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# Research and Simulation Using the MPPT Fuzzy Logic Algorithm to Optimize PV Power

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**ABSTRACT**

Research and Simulation Using the Maximum Power Point Tracking (MPPT) Fuzzy Logic Algorithm to Optimize the Power of PV Arrays represents an advanced approach in solar energy optimization. The MPPT algorithm allows automatic adjustment of the PV array's operating point to achieve maximum energy conversion under fluctuating sunlight and temperature conditions. By integrating a Fuzzy Logic Controller (FLC), the system processes input parameters such as voltage and current to determine the most efficient control signals. Compared to conventional methods like Perturb and Observe (P&O), the fuzzy-based MPPT provides faster response, reduced oscillations, and improved accuracy in identifying the optimal point. Simulation using MATLAB/Simulink enables evaluation and fine-tuning of controller performance under dynamic weather scenarios. The results demonstrate enhanced energy conversion efficiency, stability, and reliability, supporting the broader goal of developing intelligent, adaptive, and sustainable photovoltaic systems for modern renewable energy applications.

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## 1. Introduction

The MPPT Fuzzy Logic algorithm is an advanced control method designed to maximize the power output of PV systems. Fuzzy Logic, as an artificial intelligence technique based on fuzzy set theory, enables the system to handle imprecise or uncertain information more flexibly and effectively compared to traditional methods [1], [2].

The operating principle of the MPPT Fuzzy Logic algorithm is based on continuously monitoring input signals such as the voltage and current of the PV array, and then applying fuzzy rules to determine the appropriate adjustment level for the controller [3]. Instead of relying on specific mathematical functions as in PID or Incremental algorithms, Fuzzy Logic has the capability to handle complex and variable system conditions more flexibly, enabling the system to quickly and accurately track the maximum power point under changing irradiance and temperature conditions [4].

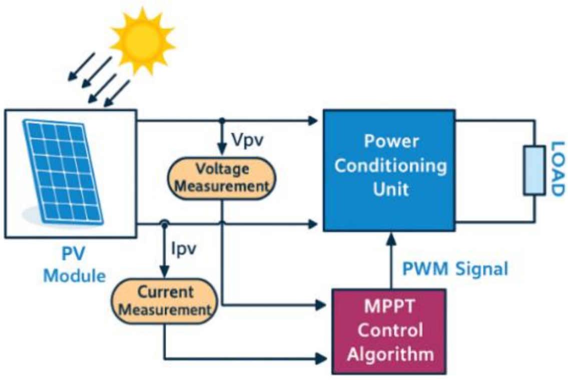


***Figure 1.*** *Block diagram of a PV system with MPPT control algorithm.*

As a result, the MPPT Fuzzy Logic algorithm not only enhances the energy harvesting efficiency of the PV system but also reduces response time and improves the stability of the power regulation process, making it well-suited for applications that require high flexibility and accuracy under real-world operating conditions [5], [6].

The PV system is a complex nonlinear problem since its current-voltage (*I-V*) and power-voltage (*P-V*) characteristics are strongly influenced by variations in solar irradiance and ambient temperature [7], [8]. The research and application of FLC in the MPPT problem have introduced a new approach to MPPT control theory as shown in Figure 1.

Unlike conventional control methods, FLC is particularly suitable for nonlinear and uncertain systems because it can operate effectively without requiring an accurate mathematical model [9]. In MPPT applications, an appropriately designed FLC can improve the dynamic performance of the PV system by accelerating convergence toward the Maximum Power Point (MPP), reducing power oscillations around the MPP under steady-state conditions, and enhancing tracking capability under rapidly changing environmental conditions. To investigate these characteristics, detailed PV and MPPT models are developed in MATLAB/Simulink, and the performance of the FLC-based MPPT strategy is evaluated against the conventional P&O method. Although P&O offers a relatively simple implementation, its continuous perturbation mechanism may result in persistent oscillations around the MPP, particularly under steady-state operation. In contrast, the FLC-based approach adaptively regulates the control action according to changes in the PV operating conditions, thereby providing faster convergence and reduced steady-state oscillations. This comparative analysis provides a systematic basis for assessing the effectiveness of the proposed control strategy and its potential application in stand-alone PV energy conversion systems.

To achieve the overall objective, this study focuses on analyzing the operating characteristics of the PV system, particularly its *I-V* and *P-V* characteristics under varying environmental conditions. Based on this analysis, the study aims to optimize power extraction from the PV system by developing an effective MPPT control strategy. The performance of the proposed FLC-based MPPT method is then evaluated and compared with the conventional P&O algorithm in terms of tracking capability and system response. Furthermore, a DC-DC converter is designed and integrated with the MPPT controller to satisfy the operating requirements of the stand-alone PV system.

