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MATLAB BASED MPPT OPTIMIZATION FOR ENHANCING PV SYSTEM PERFORMANCE UNDER PARTIAL SHADING CONDITIONS

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ABSTRACT

Partial shading in PV systems significantly reduces performance by introducing multiple local maxima in the voltage current characteristics, leading to power loss and decreased efficiency. While traditional methods such as bypass diodes and MPPT aim to mitigate these effects, they often fall short, especially under complex or dynamic shading conditions. This paper presents a novel approach using optimization algorithms to address the impact of partial shading in PV systems. The proposed method utilizes simulation models to predict and identify shading patterns, with optimization techniques dynamically adjusting the system's configuration and operating points to maximize power output. The approach is validated through MATLAB simulations, incorporating irradiance, temperature, and shading data to train the models. Simulation results show significant improvements in energy conversion efficiency compared to conventional methods, with faster adaptation to changing shading conditions. The paper also discusses the advantages and challenges of implementing optimization-based strategies for real-time PV monitoring and control.

Keywords— PV Array, Fuzzy logic controller, boost converter, Maximum power point tracking.

1. INTRODUCTION

PV energy generation plays a pivotal role in renewable energy systems, significantly contributing to the reduction of carbon emissions and fostering sustainable development. The performance of PV systems is highly dependent on consistent and optimal solar irradiance. However, partial shading, caused by factors such as clouds, nearby buildings, or trees, can drastically reduce the efficiency of PV arrays. Under partial shading, the VI characteristics of the modules become non-ideal, often producing multiple local maxima on the power curve. This phenomenon, known as partial shading, leads to energy losses and reduced conversion efficiency, presenting a major challenge in maximizing the energy yield of PV systems [1], [2].

Traditional methods such as bypass diodes and MPPT are commonly used to mitigate partial shading effects. However, these approaches have limitations in dynamic and complex shading scenarios, as they primarily address electrical characteristics without accounting for the changing environmental conditions influencing shading patterns. Moreover, conventional MPPT techniques may struggle to identify and track the global maximum power point when multiple peaks appear due to partial shading [3].

In contrast, Artificial Intelligence techniques, particularly machine learning and optimization algorithms, have emerged as more effective solutions for improving PV system performance under partial shading conditions. AI models can predict and detect shading patterns in real-time, enabling adaptive adjustments to the system's operating points and configuration for optimal power generation. Machine learning models, such as decision trees, support vector machines, and neural networks, have demonstrated significant potential in forecasting shading conditions and enhancing PV system operation [4]. Additionally, optimization algorithms, including genetic algorithms and PSO have been applied successfully to identify the optimal configuration that minimizes shading effects and maximizes power output [5], [6].

This paper introduces an AI-driven approach that combines machine learning for shading detection and prediction with optimization techniques for real-time system configuration adjustments. Using MATLAB simulations, we validate the proposed method, demonstrating its effectiveness in reducing the impact of partial shading, enhancing energy conversion efficiency, and ensuring improved performance across a range of environmental conditions.

How a PV Cell Works

The operation of a PV cell is based on the photoelectric effect, where light energy causes the ejection of electrons from a material. In the case of a PV cell, sunlight absorbed by the semiconductor material, usually silicon, excites the electrons. When the energy from the absorbed light exceeds the material's bandgap energy, electrons move from the valence band to the conduction band, creating electron-hole pairs.

The p-n junction within the PV cell, which is formed by doping the silicon, generates an electric field that drives the movement of these free electrons in a specific direction. This flow of electrons results in an electric current. The current is collected through metal contacts on the top and bottom surfaces of the cell, while the electric field at the junction also creates a voltage across the cell.Together, the current and voltage enable the generation of usable power [7].

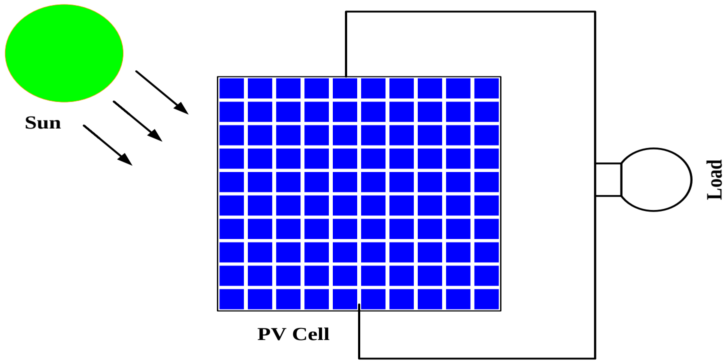

Figure 1 Working of PV Cell

PV cells are primarily made from monocrystalline or polycrystalline silicon, the most commercially viable materials. These cells are designed as a thin layer of silicon with one side doped to form the p–n junction. Their efficiency and performance depend on factors like material purity, sunlight intensity, and manufacturing processes.

