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Comparative assessment of an improved asymmetrical fuzzy logic control-based maximum power point tracking for photovoltaic systems under partially shaded conditions

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ABSTRACT

This paper presents an enhanced asymmetrical fuzzy logic control (AFLC) based maximum power point tracking (MPPT) algorithm designed for photovoltaic (PV) systems under partial shading conditions (PSCs). With the increasing global energy demand and growing environmental concerns, maximizing solar energy efficiency has become more essential than ever. The proposed AFLC-MPPT algorithm tackles the challenges of accurately tracking the global maximum power point (GMPP) in PSCs, where conventional methods frequently underperform. By utilizing asymmetrical membership functions and optimized rule sets, the algorithm significantly improves sensitivity and precision in detecting and responding to variations in shading. Simulations conducted in MATLAB/Simulink compare the performance of the proposed AFLC-based MPPT with the conventional perturb and observe (P&O) method across multiple shading scenarios. The results demonstrate that the AFLC approach outperforms the conventional method in terms of tracking speed, stability, and overall efficiency, particularly in dynamically changing environmental conditions. Furthermore, the AFLC algorithm provides substantial improvements in voltage regulation, reduces settling time, and minimizes steady-state oscillations, contributing to the more efficient and reliable operation of PV systems under partial shading conditions.

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1. INTRODUCTION

Energy is vital for meeting basic human needs, including health, everyday living, communication, and mobility, as well as for economic and social development and well-being. Worldwide energy demand is increasing annually, in line with corresponding growth. According to the U.S. Energy Information Administration (EIA), global energy consumption is projected to rise by nearly 50% [1]. Since the industrial revolution, fossil fuels have been the primary source of energy, currently supplying about 80% of the world's energy [2]. However, the depletion of fossil fuels presents a significant challenge in meeting this growing demand, as these resources are neither sustainable nor environmentally friendly. Fossil fuels contribute to severe issues such as global warming and air pollution due to carbon dioxide (CO_2) emissions released into the atmosphere [3]. In response to these challenges, the focus has shifted toward renewable energy sources, including wind, solar, tidal, and geothermal energy, as viable alternatives to address the energy shortfall [4]. Among these, solar energy stands out as a compelling solution due to its limitless and eco-friendly characteristics, providing a sustainable energy source without causing harmful environmental impacts [5]. Furthermore, solar energy is one of the most efficient solutions proposed to reduce both the economic and environmental footprints of energy [6].

In photovoltaic (PV) systems, the primary method for harnessing solar energy is the conversion of sunlight into electrical energy through the PV effect. This process utilizes solar cells made from semiconductor materials such as silicon, which are capable of transforming sunlight into electricity. A photovoltaic system includes one or more solar panels, an inverter, and other electrical and mechanical components. These elements work together to capture solar energy and generate electricity, illustrating the fundamental operation of a photovoltaic system [7]. The performance of a PV system is influenced by its unique characteristic, known as the maximum power point (MPP), which varies with external factors such as irradiation and temperature [8]. A key function of PV systems is to efficiently and rapidly extract the maximum available solar energy under varying environmental conditions, a process known as maximum power point tracking (MPPT) [9], [10].

Over the years, numerous MPPT algorithms have been developed to optimize power tracking in PV systems, including perturb and observe (P&O), incremental conductance (INC), fuzzy logic control (FLC) [11]–[13] and adaptive fractional order PID (A-FOPID) controllers [14]. Conventional methods such as P&O and INC are widely used due to their simplicity and ease of implementation. The P&O method perturbs the PV array voltage or current to track the maximum power point (MPP), while INC determines the MPP by analyzing the slope of the PV power curve [15], [16]. However, these methods face significant challenges under partial shading conditions (PSCs), where the power-voltage (P-V) curve contains multiple peaks, including a global maximum power point (GMPP) and several local maximum power points (LMPPs). This often causes P&O and INC to become trapped at local maxima, leading to power losses. In contrast, FLC offers greater adaptability through rule-based systems, and A-FOPID demonstrates improved tracking accuracy and response speed. The proposed asymmetrical FLC approach builds upon these advancements by balancing adaptability, simplicity, and flexibility, making it highly suitable for real-world PV systems under PSCs. Addressing the challenges posed by PSCs requires robust algorithms capable of accurately distinguishing GMPP from LMPPs under varying shading scenarios [17].

FLC algorithm is another widely used approach for tracking the maximum power point in PV systems, particularly under partial shading conditions. The fuzzy control strategy can effectively address the inherent flaws in PV systems by dynamically adjusting to variations in operating conditions [18], [19]. One of the key advantages of fuzzy theory is its ability to handle uncertainties and inaccuracies related to MPP detection, which often arise from fluctuations in solar irradiance and load changes [20], [21]. Additionally, the flexibility of fuzzy logic allows for the development of rule-based systems that can adapt to a wide range of input conditions, ensuring more reliable and efficient MPP tracking in complex environments. The FLC system uses two input variables and one output variable, with the control process divided into three stages: fuzzification, fuzzy inference, and defuzzification.