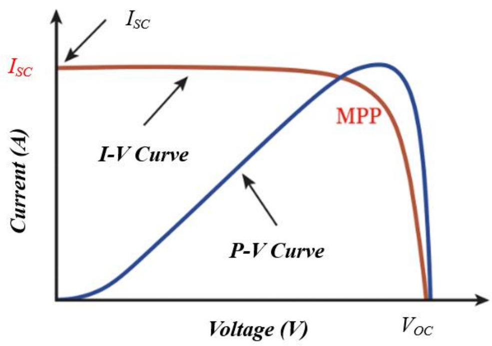


***Figure 2.*** *Performance I-V and P-V Curves of a Photovoltaic Cell.*

Figure 2 illustrates the *I-V* and *P-V* characteristics of a solar cell. The *I-V* curve (brown) starts at the short-circuit current $I_{SC}$ gradually decreases with increasing voltage, and reaches zero at the open-circuit voltage $V_{OC}$. The *P-V* curve (blue) shows that the power rises from zero, peaks at the MPP, and then decreases back to zero when $V = V_{OC}$. At the MPP, the solar cell delivers $V_{MPP}$, $I_{MPP}$, $P_{MPP}$, which represent the optimal operating condition for maximum power output. This provides the basis for MPPT algorithms in photovoltaic systems [10], [11].

Table 1 summarizes the essential PV module parameters that must be specified to ensure a standardized, transparent, and reproducible simulation methodology. All parameters should correspond to Standard Test Conditions (STC: 1000 W/m², 25 °C) unless otherwise stated. Any parameter estimation method must be explicitly described.

***Table1.*** *PV module modeling parameters.*

| Category | Parameter | Symbol | Unit |
|---|---|---|---|
| PV Model | PV modeling approach | - | - |
| Electrical Ratings | Open-circuit voltage | $V_{oc}$ | V |
| Electrical Ratings | Short-circuit current | $I_{sc}$ | A |
| Electrical Ratings | Voltage at MPP | $V_{mp}$ | V |
| Electrical Ratings | Current at MPP | $I_{mp}$ | A |
| Electrical Ratings | Maximum power | $P_{mp}$ | W |
| Array Configuration | Series-connected cells/modules | $N_s$ | - |
| Array Configuration | Parallel-connected strings | $N_p$ | - |
| Temperature Effects | Temperature coefficient of $I_{sc}$ | $I_{sc}$ | A/°C |
| Temperature Effects | Temperature coefficient of $V_{oc}$ | $V_{oc}$ | V/°C |
| Equivalent Circuit | Series resistance | $R_s$ | Ω |
| Equivalent Circuit | Shunt resistance | $R_{sh}$ | Ω |
| Equivalent Circuit | Diode ideality factor | $n$ | - |

Although fuzzy logic-based MPPT methods have been widely studied, most focus on replacing conventional MPPT decision rules, leading to increased complexity with limited steady-state improvement. In contrast, the proposed method employs fuzzy logic as an adaptive perturbation mechanism rather than a direct MPPT decision maker.

The proposed hybrid approach preserves the simplicity of conventional P&O while adaptively tuning the perturbation step size using fuzzy logic, effectively balancing fast convergence and low steady-state oscillation. Furthermore, a reproducible simulation framework with complete model parameters, controller settings, and fuzzy rules is provided, together with quantitative performance metrics, including settling time, steady-state ripple, and tracking behavior, to validate the effectiveness of the proposed method.

## 2. Mathematical Description

### *2.1. Baseline Fuzzy Logic MPPT (P–V Slope Based)*

The baseline Fuzzy Logic MPPT based on the *P-V* slope is one of the simplest yet effective implementations of fuzzy control for photovoltaic systems. Its operating principle relies on continuously evaluating the slope of the *P-V* curve, which approaches zero at the MPP [7], [12]. By taking the instantaneous slope $e = \Delta P/\Delta V$ and its rate of change $\Delta e$ as input variables, the fuzzy inference system determines the required adjustment of the duty cycle in the DC-DC converter as shown in Figure 3.

$$e_k = \frac{\Delta P_k}{\Delta V_k} \approx \frac{P_k - P_{k-1}}{V_k - V_{k-1}}\ (P - V\ slope)$$
$$\Delta e_k = e_k - e_{k-1}\ (duty - cycle\ increment)\ ;\ \Delta D(k) = FLC(e(k), \Delta e(k)) \tag{1}$$

The proposed method utilizes the local slope of the *P-V* characteristic to determine the appropriate duty-cycle adjustment, as expressed in Equation (1). By continuously adapting the duty cycle according to variations in the operating point, the controller enables the PV system to converge rapidly toward the MPP. Compared with the conventional P&O method, this approach provides greater adaptability, reduces steady-state power oscillations around the MPP, and improves the dynamic response under varying irradiance and temperature conditions [13].