2. PROPOSED SYSTEM

PV System Modeling Under Partial Shading

Partial shading introduces non-uniform irradiance across PV modules, causing disruptions in current generation and leading to reduced efficiency. This performance degradation occurs due to mismatched currents in series-connected cells and voltage discrepancies in parallel strings. The equivalent circuit of a PV cell under partial shading consists of a current source, a diode, series resistance, and shunt resistance. The output current of the PV cell can be expressed by the following equation:

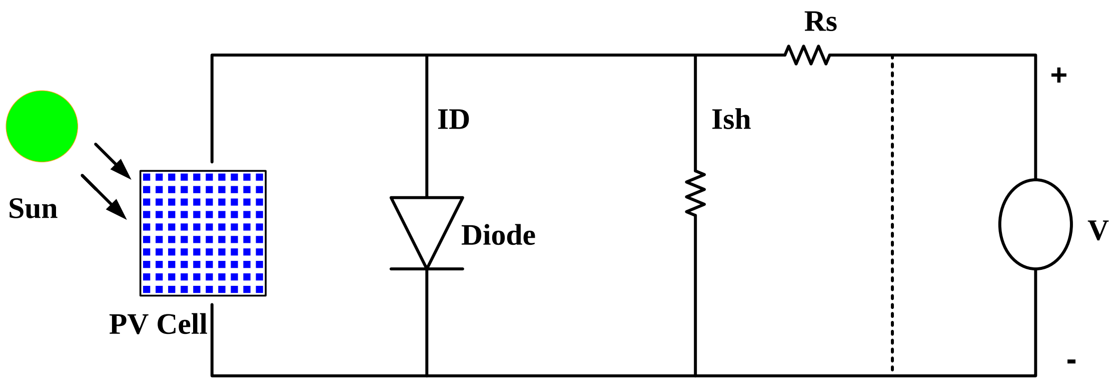

Figure 2 The equivalent circuit of the PV module

$$I_{ph} = I_d + I_{sh} + I \tag{1}$$

The current in the diode is offer via:

$$I_d = I_0 \left[\exp\left\{\frac{V + RI}{V_i a}\right\} \text{-1}\right] \tag{2}$$

The current R resistance is offered via:

$$I_{sh} = \left(\frac{V + R_s I}{R_{sh}}\right) \tag{3}$$

From equation, we get the expression of current I:

$$I = I_{ph} - I_d - I_{sh} \tag{4}$$

Changing (4) in the equation (2) and (3) the characteristics equation become:

$$I = I_{ph} - I_0 \left[\exp\left\{\frac{V + R_s I}{V_i a}\right\} \text{-1}\right] - \left(\frac{V + RI}{R_{sh}}\right) \tag{5}$$

Where the junction thermal voltage V_t is defined by:

$$V_t = \frac{N_t KT}{q} \tag{6}$$

Table 1 PV MODULE PARAMETERS

Parameters	Symbol	Value
Maximum Power	Pm	255
Open Circuit Voltage	Voc	37.6
Short Circuit Current	Isc	9.09
Voltage At MPP	Vmp	30.4
Current At MPP	Imp	8.39

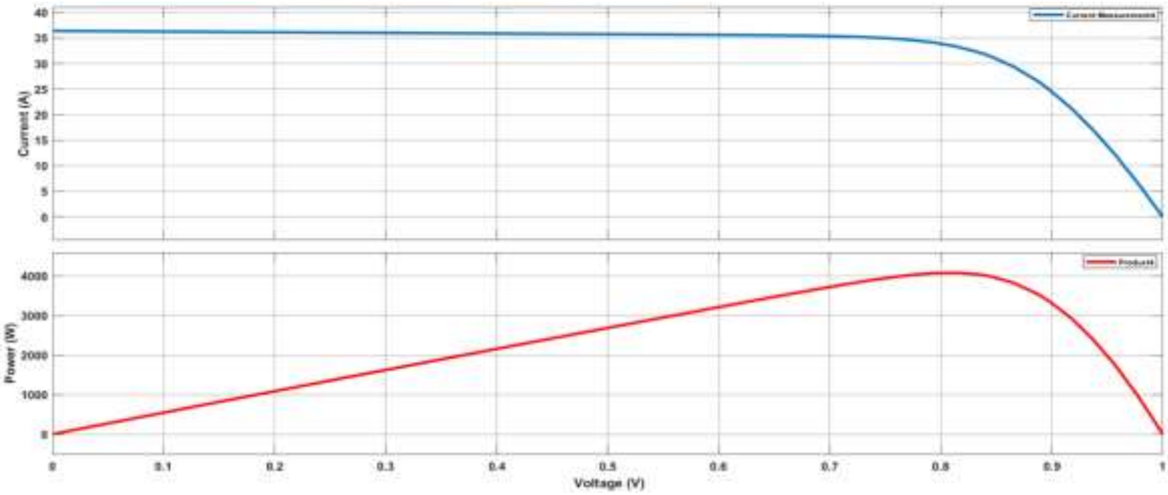

Figure 3 I-V and P-V characteristics of model a PV module under STC (25^0C and 1000W/m^2)

