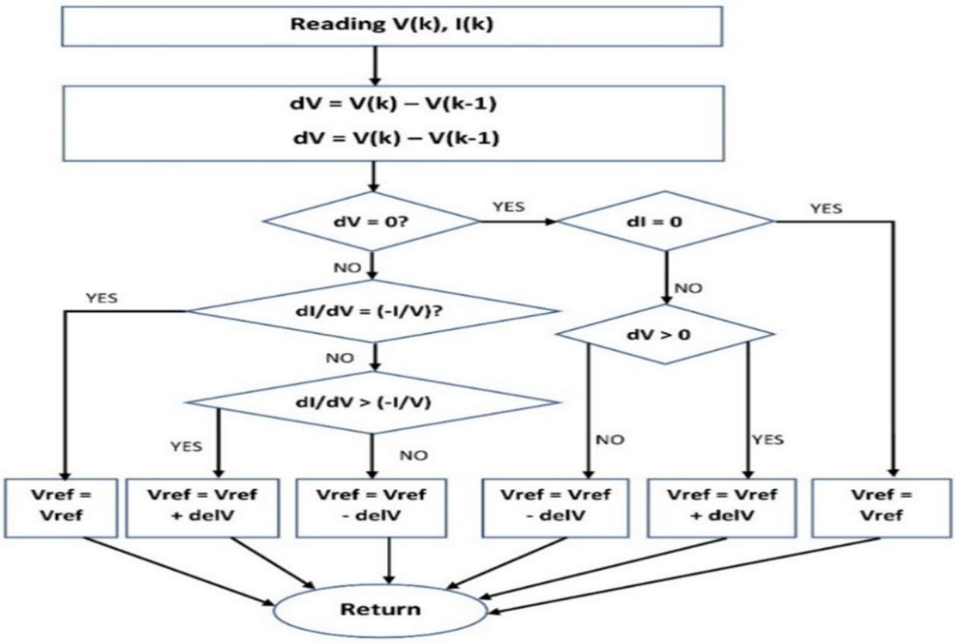

Fig. 14 Flowchart of the Incremental conductance (InC) algorithm

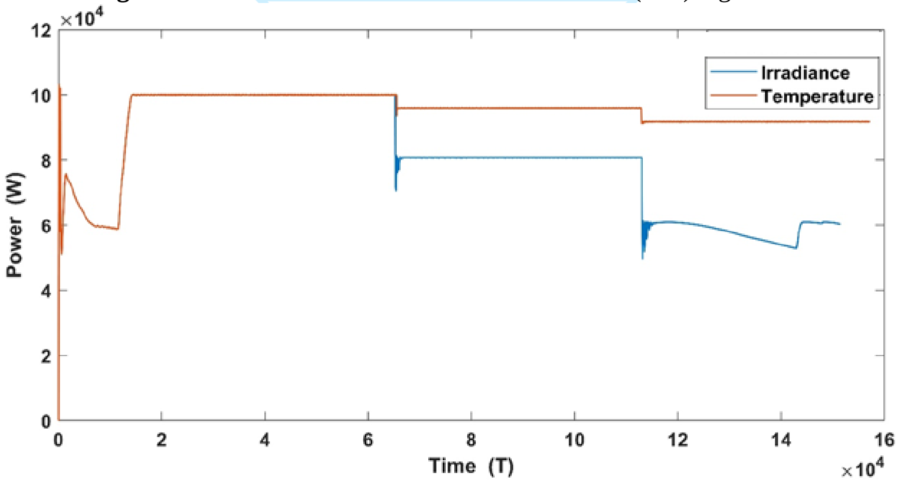

Fig. 15 Output power of the InC algorithm under varying irradiance and temperature

3.3 Fuzzy Logic Algorithm

A computational method known as fuzzy logic is utilized to handle imprecise and uncertain data. Utilizing fuzzy sets and rules, decisions and control systems are developed using fuzzy logic techniques. Here is a breakdown of the stages in a fuzzy logic algorithm:

1. Identify the particular issue or decision that requires attention.
2. Identifying input and output variables involves selecting the variables that will serve as inputs and outputs for the fuzzy logic system. The system in question includes an input two variables, $\Delta \text{Vpv}[\text{i/p}]$ and $\Delta P\text{pv}[\text{i/p}]$, output one variable $\Delta \text{Vpv} * [\text{o/p}]$ are as shown in table 3.