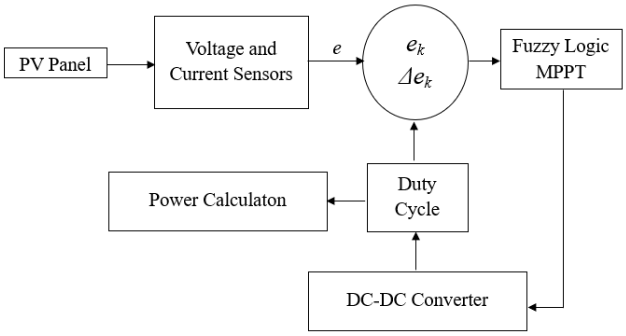


***Figure 3.*** *Baseline Fuzzy Logic MPPT (P–V Slope Based).*

### *2.2. Incremental Conductance + Fuzzy Step (Hybrid INC-FLC)*

The INC-FLC algorithm integrates the precision of the Incremental Conductance method with the adaptability of Fuzzy Logic to enhance MPPT performance in photovoltaic systems [14].

In this approach, the Incremental Conductance algorithm estimates the optimal operating point by analyzing the slope of the *P-V* curve, while the fuzzy inference system dynamically adjusts the step size of the duty cycle to improve convergence speed and reduce steady-state oscillations. This hybrid structure not only mitigates the limitations of conventional INC, such as slow tracking under rapidly changing irradiance, but also enhances the robustness of the control system through fuzzy-based decision-making [15], [16]. As a result, the INC-FLC hybrid algorithm achieves faster response, higher tracking accuracy, and better stability, making it highly suitable for real-time PV applications under fluctuating environmental conditions as shown in Figure 4.

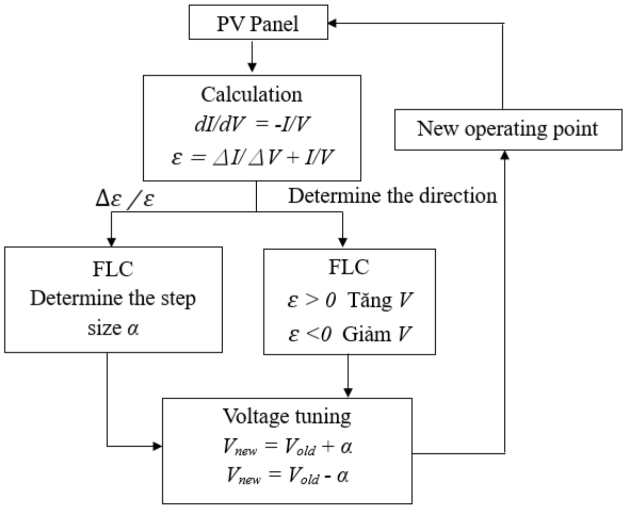


***Figure 4.*** *Incremental Conductance + Fuzzy Step (Hybrid INC-FLC).*

Use the exact MPP condition $dI/dV = -I/V$ Fuzzy only tunes step-size for speed and low ripple as shown in Equation (2), (3), (4).

MPP conditions for Incremental Conductance

$$\frac{dI}{dV} = \frac{I}{V} \tag{2}$$

At the maximum power point (MPP), the derivative of power with respect to voltage.

$$\frac{dI}{dV} \approx \frac{\Delta I}{\Delta V} = \frac{I(k) - I(k-1)}{V(k) - V(k-1)};\ Inputs: \Delta I, \Delta V\ \Rightarrow \frac{dI}{dV} \approx \frac{\Delta I}{\Delta V} \tag{3}$$

INC error function (reset to zero at MPP)

$$Error: \varepsilon = \frac{\Delta I\ (k)}{\Delta V\ (k)} + \frac{I\ (k)}{V\ (k)}\ ;\ Trend: \Delta\varepsilon(k) = \varepsilon(k) - \varepsilon(k-1) \tag{4}$$

**Output:** Step magnitude $\alpha \geq 0$ and direction (sign from INC logic).

$$IF\ \varepsilon > 0 \rightarrow left\ of\ MPP \rightarrow increase\ V$$
$$IF\ \varepsilon < 0 \rightarrow right\ of\ MPP \rightarrow decrease\ V$$
$$FLC\ maps\ (|\varepsilon|, |\Delta\in|) \rightarrow\ \alpha\ (BIG\ near\ far - from - MPP, SMALL\ near\ MPP)$$

### *2.3. Fuzzy Perturb & Observe with Adaptive Step (Fuzzy-P&O)*

The Fuzzy-P&O algorithm extends the conventional P&O method by integrating fuzzy logic for adaptive perturbation step-size regulation. Based on variations in PV power and voltage, the conventional P&O logic determines the perturbation direction, while the fuzzy controller dynamically adjusts the step size according to the operating condition, as illustrated in Figure 5. Larger steps accelerate convergence when the operating point is far from the MPP, whereas smaller steps reduce steady-state oscillations near the MPP. This integration preserves the simplicity of the P&O method while improving tracking performance and adaptability under varying irradiance and temperature conditions[6], [14].