This study aims to develop an improved MPPT algorithm that leverages asymmetrical FLC to enhance tracking performance under PSCs. The novelty of this research lies in the implementation of asymmetrical membership functions and tailored fuzzy rule sets, which improve tracking accuracy, stability, and efficiency in dynamically changing environmental conditions. Unlike conventional fuzzy logic methods, the proposed approach is specifically designed to adapt to the complex and non-linear characteristics of PV systems under PSCs. The structure of this paper is as follows: Section 2 provides an overview of the PV system and its components. Section 3 introduces the proposed asymmetrical FLC algorithm. Section 4 discusses the MATLAB/Simulink simulation results, and Section 5 concludes the paper.

2. DESCRIPTION OF THE PHOTOVOLTAIC SYSTEM

2.1. Photovoltaic (PV) system

Figure 1 illustrates the block diagram of a PV system with an MPPT controller. The system employs an MPPT controller based on asymmetrical fuzzy logic control (AFLC), which processes voltage and current inputs from the PV panel to adjust the duty cycle accordingly. The direct current (DC)-to-direct current (DC) converter serves to regulate the DC output, ensuring it can be adjusted for maximum power extraction [22]. The AFLC algorithm involves three main processes: fuzzification, inference, and defuzzification.

2.2. Photovoltaic cell

Figure 2 depicts a circuit model of a solar PV cell, which serves as an electrical transducer to transform photon energy from light into electrical energy. A current source, resistors, and a diode make up the circuit. This model is identified as the single diode model comprises of series resistance (R_S) and parallel resistance (R_P). Ideally, R_S and R_P are negligible, but in practice, these resistances cannot be ignored, as they affect the efficiency of the solar PV cell [23]. Solar PV cells are attached in series or parallel combinations to form PV modules, which are then linked to create PV arrays with the required output. The solar PV cell's output can be derived using Kirchhoff's Law:

$$I_{o(PVcell)} = I_{ph} - I_d - I_p \tag{1}$$

$$I_{o(PVcell)} = I_{ph} - I_{sat} * \left[\exp\left(\frac{q(V_{o(cell)}+I_{o(PVcell)}*R_S)}{AkT_{ac}}\right) - 1\right] - \frac{V_{o(cell)}+I_{o(cell)}R_S}{R_{sh}} \tag{2}$$

while the output current for the PV array is given as

$$I_o = p.I_{ph} - p.I_{sat} * \left[\exp\left(\frac{q(V_o+I_o*R_S(s/p))}{sAkT_{ac}}\right) - 1\right] - \frac{V_{o/p}+I_{o/p}R_S(s/p)}{R_p(s/p)} \tag{3}$$

Here, I_o denotes the output current, while V_o represents the voltage of the PV array. I_{sat} is the diode's reverse saturation current, s refers to the number of cells connected in series, and p is the number of parallel cells. q represents the elementary charge with a value of 1.602×10^{-19}, A is the ideality factor, k is Boltzmann's constant (1.38×10^{-23} J), and T_{ac} denotes the actual temperature.

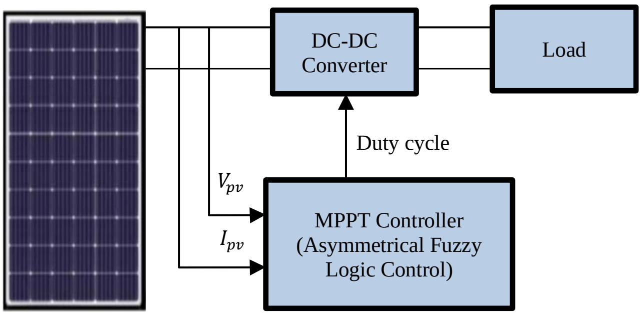


Figure 1. Block diagram of PV system

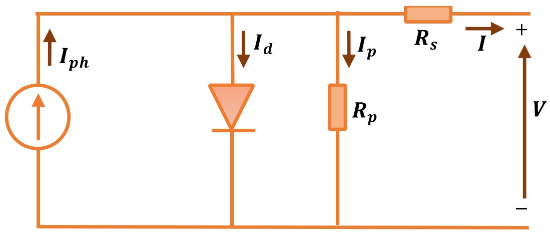


Figure 2. Equivalent circuit of PV cell

2.3. PV systems under partial shading conditions

In large PV systems, solar panels are typically connected in series to increase the string voltage or in parallel to boost output power [24]. Due to the extensive exterior area of PV modules, they are often uncovered to varying solar irradiance, which is a major cause of power losses in PV systems. In a string of PV modules, when individual panels exhibit different short-circuit currents, the module with a lower current than the string current will experience reverse voltage and begin to absorb energy from the other modules [25]. This can lead to significant power dissipation in the form of heat, potentially causing permanent destruction to the affected PV panels. These mismatched conditions, particularly resulting from solar irradiance fluctuations, emphasize the importance of MPPT for ensuring optimal performance control.

In Figure 3, the PV system is displayed with partial shade and uniform illumination. Figures 3(a) and 3(b) show the operation of a PV array comprising of three PV modules attached in parallel with bypass diodes. Under uniform irradiation, the bypass diodes do not conduct and have no impact on the performance of the PV array. However, during PSCs, the bypass diodes activate, allowing current to bypass the shaded cells. Without bypass diodes, the output power would drop significantly. Therefore, to maintain higher output power under PSCs, bypass diodes must continually be linked in parallel with a set of PV cells in the PV modules. In Figure 3(c), the P-V curve of the PV array displays several LMPPs and one global maximum power point (GMPP) under PSCs. Hence, it is critical to distinguish between the GMPP and LMPPs.