Table Error! No text of specified style in document. PV cells fuzzy rule

$\Delta \mathbf{Vpv} * [\mathbf{o/p}]$	$\Delta \mathbf{Vpv}[\mathbf{i/p}]$					
		NB	NS	ZE	PS	PB
$\Delta \boldsymbol{P}\mathbf{pv}[\mathbf{i/p}]$	NB	PS	PB	NB	NB	NS
	NS	PS	PS	NS	NS	NS
	ZE	ZE	ZE	ZE	ZE	ZE
	PS	NS	NS	PS	PS	PS
	PB	NS	NB	PB	PB	PS

3. Generate fuzzy sets based on the input and output variables utilizing membership functions to define the level of membership for each set member. The five fuzzy sets include Negative Big (NB), Negative Small (NS), Zero Equivalent (ZE), Positive Small (PS), and Positive Big (PB), as depicted in Fig 16. Developing guidelines to specify the correlation between input and output variables is crucial for formulating fuzzy rules.
4. Transform the input values into fuzzy values by allocating membership degrees to each fuzzy set based on the input values.
5. Combine the membership levels of input variables using logical operators (AND, OR) to analyze fuzzy rules.
6. Synthesize a fuzzy output by consolidating the results obtained from the fuzzy rules. Approaches such as max-min or max-product can be employed for this purpose.
7. Utilize a defuzzification strategy to convert the fuzzy output into a definitive numerical value. Typical defuzzification techniques include the weighted average, centroid, and mean of maximum.
8. Based on the defuzzified output, choose the most appropriate action to effectively tackle the current problem.
9. Assess the efficiency of the fuzzy logic algorithm and make necessary adjustments to enhance the results. Fig 17 display the fuzzy logic algorithm's output voltage $\Delta \mathbf{Vpv} * [\mathbf{o/p}]$ of fuzzy logic algorithm.