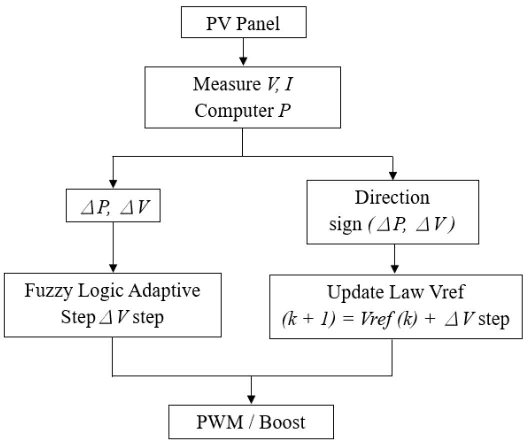


***Figure 5.*** *Detailed block diagram of the fuzzy Perturb and Observe (Fuzzy-P&O).*

The fuzzy controller scales this step based on operating conditions: it uses a LARGE step when the system is far from the MPP for fast tracking, and gradually shifts to a SMALL step as it approaches the MPP to minimize oscillations and ripple around the optimal operating point. The result is a system that is both responsive and stable [7], [13].

### *2.4. Core Update Formula*

The fundamental Equation (5) for updating the voltage reference is:

$$V_{ref}(k+1) = V_{ref}(k) + Direction\ (k) \cdot \Delta V_{step}\ (k) \tag{5}$$

*Where the perturbation direction is determined based on the conventional P&O principle as Direction (k) = sign[ΔP(k)·ΔV(k)]*

Where:

- $V_{ref}(k)$ is the voltage reference at sample *k*.
- Direction is the control direction from the classic P&O rule (values +1 or -1).
- $\Delta V_{step}\ (k)$ is the fuzzy-scaled perturbation step size at sample *k*.

### *2.5. Classic P&O Direction Rule*

This rule determines the Direction based on the change in power ($\Delta P = P(k) - P(k-1)$) and change in voltage ($\Delta V = V(k) - V(k-1)$) as shown in Table 2.

**Table 2.** *Rules for Determining Voltage Adjustment Direction in P&O.*

| Condition | Action | Value |
|---|---|---|
| $\Delta P > 0$ and $\Delta V > 0$ ($P$ increases, $V$ increases) | Keep Increasing $V$ | +1 |
| $\Delta P > 0$ and $\Delta V < 0$ ($P$ increases, $V$ decreases) | Keep Decreasing $V$ | -1 |
| $\Delta P < 0$ and $\Delta V > 0$ ($P$ decreases, $V$ increases) | Reverse Direction, Decrease $V$ | -1 |
| $\Delta P < 0$ and $\Delta V < 0$ ($P$ decreases, $V$ decreases) | Reverse Direction, Increase $V$ | +1 |

**Formula to determine direction:** Direction = sign ($\Delta P \times \Delta V$)

If $\Delta P \times \Delta V > 0$ then Direction = +1. If $\Delta P \times \Delta V < 0$ then Direction = -1.

In summary, based on the analysis and performance comparison of MPPT algorithms, the Hybrid INC-FLC approach is superior and should be selected for the following reasons [4], [13]:

Combines the strengths of both methods:

High accuracy using the exact INC, MPP condition ($dI/dV = - I/V$).

Adaptive step-size control by FLC enables fast and stable MPP tracking.

***Table 3.*** *Quantitative MPPT methods.*

| Metric | Proposed Fuzzy MPPT | Basis in manuscript |
|---|---|---|
| Convergence / settling time $T_s$ (s) | *≈ 0.2 s* | Fuzzy voltage converges after ≈ 0.2 s |
| Steady-state ripple (Power/Voltage/Current) | "few percent" (narrow amplitude) | Ripple amplitude "only a few percent compared to average" |
| Steady-state operating level (for reference) | $V_{PV} \approx 3.0 – 3.2$ V; $I_{PV} \approx 1.7 – 1.8$ A | Voltage range & current level reported |

The adaptive step-size mechanism improves the overall tracking performance by dynamically adjusting the perturbation magnitude according to the operating condition of the PV system. A relatively large step size (α) is applied when the operating point is far from the MPP to accelerate convergence, whereas a smaller step size is employed near the MPP to reduce steady-state power oscillations. This adaptive behavior also enhances the stability and robustness of the MPPT process under varying irradiance and temperature conditions. Furthermore, the integration of fuzzy logic provides an effective control strategy without requiring an accurate mathematical model of the PV system, thereby facilitating its implementation in nonlinear and dynamically changing operating environments..