3. RESEARCH METHODOLOGY

1. Configuration of PV Module

The Total Cross-Tie (TCT) configuration is an advanced method for connecting PV (PV) arrays, designed to increase energy efficiency, minimize mismatch losses, and boost reliability. It excels at reducing power losses caused by partial shading or module degradation when compared to the traditional series-parallel (SP) configuration. In a typical SP setup, PV modules are connected in series to create strings, which are then connected in parallel. However, if one module becomes shaded, it can degrade the performance of the entire string. The TCT configuration addresses this issue by incorporating cross-ties between adjacent strings, allowing current to flow more efficiently and ensuring better power output. These cross-ties provide alternative current pathways, reducing the impact of shading on individual modules. This design helps to minimize voltage imbalances and improves the system's fault tolerance. Furthermore, TCT systems are less prone to hot-spot formation, a phenomenon that can lead to long-term damage to the modules. One of the main advantages of TCT is its ability to sustain a higher energy yield under non-uniform irradiation conditions, making it an ideal choice for solar farms, rooftop installations, and hybrid PV systems. Additionally, TCT enhances load distribution, contributing to greater system stability.

[9].

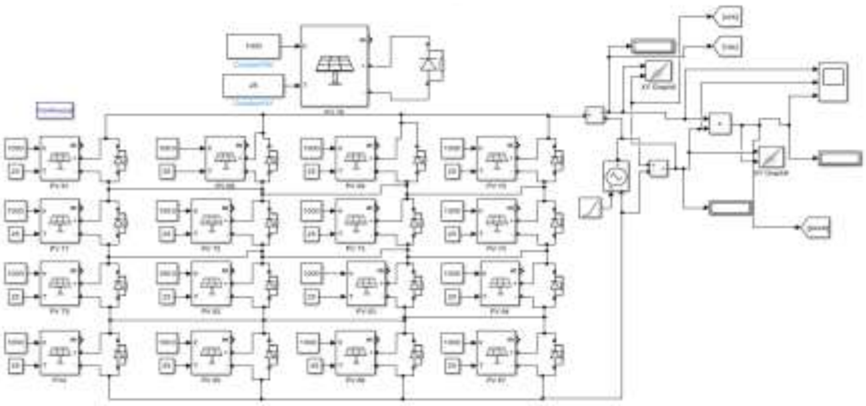

Figure 4 Solar Panel PV Configuration

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2. Shading Patterns in PV Modules

Shading patterns can significantly affect the performance of PV modules, particularly in configurations like the 4x4 PV module.

Uniform shading occurs when the entire module is shaded, causing a reduction in output from all cells and resulting in a significant loss of power. Edge shading happens when only the perimeter cells are shaded while the central cells remain fully illuminated.

This type of shading reduces the output current due to the series connection, but the central cells continue to generate power.

Central shading impacts the middle cells of the module, causing a decrease in current because the series connection limits the module's performance to the lowest-performing cell. In all these scenarios, techniques such as bypass diodes and MPPT algorithms are crucial for minimizing power loss and enhancing the overall system performance under real-world conditions [10][11].

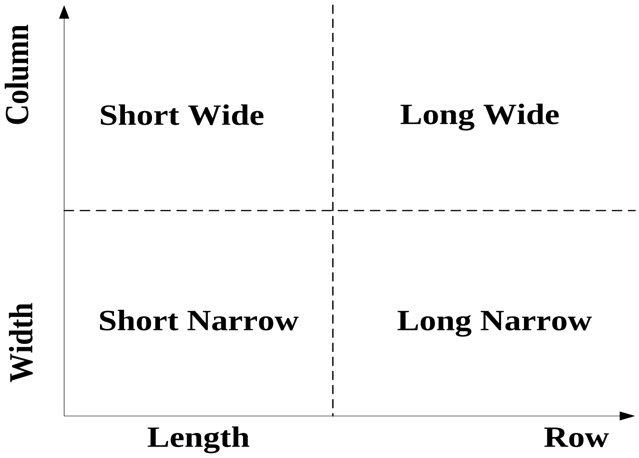

Figure 5 Different types of partial shading conditions

Table 2 Short Wide Range

300	300	1000	1000
300	300	1000	1000
1000	1000	1000	1000
1000	1000	1000	1000

Table 3 Short Narrow Range

1000	1000	1000	1000
1000	1000	1000	1000
400	400	600	1000
400	400	600	1000

Table 4 Long Wide Range

1000	1000	500	500
1000	1000	500	500
1000	1000	300	300
1000	1000	1000	1000

Table 5 Long Narrow Range

1000	1000	1000	1000
1000	1000	1000	1000
1000	1000	700	700
1000	1000	700	700

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4. SIMULATION OF PERTURB & OBSERVER TECHNIQUE UNDER SHADING CONDITION

4.1 Perturb and Observe (P&O) Technique

The Perturb and Observe (P&O) method is widely used for MPPT (MPPT) in PV (PV) systems due to its simplicity and effectiveness. However, traditional P&O algorithms face challenges such as oscillations and inaccuracies, especially under rapidly changing environmental conditions [11]. Recent modifications have significantly improved performance. For instance, the Multiple Perturb and Observe (MP&O) method enhances tracking accuracy during rapid irradiance changes. Another modification, the Variable Step Size Threshold, improves the speed of tracking while minimizing fluctuations, proving effective in simulations. Furthermore, techniques that initialize reference voltages based on maximum voltage distribution have shown superior convergence speed and accuracy, particularly under partial shading conditions, outperforming traditional P&O methods. Adaptive Step Size methods dynamically adjust the perturbation step size based on the rate of change in PV output power, which reduces oscillations and improves tracking accuracy during rapid irradiance variations [12].