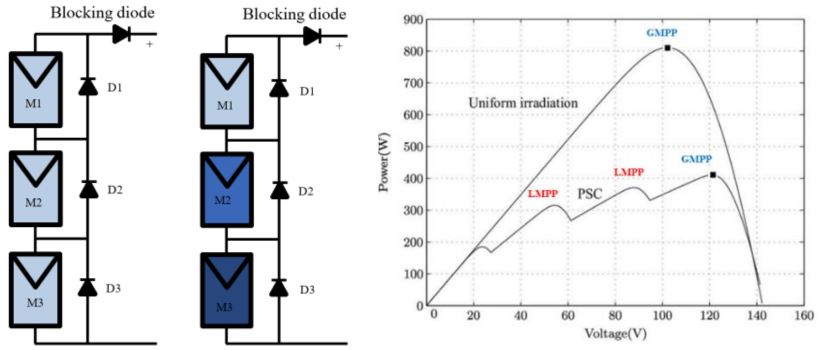


Figure 3. PV Generator (a) under uniform irradiation, (b) under PSCs and (c) P-V curve under uniform irradiation and PSCs

A boost converter is a DC-to-DC converter that lowers current from the supply to the output (load) and raises voltage. Figure 4 presents the schematic diagram of a DC-DC boost converter. The insulated-gate bipolar transistor (IGBT) switch, inductor, shunt capacitor, and diode are components of the boost converter. The values for inductance, capacitance, duty ratio, and resistive load can be ascertained as (4)-(7).

$$L = \frac{V_{i/p} * (V_{o/p} - V_{i/p})}{(\Delta I f_{sw} V_{o/p})} \quad (4)$$

$$\alpha = 1 - \left(\frac{V_{i/p}}{V_{o/p}}\right) \quad (5)$$

$$C = \frac{I_a \alpha}{(V_{o/p} \Delta V f_{sw})} \quad (6)$$

$$R_{in} = (1 - \alpha)^2 R_l \quad (7)$$

Here, $V_{o/p}$ represents the output voltage, α is the duty ratio, ΔI is the ripple in output current, which is 10% of the input current, f_{sw} denotes the switching frequency, ΔV indicates the ripple in peak voltage, I_a is the average output current considered as 3% of the output voltage, $V_{i/p}$ is the input voltage, and R_{in} refers to the input resistance.

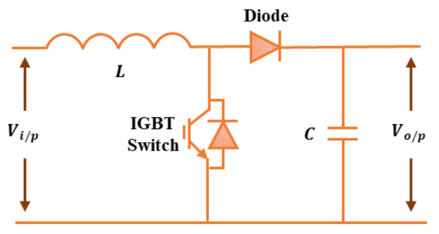


Figure 4. Schematic diagram of DC-DC boost converter

3. PROPOSED ASYMMETRICAL FUZZY LOGIC CONTROL-BASED MPPT ALGORITHM

3.1. Conventional P&O

In this study, the conventional P&O method is adopted as a benchmark to compare with the proposed algorithm. The P&O algorithm is extensively employed for MPPT in photovoltaic systems because it is straightforward and simple to use. The algorithm operates by periodically perturbing (adjusting) the operating voltage of the PV system and observing the resulting changes in power output [16]. Initially, the system measures the voltage (V) and current (I) from the PV array to compute power (P). A small perturbation is then introduced to the voltage, either increasing or decreasing it. To determine the updated power after the disturbance, the new voltage and current are measured. The new power and the prior value are compared by the algorithm. The perturbation persists in the same direction for the subsequent cycle if the power is increased. On the other hand, the direction of disturbance is reversed if the power drops. This operation of perturbation and observation is repeated, with the algorithm iteratively adjusting the voltage to locate and maintain the maximum power point. Although effective, the P&O algorithm may cause fluctuations around the MPP and can be slow to adapt to environmental changes.

3.2. Conventional FLC algorithm

The FLC algorithm is an intelligent control system that uses fuzzy logic principles to regulate complex systems, including MPPT in photovoltaic systems. Within the framework of tracking the GMPP under partial shading conditions, FLC provides a flexible approach for adjusting system parameters based on imprecise inputs. It utilizes linguistic variables, fuzzy rules, and membership functions to model system behavior and make decisions under uncertain conditions. However, conventional FLC may struggle to distinguish between local MPPs and the global MPPs during partial shading conditions, leading to suboptimal tracking, oscillations, and efficiency losses. To address these issues, the design of fuzzy logic membership functions and rules was adapted from methodologies outlined by [20], [26], with modifications to incorporate asymmetrical characteristics for improved adaptability under PSCs.

3.3. Proposed asymmetrical FLC-based algorithm

In the conventional FLC algorithm, the membership functions (MFs) are designed symmetrically around the zero or neutral point of the input variables. While designing MFs is relatively straightforward, involving the uniform definition of the shape and spread of the functions, there are certain limitations, such as uniform sensitivity and reduced adaptability. Conventional FLC with symmetrical MFs may not perform optimally in PV systems with highly non-linear characteristics, as it struggles to adapt to quickly altering conditions, particularly under partial shading.

To address the limitations of conventional FLC, an improved AFLC is proposed in this paper. The AFLC membership functions are designed asymmetrically to provide different levels of sensitivity and adaptability under partial shading conditions. For the fuzzy variables, the asymmetric distribution of input and output membership functions exhibit both divergent and convergent forms of asymmetry. The parameters were adjusted to balance the sensitivity and robustness of the algorithm, allowing it to converge to the maximum power point with reduced oscillations.