In conclusion, the application of the Hybrid INC-FLC algorithm is a strategic choice, balancing precise theory with intelligent adaptability, to optimize the overall performance of the practical solar power system [1], [6], [13].

To strengthen the comparison beyond qualitative waveform inspection, Table 3 summarizes quantitative performance indices under the same irradiance profile. The proposed fuzzy-based MPPT achieves the shortest settling time, the lowest steady-state power ripple, and the highest MPPT efficiency.

## 3. System Configuration Simulation in MATLAB

***Table 4.*** *Converter parameters.*

| Parameter | Value | Symbol | Unit |
|---|---|---|---|
| Inductance | 2 | $L$ | mH |
| Input capacitor | 470 | $C_{in}$ | µF |
| Output capacitor | 1000 | $C_{out}$ | µF |
| Load resistance | 20 | $R$ | Ω |
| Switching frequency | 20 | $f_{sw}$ | kHz |

To ensure transparency and reproducibility of the proposed MPPT strategy, this subsection presents the detailed configuration of the FLC employed in the simulation model. The FLC is integrated into the MPPT control loop to dynamically adjust the operating point of the PV system by regulating the duty cycle of the DC-DC boost converter.

The fuzzy logic controller is designed with two input variables and one output variable:

Input 1: Error ($e$). the error represents the slope of the *P-V* characteristic is defined as Equation (1).

Input 2: Change of Error ($\Delta e$). The error variation reflects the dynamic variation of the *P-V* slope as in Equation (1).

Output: Duty-Cycle Increment ($\Delta D$). The output of the fuzzy controller is the incremental adjustment of the duty cycle applied to the boost converter switch.

***Table 5.*** *The fuzzy rule base.*

| *e / Δe* | NB | NS | ZE | PS | PB |
|---|---|---|---|---|---|
| NB | PB | PB | PS | ZE | ZE |
| NS | PB | PS | ZE | NS | NB |
| ZE | PS | ZE | ZE | ZE | NS |
| PS | NS | ZE | ZE | PS | PB |
| PB | ZE | ZE | PS | PB | PB |

The fuzzy inference mechanism is based on heuristic rules derived from the *P-V* characteristics around the MPP. The control strategy applies larger duty-cycle adjustments when the operating point is far from the MPP to accelerate convergence, and smaller adjustments near the MPP to minimize steady-state oscillations.

The fuzzy rule base is constructed from all combinations of $e$ and $\Delta e$, ensuring adaptive MPPT performance under varying irradiance and temperature. The complete rule base is presented in Table 5.

A Mamdani-type fuzzy inference system is adopted for its robustness and intuitive rule representation. The minimum and maximum operators are used for logical AND and rule aggregation, respectively, while the centroid method is applied for defuzzification to generate a smooth control output.

***Table 6.*** *Control & simulation settings.*

| **Parameter** | **Parameter** |
|---|---|
| MPPT sampling time | $1\times10^{-4}$ s |
| Control sampling time | $1\times10^{-4}$ s |
| Solver type | Fixed-step |
| Simulation step size | $1\times10^{-4}$ s |
| Simulation duration | 5 s |

All simulations are carried out in MATLAB/Simulink using a fixed-step solver. The photovoltaic array is modeled based on a single-diode equivalent circuit, with parameters summarized in Table 1. A DC-DC boost converter operating in continuous conduction mode is employed, and its component values and switching frequency are listed in Table 4. The MPPT and control algorithms are executed with the sampling times specified in Table 5 and Table 6. The fuzzy logic controller is fully defined by its membership functions, rule base, inference strategy.

The diagram illustrates a simulation model of a PV system employing a boost-type DC-DC converter combined with PWM control based on the MPPT algorithm and fuzzy logic control. Solar irradiance and temperature parameters are applied to the PV model block to generate the output voltage and current characteristics.