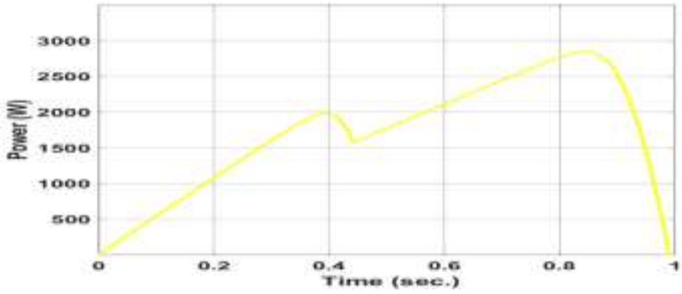

Figure 6 Short Wide

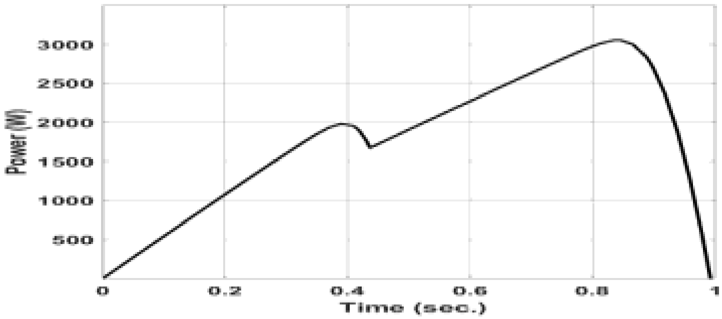

Figure 7 Short Narrow

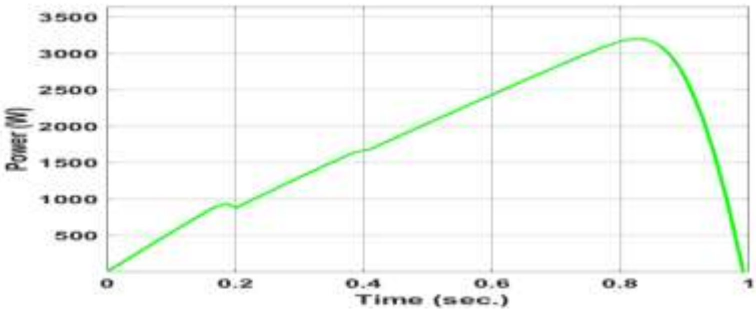

Figure 8 Long Wide

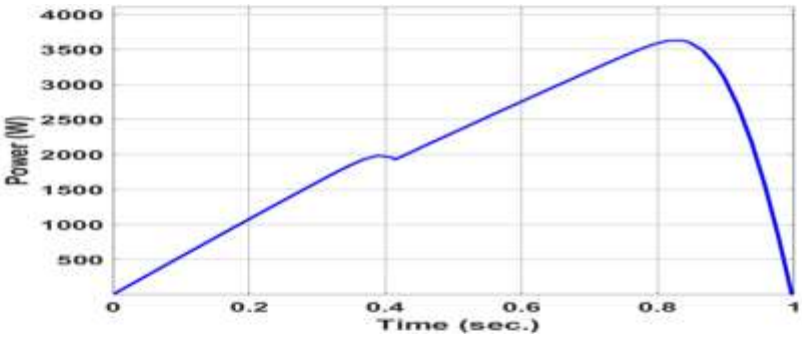

Figure 9 Long Narrow

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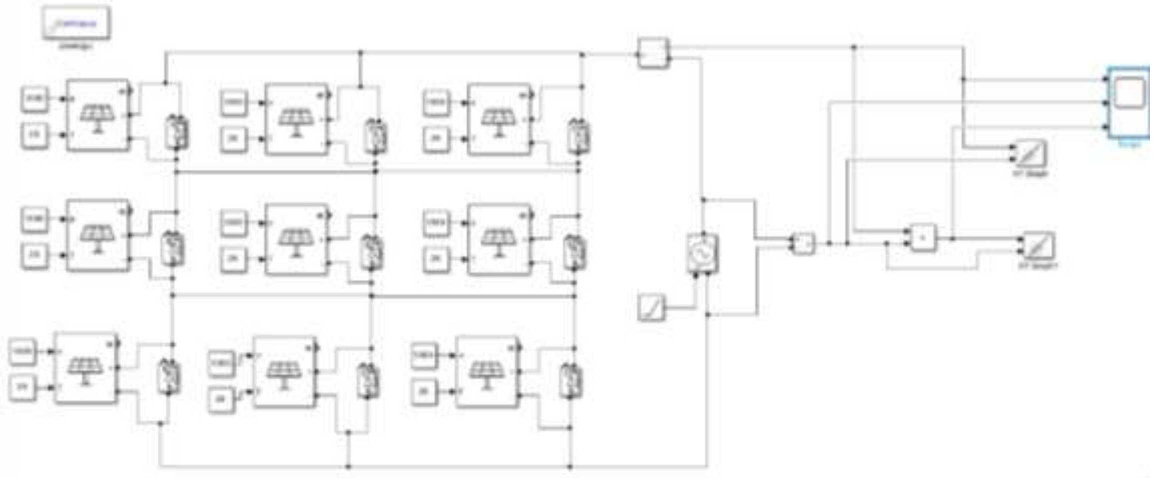


Figure 10 3x3 PV Module Configuration

4.2 FLC Based MPPT

The Fuzzy Logic Controller based MPPT method is recognized for its simplicity and reliability, as it doesn't require a deep understanding of the PV panel characteristics. The operation of the FLC is divided into three main stages: fuzzification, rule evaluation, and defuzzification.