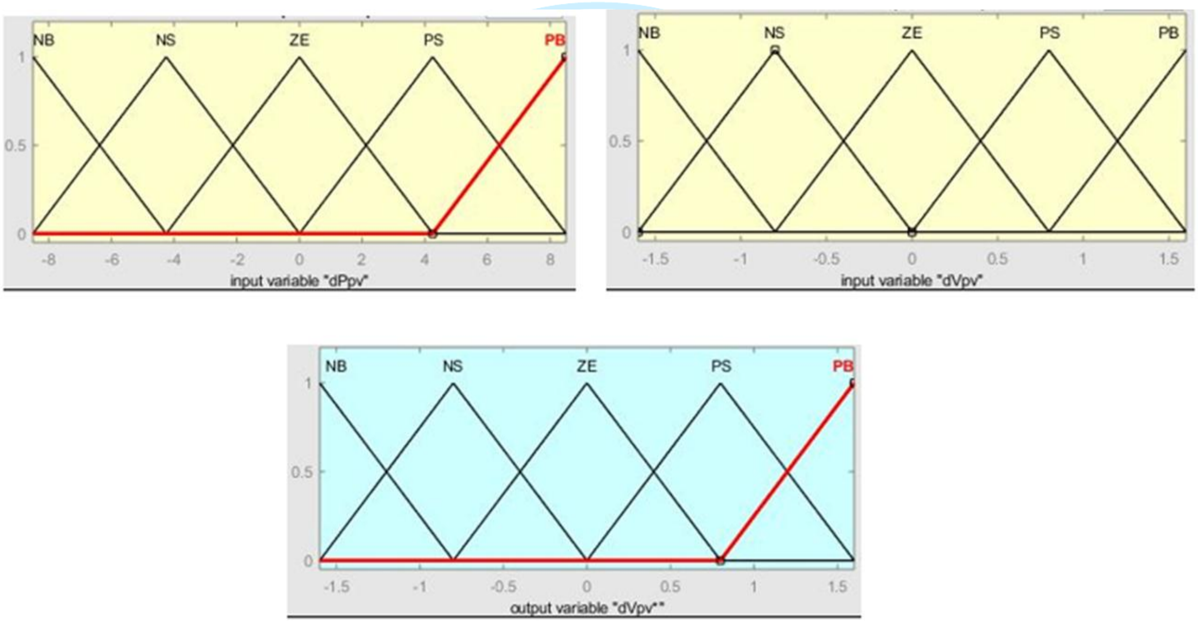

Fig. 16 Memberships functions

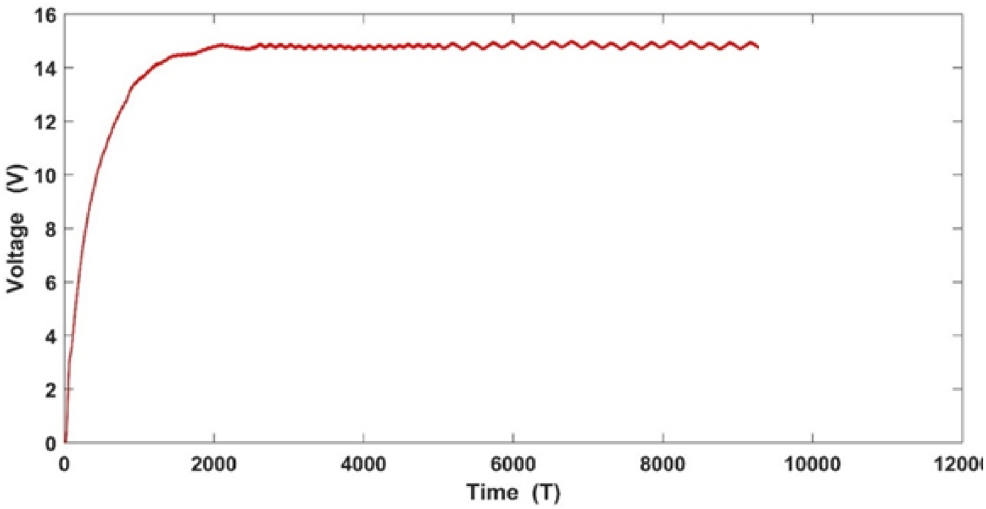

Fig. 17 Fuzzy logic algorithm output voltage

4. MPPT Algorithms Comparative Analysis

Finally, the outcomes of different MPPT algorithms are evaluated to determine which one provides an efficiently harvested maximum power. The P&O algorithm stands out the most utilized MPPT methods, fine-tuning the PV module operating voltage to reach the optimum power point with minimal disruptions. On the other hand, InC and fuzzy logic algorithms are more convenient and implementable in MATLAB Simulink, but they exhibit a higher distortions, as depicted in Fig 18.

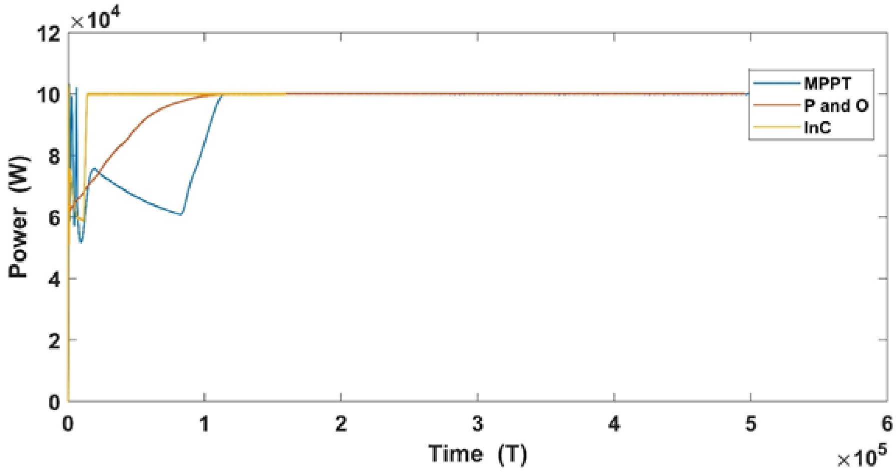

Fig. 18 Algorithms output power

In the provided environment, the power decreases in the P&O algorithm compared to the InC and fuzzy logic algorithms. The results of reported results are elaborated in Table 4.

Table 4 MPPT algorithms comparative analysis

Algorithm	Parameters sensed	Convertor used	Accuracy	Complexity to implement	Performance at different atmosphere condition	Converg. speed	Eff.	Ref.
MPPT		DC-DC	Less	Less	Reduce	Normal	97.8%	[15]
P&O		DC-DC	Medium	Less	Reduce	Varies	98%	
InC		DC-DC	Medium	Less	Reduce	Medium	98.7%	
Fuzzy logic			High		Reduce	Fast	99 %	
MPPT	Current, Voltage	DC-DC						[16]
P&O		DC-DC						
InC		DC-DC						
Fuzzy logic		DC-DC						
InC	Current, Voltage			Medium				[17]
Fuzzy logic	Voltage			High				
MPPT							97.8%	[This work]
P&O	Current, Voltage	DC-DC	High				98.1%	
InC	Current, Voltage	DC-DC	High				98.7%	
Fuzzy logic	Voltage	DC-DC	High				99.4%	