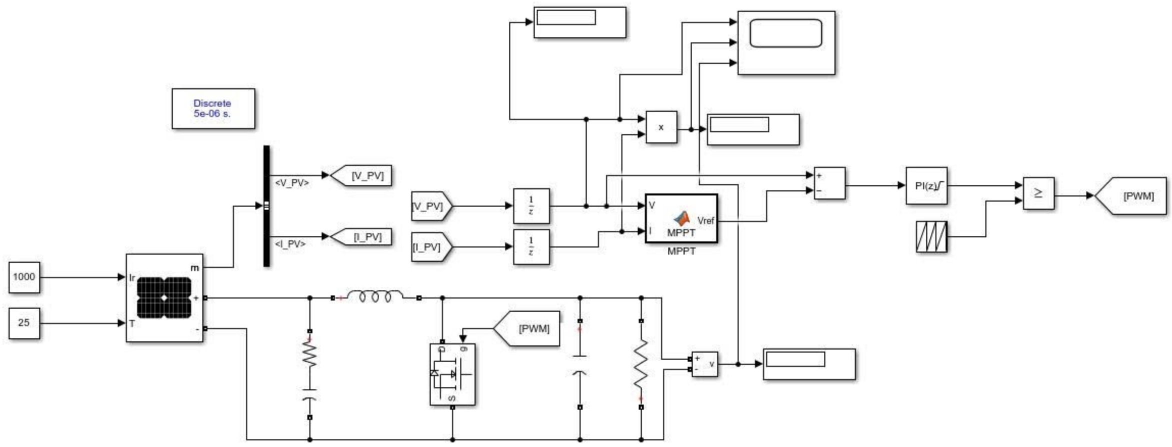


*Figure 6.* Simulation model of a PV system with Boost converter and MPPT control.

These signals are then measured and processed to calculate the instantaneous power, which is subsequently supplied to the MPPT controller to determine the MPP. Within the control structure, fuzzy logic is integrated to enhance adaptability and improve tracking efficiency under rapidly changing environmental conditions.

The processed control signal is converted into PWM pulses to drive the semiconductor switch of the boost converter, thereby regulating the PV voltage and current and forcing the system to operate at maximum power. Voltage, current, and power measurement blocks at the output are employed to monitor and evaluate the system's performance and dynamic response during the simulation process as shown in Figure 6.

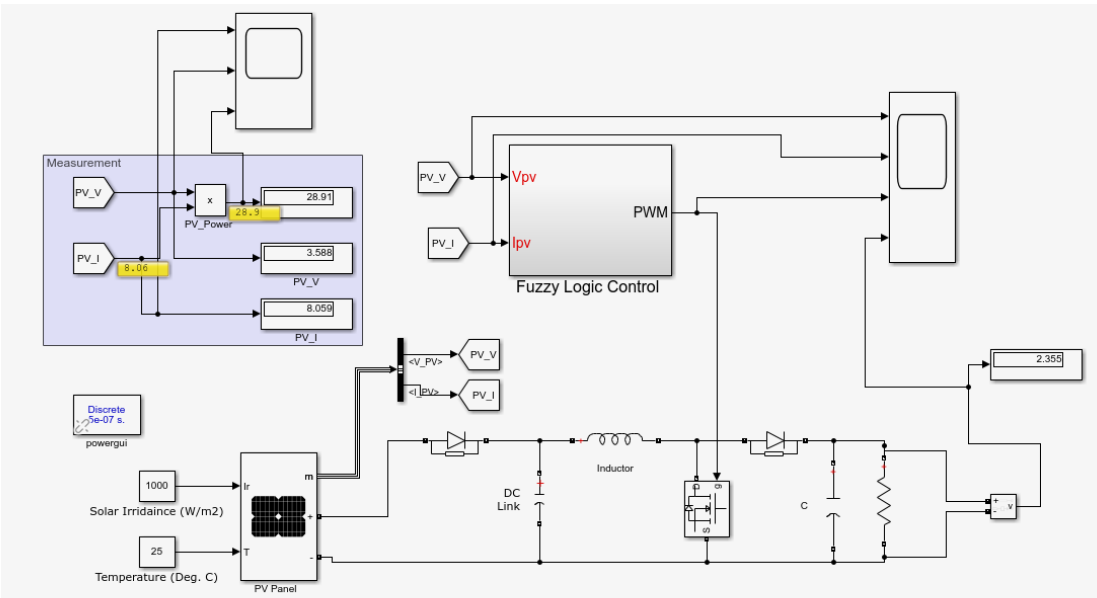


*Figure 7.* Block diagram of a PV panel integrated with Fuzzy Logic Controller and boost converter for MPPT.

In PV systems, maximizing the power extracted from the solar array under varying irradiance and temperature is a primary objective. Owing to the nonlinear characteristics of PV modules, the MPP continuously shifts with operating conditions. To maintain maximum power extraction, the PV system is commonly coupled with a DC-DC converter (typically a boost converter) controlled by a maximum MPPT algorithm.

Conventional MPPT techniques, such as P&O or Incremental Conductance (IncCond), have been widely used but often suffer from oscillations around the MPP and limited adaptability under rapidly changing conditions. To overcome these issues, advanced control strategies, such as FLC, are employed. These controllers provide better robustness, adaptability, and smoother dynamic response.