In the fuzzification stage, the changes in the PV panel's output voltage and current are monitored to establish the input membership functions for the MPPT controller [13]. During rule evaluation, the FLC applies a set of predefined rules to define the relationship between the input and output membership functions, determining the necessary control actions. The output generated at this stage is fuzzy, representing the control action to be applied.

The defuzzification stage then converts this fuzzy output into precise values for control, ensuring accurate operation. The two key input variables, voltage and current, are analyzed during fuzzification, serving as the foundation for the MPPT control actions.

In the FLC, two essential inputs are used: error (E) and change in error (CE). These inputs are fuzzified using a rule-based method to assign corresponding fuzzy membership values. The FLC works with five fuzzy subsets to represent these variables: Negative Large (NL), Negative Small (NS), Zero (ZE), Positive Small (PS), and Positive Large (PL). These subsets are used to map the membership function values to the linguistic terms, which help capture variations in both the error and its rate of change. This method enables the system to adjust dynamically to the maximum power point, efficiently guiding the MPPT process [14].

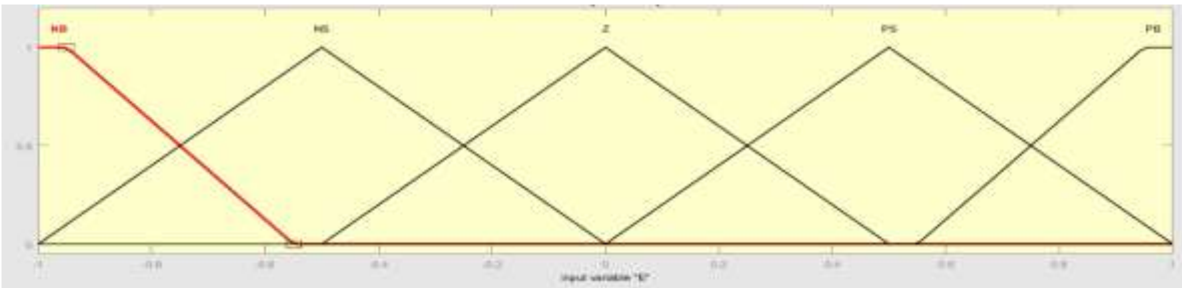


Figure 11 . Error Input (E)

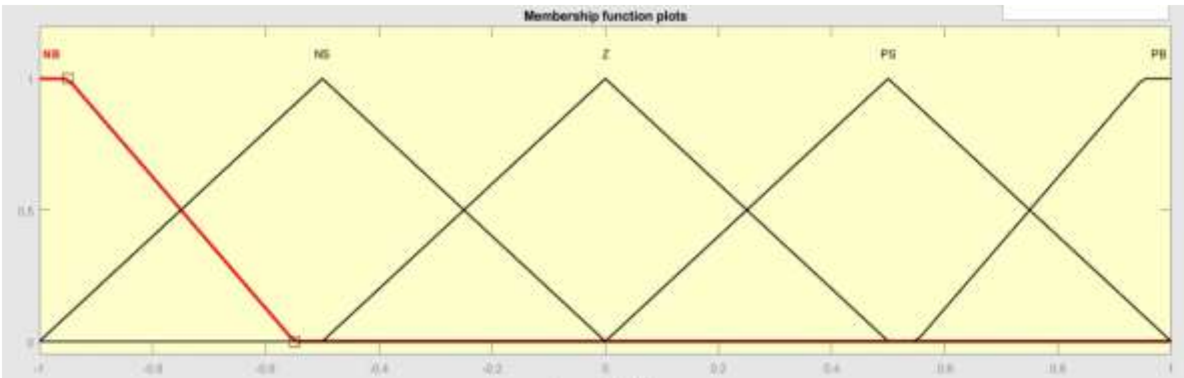


Figure 12 Change in Error (CE)