The block diagram for the asymmetrical FLC-based control algorithm is displayed in Figure 5 and illustrates its flow. The system has two main inputs, output voltage $V_{o/p}$ and output current $I_{o/p}$, which undergo initial processing through multiplication and subtraction operations. These processed inputs are then used to calculate the "error" and "change of error." The asymmetrical fuzzy logic controller consists of three stages: fuzzification, an inference engine, and defuzzification. The final output of the process is the duty ratio, a critical parameter for controlling the DC-DC converter in the photovoltaic system to optimize performance.

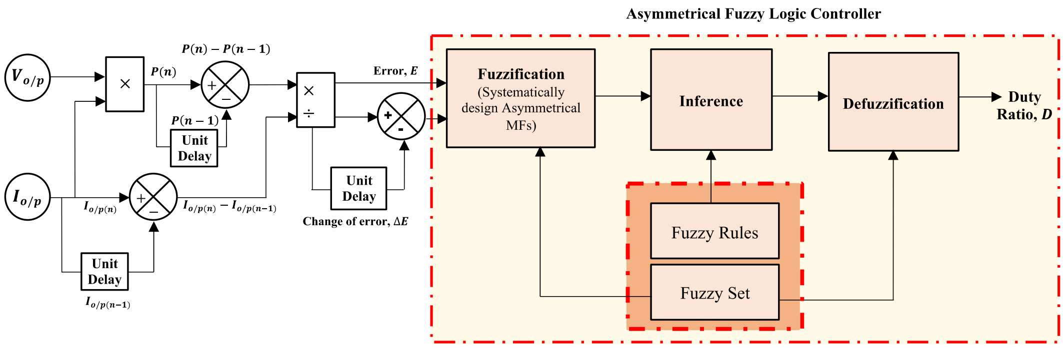


Figure 5. Block diagram of the asymmetrical FLC-based algorithm

3.3.1. Fuzzification

The fuzzification process involves transforming numerical input variables into degrees of membership in corresponding fuzzy sets. The effectiveness of this process largely depends on the design and characteristics of the membership functions. Two input variables are present: error (E) and change of error (ΔE), both sampled at the instant n. In regard to the voltage and current detected, the power is computed. The variables E and ΔE are derived as (8) and (9).

$$E(n) = \frac{P_{(n)} - P_{(n-1)}}{I_{o/p\,(n)} - I_{o/p\,(n-1)}} \tag{8}$$

$$\Delta E(n) = E(n) - E(n-1) \tag{9}$$

where $P_{o/p}$ is the power output and $I_{o/p}$ is the current output of the PV system.

The flowchart of the overall system is presented in Figure 6. The process initiates by setting the initial value of the duty ratio based on the system parameters. It then measures the voltage and current of the PV system. Using these measured values, the power of the PV system is calculated. Next, the MPPT algorithm computes the error (E) and change of error (ΔE) based on the present and previous power and current values. These values are then input into the AFLC-based algorithm and undergo fuzzification using asymmetrical membership functions. The fuzzified values are processed through the inference method, which utilize predefined fuzzy sets and rules. The output from the inference method is then defuzzified to produce a crisp value for the change in duty ratio (D). The new duty ratio is calculated and fed back into the beginning of the process, where it is used to adjust the operating point of the PV system.