References

1. Khan, A. S., & Khan, F. U. (2022). A wearable solar energy harvesting based jacket with maximum power point tracking for vital health monitoring systems. *IEEE Access*, *10*, 119475–119495. https://doi.org/10.1109/access.2022.3220900
2. Khan, A. S., & Khan, F. U. (2021). A survey of wearable energy harvesting systems. *International Journal of Energy Research*, *46*(3), 2277–2329. https://doi.org/10.1002/er.7394
3. Khan, A. S., & Khan, F. U. (2021b). Experimentation of a wearable Self-Powered jacket harvesting body heat for wearable device applications. *Journal of Sensors*, *2021*, 1–22. https://doi.org/10.1155/2021/9976089
4. Bakhtiar, S., Khan, F. U., Rahman, W. U., Khan, A. S., Ahmad, M. M., & Iqbal, M. (2022). A Pressure-Based electromagnetic energy harvester for pipeline monitoring applications. *Journal of Sensors*, *2022*, 1–16. https://doi.org/10.1155/2022/6529623

5. Wahad Ur Rahman, Atif Sardar Khan, & Farid Ullah Khan. (2024). Analytical and FEA of piezoelectric vibration energy harvester for IoT-based railway track. *JOURNAL OF LIAONING TECHNICAL UNIVERSITY (NATURAL SCIENCE EDITION)*, *18*(4), 34–45.
6. Wahad Ur Rahman, Basit Iqbal, Atif Sardar, & Farid Ullah Khan. (2024). A Solar powered Radio Frequency Based Wireless Sensor Network for Pneumatic and Gas Pipeline Monitoring. *Journal of Xi'an Shiyou University, Natural Science Edition*, *20*(1), 629–637.
7. Zulfiqar Ali Ramzan, Atif Sardar Khan, Wahad Ur Rahman, Sadaf Sardar, & Farid UllahKhan. (2024). An Environmental Remediation: Approach for Clean and Eco-Friendly Renewable Energy. *Journal of Xi'an Shiyou University, Natural Science Edition*, *20*(1), 888–901.
8. Pachpande, S. G., & Zope, P. H. (2012). Studying the effect of shading on Solar Panel using MATLAB. *International Journal of Science and Applied Information Technology*, *1*(2).
9. Teo, J., Tan, R., Mok, V., Ramachandaramurthy, V., & Tan, C. (2018). Impact of partial shading on the P-V characteristics and the maximum power of a photovoltaic string. *Energies*, *11*(7), 1860. https://doi.org/10.3390/en11071860
10. Reddy, G. S., Reddy, T. B., & Kumar, M. V. (2017). A MATLAB based PV Module Models analysis under Conditions of Nonuniform Irradiance. *Energy Procedia*, *117*, 974–983. https://doi.org/10.1016/j.egypro.2017.05.218.
11. Fialho, L., Melicio, R., Mendes, V., Figueiredo, J., & Collares-Pereira, M. (2014). Effect of shading on series solar modules: Simulation and experimental results. *Procedia Technology*, *17*, 295–302. https://doi.org/10.1016/j.protcy.2014.10.240
12. Patel, H., & Agarwal, V. (2008). MATLAB-Based modeling to study the effects of partial shading on PV array characteristics. *IEEE Transactions on Energy Conversion*, *23*(1), 302–310. https://doi.org/10.1109/tec.2007.914308.
13. Gambino, M. (2013, December 8). Document Deep Dive: The patent for the first practical solar cell. *Smithsonian Magazine*. https://www.smithsonianmag.com/innovation/document-deep-dive-patent-first-practical-solar-cell-1-180947906/
14. Aicha DJALAB, Noureddine BESSOUS, Mohamed Mounir REZAOUI, & Imad MERZOUK (Eds.). (2018). *Study of the Effects of Partial Shading on PV System*. nternational Conference on Communications and Electrical Engineering (ICCEE), El Oued, Algeria. https://doi.org/10.1109/CCEE.2018.8634512
15. Kachhiya, K., Patel, S., Lokhande, M., & Patel, M. (2011). *MATLAB/Simulink model of solar PV module and MPPT algorithm*. National Conference on Recent Trends in Engineering & Technology.
16. Beriber, D., & Talha, A. (2013). *MPPT techniques for PV systems*. 4th International Conference on Power Engineering, Energy and Electrical Drives. https://doi.org/10.1109/powereng.2013.6635826.
17. Salman, S., Ai, X., & Wu, Z. (2018). Design of a P-&-O algorithm based MPPT charge controller for a stand-alone 200W PV system. *Protection and Control of Modern Power Systems*, *3*(1). https://doi.org/10.1186/s41601-018-0099-8
18. Das, P., Mohapatra, A., & Nayak, B. (2017). Modeling and characteristic study of solar photovoltaic system under partial shading condition. *Materials Today: Proceedings*, *4*(14), 12586–12591. https://doi.org/10.1016/j.matpr.2017.10.066.