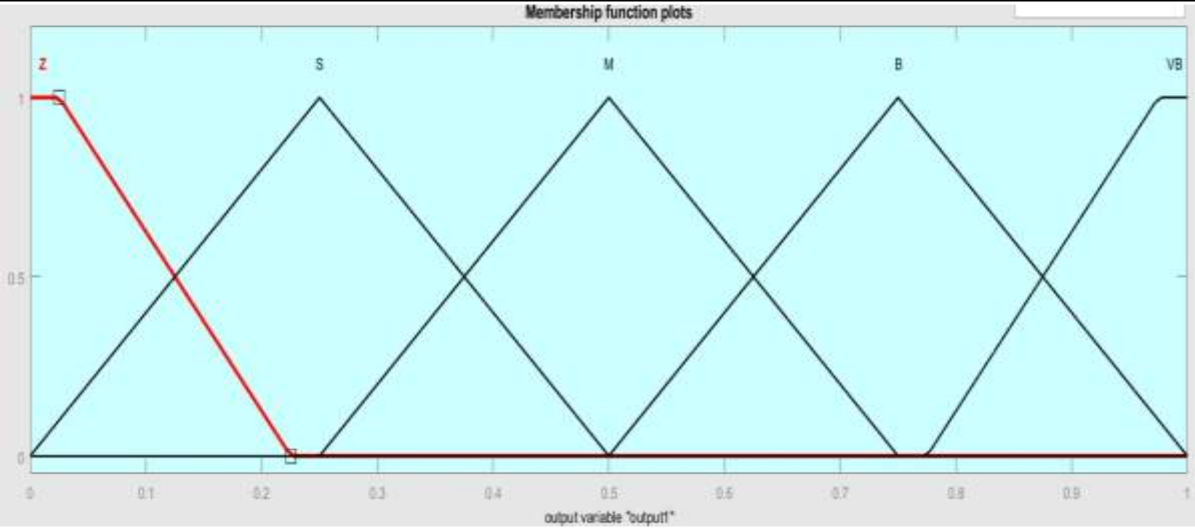


Figure 13 Duty cycle Output (D)

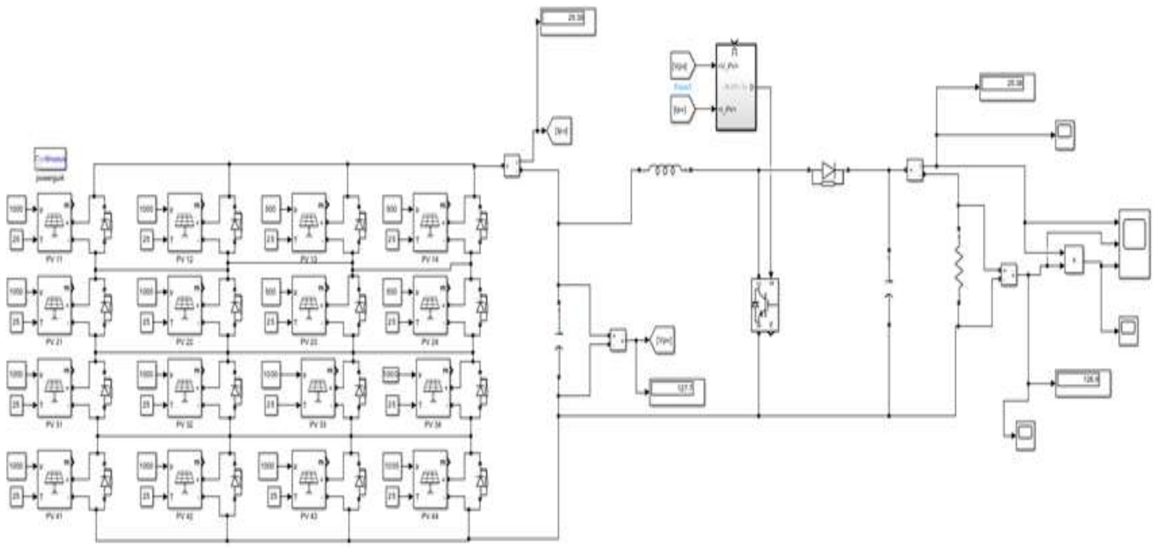
It is easier to implement as it does not necessitate an in-depth understanding of a specific MPPT model. The fuzzy inference system employed in this study follows the Mamdani type and utilizes around 25 fuzzy IF-THEN rules [12].

Table 6 Proposed Fuzzy Rule

E \ CE	NL	NS	ZE	PS	PL
NL	PL	PS	NL	NS	NS
NS	PS	PS	NL	NS	NS
ZE	NS	NS	NS	PL	PL
PS	NS	PL	PS	NL	PL
PL	NL	NL	PL	PS	PL

The fuzzy rule system implemented in this study functions based on two main scenarios. In the first scenario, when the error is positive, it indicates that the operating point is positioned to the left of the maximum power point. If the change in error is also positive, the system makes adjustments to move the operating point closer to the maximum power point. For example, when the error is classified as Positive Large and the change in error is also Positive Large, the duty cycle output is set to Positive Large, directing the system towards the maximum power point. The complete set of rules for these adjustments is outlined in Table I [12]. In the second scenario, if the error is negative, it suggests that the operating point is located to the right of the maximum power point. If the change in error is positive, the system moves further away from the maximum power point, but if the change in error is negative, the system adjusts to bring the operating point closer to the maximum power point.