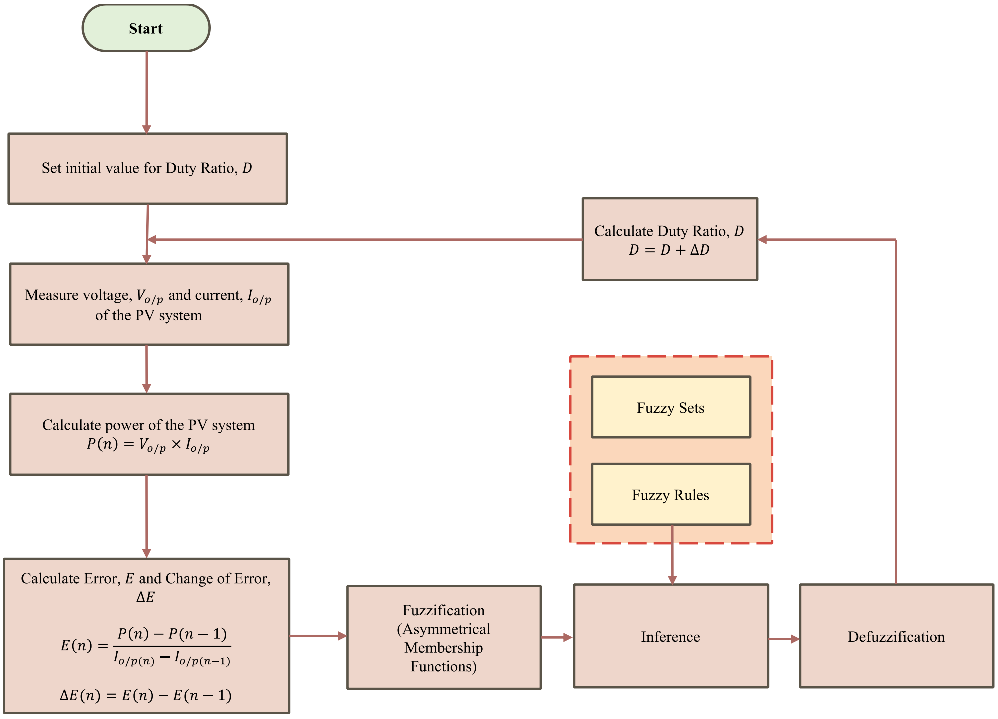


Figure 6. Flowchart of ALFC-based algorithm

A key idea in fuzzy logic are membership functions, which specify how every single point in the input space is assigned to a membership quantity between 0 and 1. These values represent the degree to which an input fits to a specific fuzzy set. In the proposed system, both the input and output fuzzy sets comprise of five triangular membership functions. The fuzzy input and output membership functions utilized to track the maximum power point under partially covered situations have an asymmetrical distribution, as shown in Figure 7. Figure 7(a) presents the asymmetrical input variable, error, where the membership functions are divided into five fuzzy sets: Negative Big (NB), Negative Small (NS), Zero (ZO), Positive Small (PS), and Positive Big (PB). Figure 7(b) depicts the input variable, change of error, which influences the controller's decision-making process. Finally, Figure 7(c) shows the output variable, duty ratio, which determines the adjustment applied to the system. The input membership functions are narrower near the zero-error point to enhance sensitivity around the MPP.

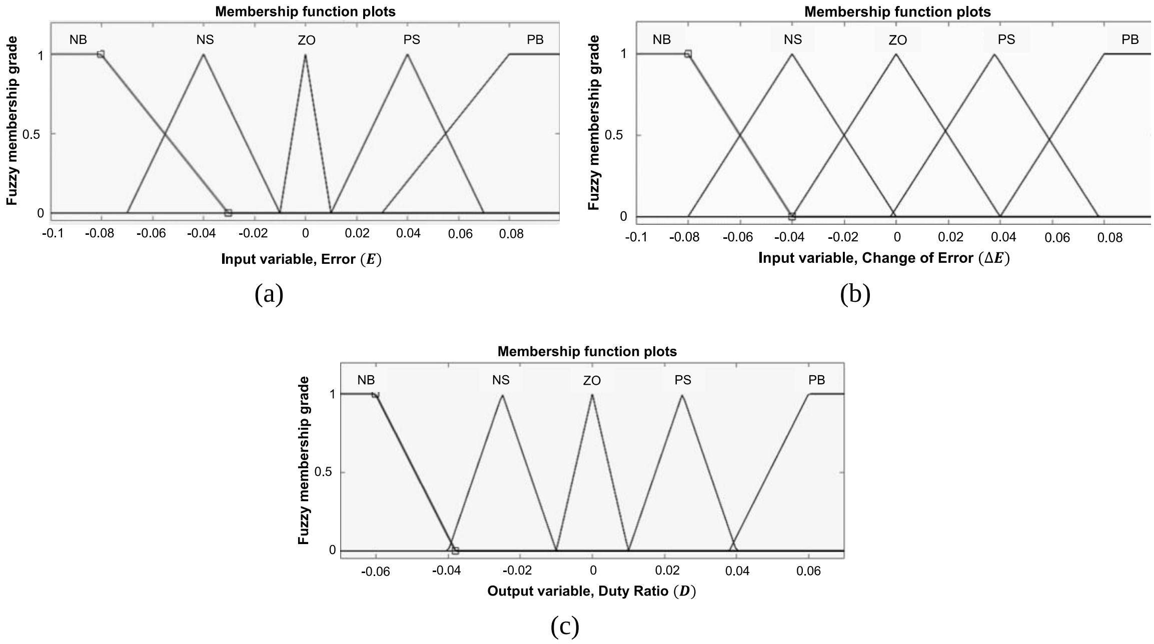


Figure 7. Membership function of AFLC algorithm for (a) Asymmetrical input variable, error (E), (b) Input variable, change of error (ΔE), and (c) Output variable, duty ratio (D)

3.3.2. Inference

The inference method in AFLC is the process of mapping fuzzified inputs to fuzzified outputs using a rule base. The rule base consists of carefully crafted rules that consider the asymmetrical relationships between input and output variables to optimize power tracking performance. This process involves applying fuzzy rules to the input membership values to derive an output fuzzy set, which is then defuzzied to produce a crisp control action. The fuzzy inference system can use either the Mamdani or Takagi-Sugeno methods, as both can incorporate symmetrical or asymmetrical membership functions [11]. In the context of AFLC for MPP tracking, the Mamdani technique is employed because it is simple to utilize.

Creating a rule base as a kind of a matrix is an effective way to systematically determine the control actions required to track the MPP in a photovoltaic system, especially under partial shading conditions. The main goal is to get the operating point nearer the MPP with minimal fluctuations by appropriately adjusting the duty ratio of the DC-DC converter. Table 1 shows the fuzzy rule base for computing the output variable of the proposed system. The rules are organized in a matrix format where rows represent the error and columns represent different values of the change in error. The fuzzy rule base consists of 25 rules, defined based on expert knowledge and simulation results. For example, if the error (E) is 'Positive Small' and the change of error (ΔE) is 'Positive Big', the output duty ratio (D) is adjusted to 'Zero'. The asymmetrical membership functions were designed to be narrower around zero-error points for higher sensitivity, with values ranging from -0.1 to 0.1. Additionally, a 3D graph called a surface viewer shows these rules as illustrated in Figure 8.