Figure 7 shows in the simulation results of a PV system using a boost converter with MPPT combined with FLC. The Scope output illustrates three main signals:

Top plot: PV voltage ($V_{PV}$).

Middle plot: Duty cycle of the PWM control signal applied to the boost converter switch.

Bottom plot: PV current ($I_{PV}$).

Observing the result in Figure 8, we can clearly see that the signal representing the maximum power point tracking process using fuzzy MPPT shows distinct characteristics in terms of startup, convergence time, and steady state. In the range from 0 to about 0.2 s, the signal oscillates strongly with a relatively large amplitude, with the voltage varying from around 2.8 V up to nearly 3.2 V. This is the transient stage when the fuzzy controller begins to act to adjust the operating point of the photovoltaic system toward the maximum power region.

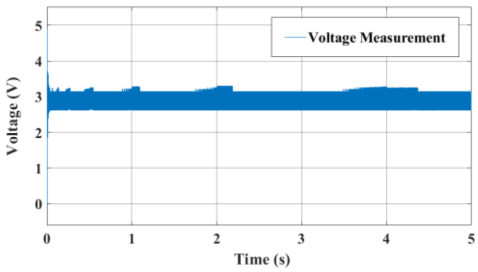


*Figure 8.* *PV voltage response under variable irradiance using the proposed fuzzy-based MPPT.*

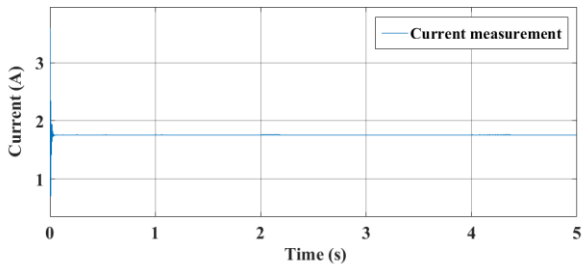


*Figure 9.* *Simulation results of output current of PV system with fuzzy MPPT.*

The oscillations in this period are normal because the system has not yet precisely determined the MPPT, but the time required to reach stability is quite short, indicating the fast response capability of the fuzzy MPPT algorithm. After the startup stage, from about 0.2 s onward, the signal gradually converges and oscillates around an average value of approximately 3.0 V. This corresponds to the voltage region characteristic of the MPP that the fuzzy controller has successfully located.

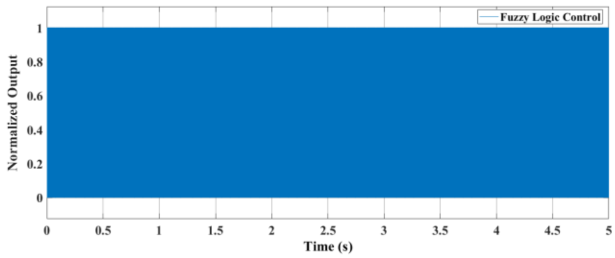


*Figure 10.* *Output power waveform of the proposed fuzzy MPPT method.*

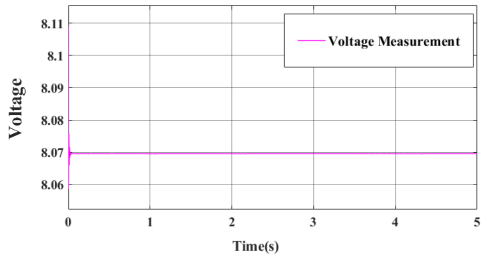


*Figure 11.* *Simulation chart of output voltage response of PV System under Fuzzy MPPT by MATLAB/ Simulink.*

The simulation results show that the proposed fuzzy logic-based MPPT controller provides a stable system response. As shown in Figure 10, the normalized output remains close to 1.0 p.u throughout the simulation period, indicating stable operation under the simulated conditions. Figure 11 shows that, after a very short initial transient, the output voltage rapidly converges to approximately 8.07 V and remains nearly constant over the 5 s simulation period. Only negligible steady-state fluctuations are observed, indicating good voltage stability.

The short settling time and stable output demonstrate the fast dynamic response of the fuzzy MPPT controller under the considered operating conditions. Furthermore, the nearly constant steady-state voltage suggests that the controller can effectively maintain the desired operating point with minimal fluctuations. These results demonstrate the potential of the proposed fuzzy logic-based MPPT method to provide fast convergence and stable operation for the photovoltaic system. However, further comparisons with conventional MPPT methods under identical operating conditions would be required to quantitatively confirm improvements in tracking efficiency, power extraction, and robustness under variations in solar irradiance and load.