5. RESULT



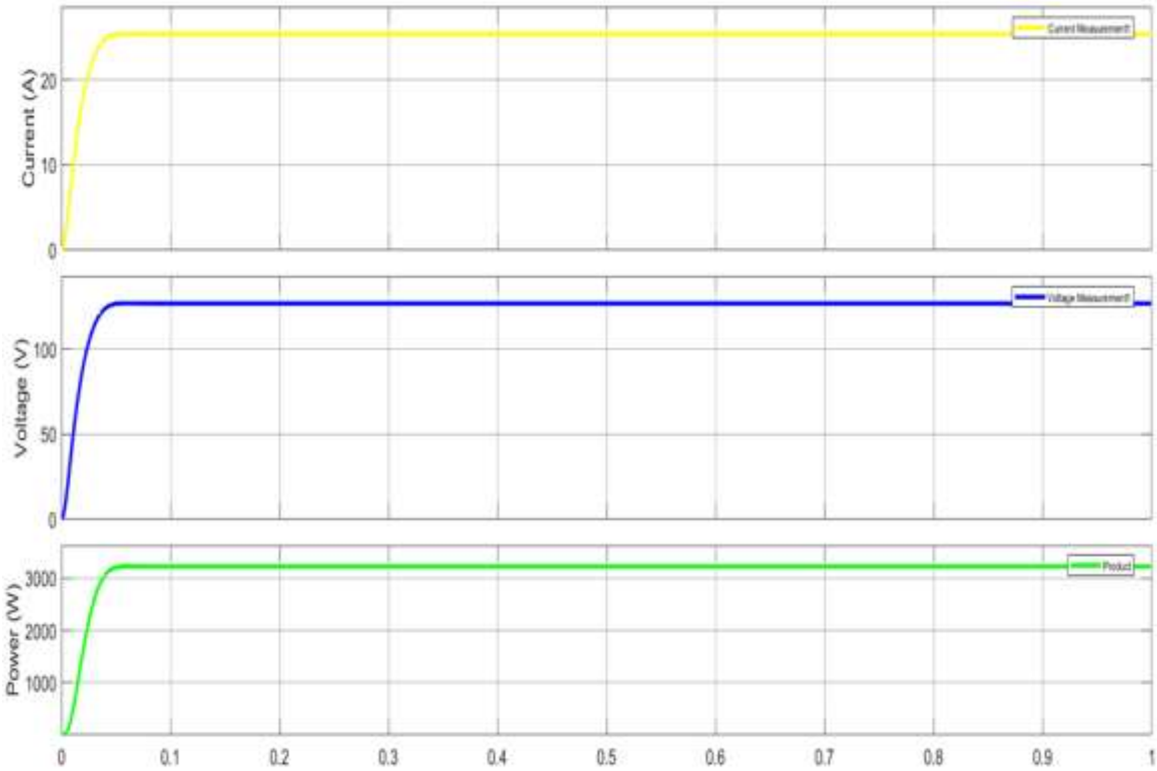


Figure 14 Output Waveform of P&O technnique

This section outlines the findings from the study on FTC-based MPPT. It begins by presenting the performance data obtained from simulations involving FTC-based MPPT applied to a solar PV array. Key parameters such as power output, voltage, and current are analyzed to assess the system's performance across different operating conditions. The results are then discussed, with a focus on how FTC-based MPPT improves the efficiency of solar PV arrays, particularly in partial shading situations. Comparisons with traditional MPPT techniques highlight the advantages of FTC-based MPPT in terms of energy generation and tracking accuracy. Additionally, the section explores the practical applications of these findings, identifying the conditions where FTC-based MPPT is most beneficial, while also considering any potential limitations or challenges in real-world use.