Table 1. Fuzzy rule base

E			ΔE		
	NB	NS	ZO	PS	PB
NB	ZO	ZO	NB	NB	NB
NS	ZO	ZO	NS	NS	NS
ZO	NS	ZO	ZO	ZO	PS
PS	PS	PS	PS	ZO	ZO
PB	PB	PB	PB	ZO	ZO

3.3.3. Defuzzification

Defuzzification in AFLC is employed to transform the fuzzy output values attained from the inference method back into crisp output values for practical implementation in the PV control system. The process involves calculating a crisp output value based on the fuzzy output membership degrees and the asymmetrical distribution of the output membership functions. Defuzzification can be performed using the center of area, known as the centroid method. In this study, the centroid method is employed for the defuzzification process, and it is represented by the (10).

$$x = \frac{\sum_{i=1}^{n} \mu(x_i) x_i}{\sum_{i=1}^{n} \mu(x_i)} \quad (10)$$

where μx_i is the activation degree of rule $'i'$, x_i is the centre of the maximum-minimum composition of the output membership functions and x is the output which is duty cycle.

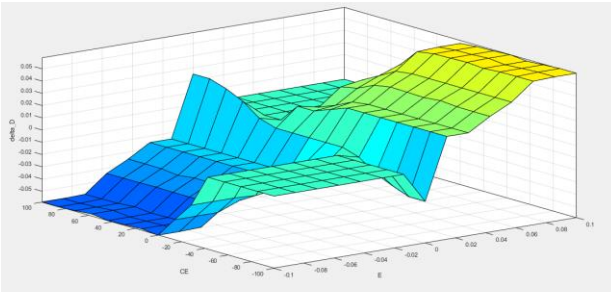


Figure 8. 3D Dimensions of fuzzy rule

4. SIMULATION RESULT AND DISCUSSION

The proposed Asymmetrical FLC-based MPPT algorithm was built and simulated in MATLAB/Simulink software in a closed-loop configuration to evaluate its stability and performance under standard test conditions and partial shading conditions. Figure 9 shows the PV system with a DC-DC boost converter and the proposed MPPT controller under standard test conditions (STC). The PV modules used in this study are 1Soltech 1STH-215-P, with a maximum power of 213.15W, consisting of 1 series module and 1 parallel string. In this study, all three PV modules in the proposed AFLC-based algorithm are connected in series and exposed to different irradiation levels with various shading patterns. Table 2 shows the global and local maximum power points of the PV system under different shading patterns. The following cases are considered, with solar irradiance varying as specified for each case and the temperature remaining constant at 25°C:

a. Case 1: All PV modules are under standard test conditions, with solar irradiance at 1,000 W/m^2.
b. Case 2: PV Module 1 is exposed to 1,000 W/m^2, Module 2 to 750 W/m^2 and Module 3 to 500 W/m^2.
c. Case 3: PV Module 1 is exposed to 500 W/m^2, Module 2 to 400 W/m^2 and Module 3 to 700 W/m^2.

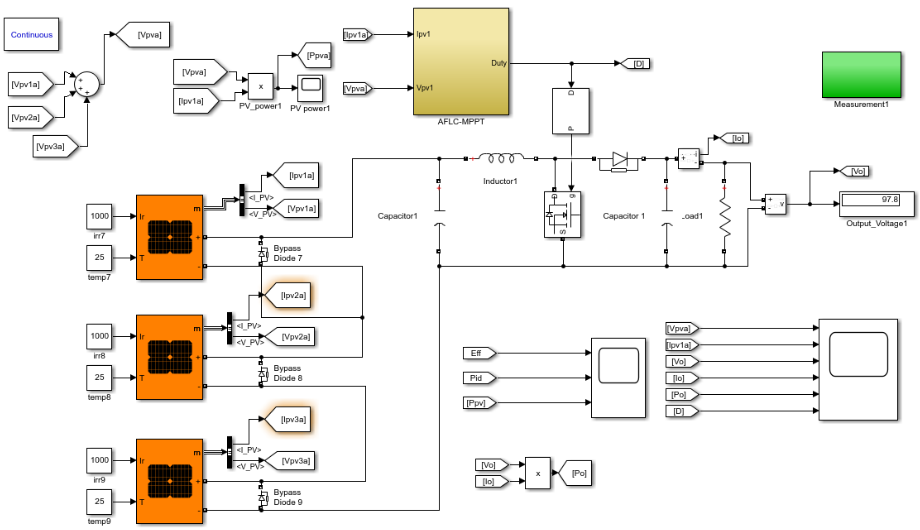


Figure 9. Circuit simulation of proposed AFLC-based MPPT under standard test conditions

Table 2. Power at GMPP and LMPP under various irradiations

	Case 1	Case 2	Case 3
P_{GMPP} (W)	213.15	213.15	150.79
P_{LMPP} (W)	-	161.33; 107.99	107.99; 86.27