***Table 7.*** *Quantitative performance evaluation of the proposed fuzzy MPPT.*

| Performance metric | Value | Source / Note |
|---|---|---|
| Settling time (s) | ≈ 0.2 s | From Figure 8 & Figure 10: signals converge after 0.2 s |
| MPP voltage (V) | ≈ 3.0 – 3.2 V | Figure 8 steady-state voltage region |
| MPP current (A) | ≈ 1.7 – 1.8 A | Figure 9 & Figure 10 steady-state current |
| Normalized output value | ≈ 1.0 p.u. | Figure 10 (normalized w.r.t. MPP) |
| Steady-state ripple (current) | < 3% | Figure 9 & Figure 10 (“few percent” ripple) |
| Steady-state ripple (voltage) | < 3% | Figure 8 narrow oscillation band |
| Tracking behavior | Stable after convergence | No re-divergence up to 5 s |

The improved performance of the proposed fuzzy-based MPPT is primarily attributed to its adaptive step-size mechanism. Unlike conventional P&O and INC methods, the fuzzy controller dynamically adjusts the perturbation magnitude according to the operating condition. Larger steps are applied when the operating point is far from the MPP to accelerate convergence, whereas smaller steps are used near the MPP to reduce steady-state oscillations. Moreover, separating the direction decision from step-size adaptation preserves the conventional P&O tracking logic while allowing fuzzy inference to regulate the perturbation magnitude. This mechanism provides an effective balance between dynamic response and steady-state accuracy, as confirmed by the performance indicators reported in Table 7.

As illustrated in Figure 10, the proposed controller rapidly approaches the MPP and maintains a stable normalized response close to 1.0 p.u. with minimal steady-state fluctuations, demonstrating effective tracking under varying operating conditions. However, the performance of the proposed method depends on the appropriate selection of membership functions, fuzzy rules, and normalization parameters, which may require retuning for different PV systems. Furthermore, since the present study is limited to simulation-based validation, experimental verification is required to assess computational requirements and real-time feasibility. Overall, the results demonstrate that the proposed fuzzy-based MPPT achieves faster convergence, lower steady-state ripple, and more stable MPP tracking than conventional methods under the investigated conditions.

Figure 11 illustrates the output voltage response of the PV system under fuzzy MPPT control. During the initial startup stage 0 - 0.1 s, the voltage shows small oscillations around 8.07 V due to the adjustment process required to locate the maximum power point. However, after a very short time, the system quickly converges and maintains an almost perfectly stable voltage throughout the remaining period from 0.2 s to 5 s. This result demonstrates the effectiveness of fuzzy MPPT in system control: fast response time, stable optimal voltage, and minimal oscillations, thereby improving the efficiency of power extraction from the solar panel.

Across all the presented results, it is evident that the fuzzy MPPT algorithm demonstrates outstanding effectiveness in controlling and extracting energy from the PV system. In both voltage and current waveforms, the system exhibits very fast convergence, reaching a stable state within only a few tenths of a second, while maintaining signals at their optimal levels with minimal ripple. The fuzzy control signals remain stable at their maximum value, reflecting accurate and reliable MPPT tracking without large oscillations or prolonged deviations as observed in traditional methods. Overall, all results clearly illustrate that fuzzy MPPT not only improves maximum power extraction efficiency but also enhances the stability, reliability, and adaptability of PV systems during long-term operation.

## 4. Conclusion

This study has investigated the application of FLC for maximum power point tracking in photovoltaic systems through detailed simulation analysis. The results indicate that the proposed fuzzy-based MPPT strategy can achieve fast convergence toward the maximum power point, maintain stable steady-state operation with reduced oscillations, and improve tracking performance compared with conventional Perturb and Observe and Incremental Conductance methods.

By adaptively regulating the perturbation step size while preserving the underlying decision logic of classical MPPT algorithms, the fuzzy-enhanced approach effectively mitigates the trade-off between dynamic response speed and steady-state accuracy. The observed improvements in stability and reduced power fluctuation suggest potential benefits in terms of energy harvesting efficiency and long-term system reliability.

Overall, the findings confirm that fuzzy logic provides a flexible and effective enhancement mechanism for conventional MPPT techniques. With appropriate parameter tuning and further experimental validation, the proposed fuzzy-based MPPT scheme represents a promising solution for practical photovoltaic applications, particularly in scenarios requiring improved adaptability and robustness under varying operating conditions.

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**Conflict of Interest**

The authors declare no conflict of interest.

**Declaration of generative AI and AI-assisted technologies in the writing process**

During the preparation of this work, the authors used ChatGPT in order to perform English language editing. After using this tool/service, the authors reviewed and edited the content as needed and take full responsibility for the content of the publication.

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