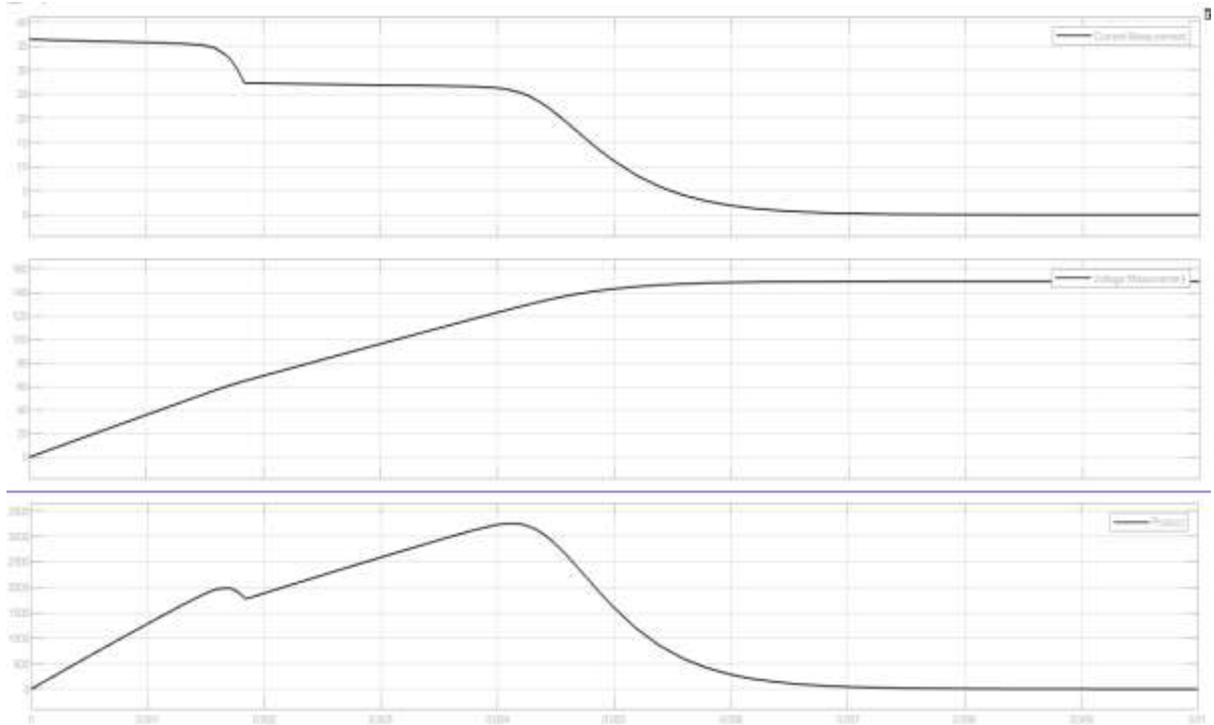


Figure 15 Current, Voltage and Power Characteristics of PV Array

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Figure 9 shows the voltage, current, and power waveforms for a solar PV array using MPPT. It highlights how the electrical outputs change over time under different conditions. The variations in voltage, current, and power provide insights into how efficiently the PV array is working, especially in response to varying light levels and partial shading. MPPT ensures the system operates as efficiently as possible, adjusting to environmental changes and optimizing power output. This understanding helps in recognizing how MPPT boosts the overall performance of solar PV systems in everyday use.

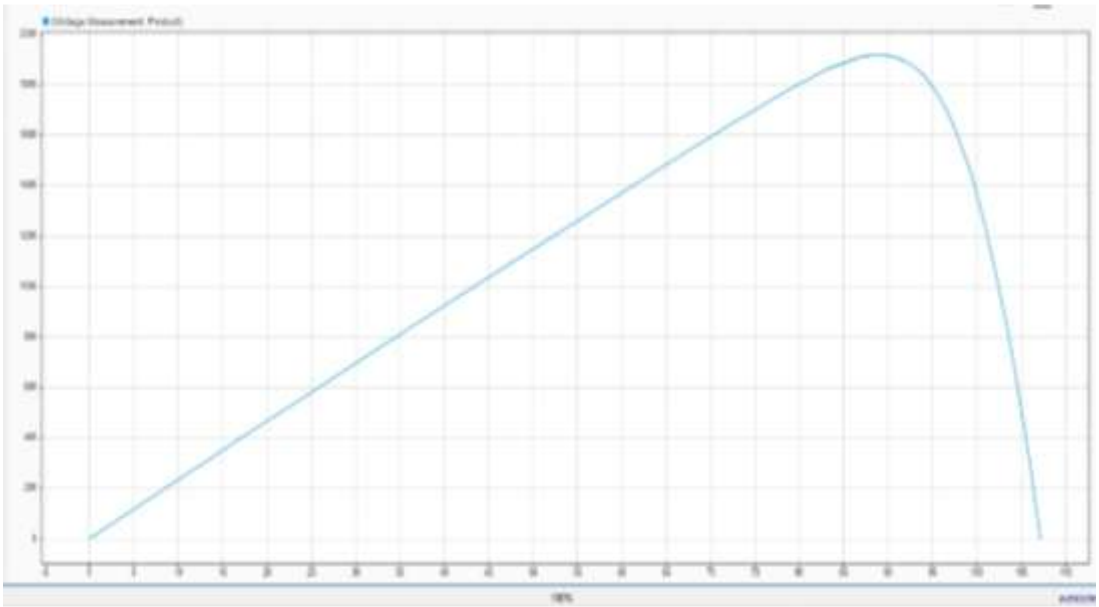

Figure 16 PV characteristics under partial shading

Figure 10 in the paper illustrates the characteristics of a solar array under partial shading with MPPT (MPPT). This diagram likely demonstrates how key performance parameters of the PV array, such as voltage, current, and power, fluctuate when shading is present. Understanding these characteristics is crucial for assessing how well the system can mitigate the adverse effects of shading on solar PV arrays. By implementing MPPT, the system maximizes power output, ensuring that the array operates at peak efficiency despite partial shading. This analysis helps evaluate the potential of MPPT configurations in enhancing the performance of solar arrays, particularly in response to changing environmental conditions.

6. CONCLUSION

A generalized model of a PV system was developed and simulated using MATLAB/Simulink software. The results of the simulation highlight the non-linear nature of the output from the system. The current-voltage characteristic curve shows that the current remains almost constant up until the open-circuit voltage. Similarly, the power-voltage characteristic curve indicates that the power reaches its maximum value at a specific voltage under particular environmental conditions. As the level of sunlight changes, the current from the cell adjusts in a linear fashion, while the voltage responds logarithmically, as described by the equations in the simulation. With an increase in temperature, the current rises to a certain threshold, but due to the short-circuit current, the voltage decreases at a rate of 2.2 millivolts per degree Celsius. This model is suitable for use in research focusing on solar energy applications, especially in systems that incorporate MPPT for both grid-connected and standalone PV systems.

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