4.1. All PV modules are under standard test conditions, with solar irradiance at 1000 W/m^2

Figure 10 illustrates the obtained graph from the simulation of PV voltage, PV current and PV power of the proposed AFLC-based algorithm under Case 1 standard test conditions respectively. The MPPT controller demonstrates exceptional performance under uniform irradiance of 1,000 W/m^2. The voltage graph in Figure 10(a) shows a stable response after a brief period. The PV voltage starts close to 0 V and quickly rises to around 100 V in a very short time (approximately 0.01 seconds). After that, it remains stable at its maximum level without any significant fluctuations. This indicates that the PV system is operating at its maximum voltage and becomes stable after the initial transition phase. As shown in Figure 10(b), the PV current exhibits a similar transient response, starting around 0 A and increasing to a stable level of approximately 5 A after 0.01 seconds. The current then remains stable throughout the simulation, indicating that the system has reached the steady current required for maximum energy output. The power output initially increases and stabilizes at around 480 W after a short period, as seen in Figure 10(c). After 0.01 seconds, the power output remains consistent, indicating that the system has reached the MPP. This simulation demonstrates the effectiveness of the AFLC-based MPPT algorithm used to ensure that the PV system operates at the maximum power level. The achievement of a maximum power of around 480 W shows that the system operates efficiently under standard test conditions, with voltage and current aligned with the PV requirements to produce optimal power output.

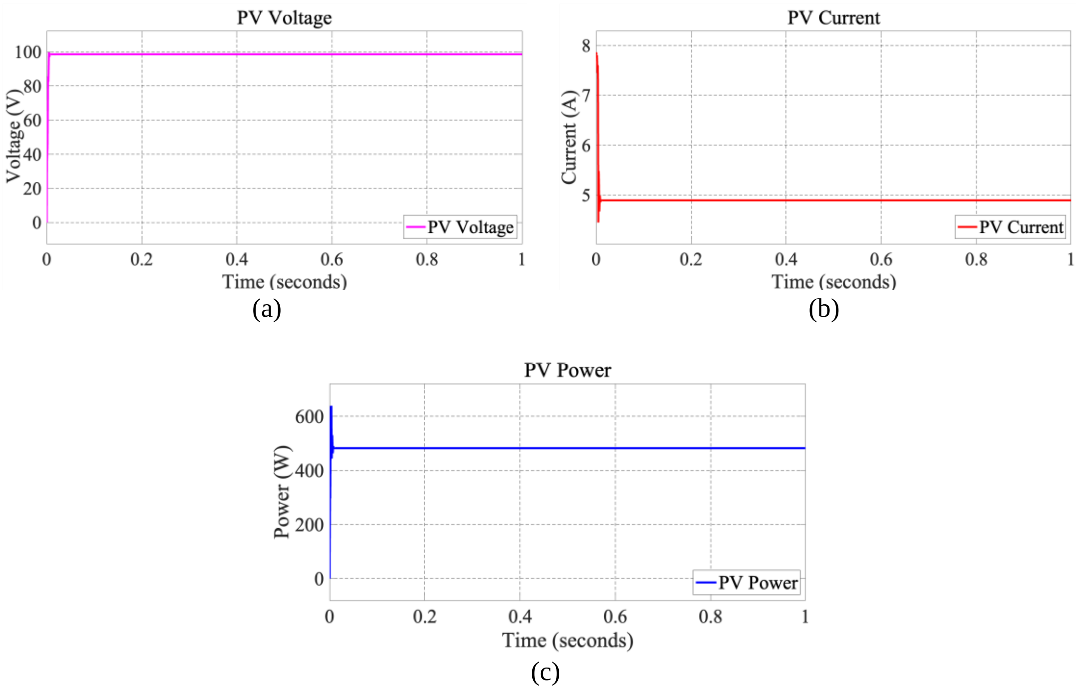
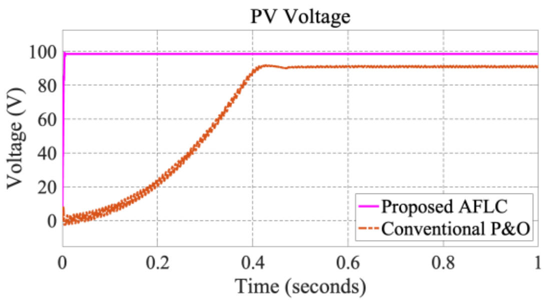


Figure 10. Simulated graph of (a) PV voltage, (b) PV current, (c) PV power of PV system under standard test conditions

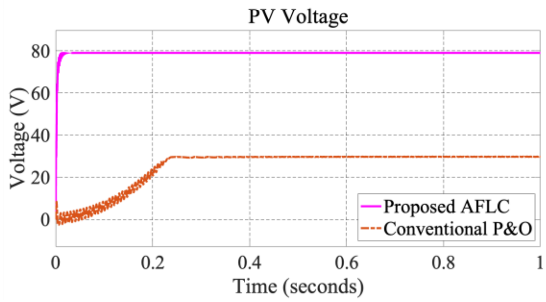
4.2. Comparison of proposed AFLC-based algorithm with conventional P&O

The results align with the study's objective of enhancing MPPT performance under partial shading conditions, demonstrating the superiority of the proposed AFLC algorithm over the conventional P&O method in terms of accuracy and adaptability. This study focuses on a direct comparison between the AFLC and P&O methods, which are widely used in MPPT applications. The asymmetry in the AFLC algorithm ensures higher sensitivity near zero error, enabling faster and more accurate responses under partial shading conditions. For instance, when the error (E) is 'Negative Small' and the change of error (ΔE) is 'Positive Big', the fuzzy inference system adjusts the duty ratio by a small decrement to maintain optimal performance. The comparison across three cases in Figure 11 highlights that AFLC consistently outperforms P&O, demonstrating faster response times, reduced steady-state oscillations, and greater stability under varying shading conditions.

In Figure 11(a), for Case 1 under STC, the AFLC-based algorithm achieved a maximum voltage of 99.78 V in just 0.004 seconds, whereas the conventional P&O method required 0.42 seconds to reach a lower voltage of 92.10 V. These results clearly illustrate that the AFLC method sustains a more stable voltage output, with a quicker response and fewer oscillations compared to P&O, which experiences larger fluctuations. Figures 11(b) and 11(c) show the performance under partial shading conditions. In Case 2 as depicted in Figure 11(b), the AFLC-based MPPT algorithm reached a maximum voltage of 79.44 V in 0.017 seconds, while the conventional P&O method took 0.98 seconds to reach 29.87 V, highlighting AFLC's ability to locate and maintain the global maximum power point despite variations in irradiance. As depicted in Figure 11(c), in Case 3 the AFLC-based algorithm reached a maximum voltage of 64.02 V in just 0.01 seconds, compared to the P&O method, which required 0.89 seconds to reach 62.06 V. Although this study focuses on comparing the proposed AFLC approach with the conventional P&O method, recent advancements like the A-FOPID controller [14] have demonstrated significant improvements in MPPT performance. Compared to A-FOPID, the AFLC method offers a simpler yet robust alternative, particularly under partial shading conditions. The simplicity of AFLC makes it a more feasible solution for real-world applications, as it requires fewer computational resources. Table 3 tabulates the simulation results of these three studies.



(a)



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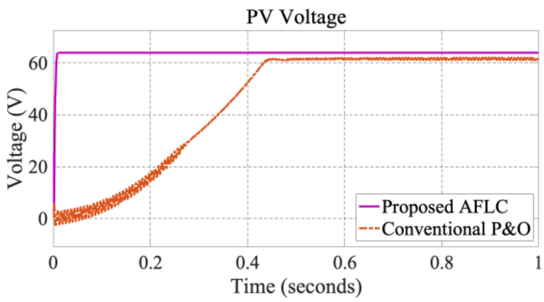

(c)

Figure 11. Comparison result of PV Voltage between the proposed AFLC-based algorithm and conventional P&O under (a) Case 1 – STC, (b) Case 2 – PSC pattern 1, and (c) Case 3 – PSC pattern 2

Table 3. Comparison of Steady-state response between the proposed AFLC-based algorithm and the conventional P&O

MPPT Techniques	Voltage (V)			Steady-State Oscillations
	Case 1	Case 2	Case 3	
Conventional P&O	92.10	29.87	62.06	Significant
Proposed AFLC-based algorithm	99.78	79.44	64.02	Minimal

Simulations demonstrated that the AFLC controller achieved stable operation with minimal steady-state oscillations and faster settling times compared to the conventional P&O method. The asymmetrical membership functions in the AFLC design were critical in maintaining stability by dynamically adjusting the output based on error magnitude and direction. However, this study is limited to simulations performed in MATLAB/Simulink, and the results have not yet been validated through hardware implementation.

Furthermore, the sensitivity of the AFLC algorithm to extreme weather conditions remains unexplored, which presents an opportunity for future research. The simulations confirmed the controller's stability under the tested scenarios, but further work is needed to validate its performance against more dynamic disturbances, such as rapid irradiance fluctuations or temperature changes. Future research can focus on hardware implementation and further optimization for specific PV system configurations.

5. CONCLUSION

The AFLC-based MPPT algorithm proposed in this study has demonstrated superior performance compared to the traditional P&O method under partial shading conditions. Through extensive simulations, the AFLC approach exhibited significant improvements in settling time, stability with reduced oscillations, and adaptability to varying shading patterns and voltage levels. For example, in Case 3, the AFLC algorithm achieved a maximum voltage of 64.02 V within 0.01 seconds, whereas the P&O method required 0.89 seconds to reach 62.06 V. These findings indicate that the AFLC-based MPPT algorithm offers a robust and efficient solution for improving PV system performance under challenging environmental conditions. Its ability to adapt dynamically to shading variations highlights its potential for real-world applications, particularly in large-scale PV installations where maximizing energy output is critical. Implementing this approach could significantly enhance energy production efficiency, reduce operational costs, and contribute to the broader adoption of renewable energy technologies. While the current work provides a solid foundation, several avenues remain for future research. These include hardware implementation of the proposed algorithm, testing it under diverse environmental conditions to validate its robustness, and optimizing the algorithm for specific PV system configurations. Additionally, conducting sensitivity analyses and exploring hybrid approaches that integrate other MPPT techniques could further strengthen its applicability and performance.

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AUTHOR CONTRIBUTIONS STATEMENT

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C : **C**onceptualization
M : **M**ethodology
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Va : **Va**lidation
Fo : **Fo**rmal analysis
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Vi : **Vi**sualization
Su : **Su**pervision
P : **P**roject administration
Fu : **Fu**nding acquisition

CONFLICT OF INTEREST STATEMENT

Authors state no conflict of interest.

DATA AVAILABILITY

Data availability is not applicable to this paper as no new data were created or analyzed in this study.

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