Rapid and efficient maximum power point tracking in photovoltaic systems with modified fuzzy logic approach

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ABSTRACT

Photovoltaic systems (PVs) often face difficulties in maximizing their output power and maintaining a stable DC-DC connection voltage, especially under variable weather conditions (VWC). The power produced by photovoltaic panels is very sensitive to changes in sunlight and temperature, which vary throughout the day. This paper presents the design of an intelligent controller approach based on modified fuzzy logic (MFLC), adapted to enable the most effective maximum power point tracking (MPPT) of a photovoltaic solar module. The technique reduces delays in MPPT and sustains efficiency despite changing environmental conditions. A DC-DC boost converter is connected to the photovoltaic solar module, which in turn is linked to a load, and computer simulations using MATLAB/Simulink were used to validate the method's effectiveness. Results reveal that the MFLC controller significantly enhances the efficiency of the PVs, achieving improvements of up to 97.05%, with a rapid settling time of less than 10 milliseconds across all test scenarios.

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1. INTRODUCTION

Given the rising global energy demand and environmental concerns as well as the depletion of fossil fuel reserves, the necessity of sustainable energy solutions has become increasingly apparent. Photovoltaic (PV) systems are an important renewable energy source as they generate clean electricity. However, the variability of solar energy affected by fluctuations in irradiance, temperature, and weather presents critical challenges in ensuring optimal energy conversion efficiency [1], [2] this variability underscores the need for advanced control strategies to enable photovoltaic systems (PVs) to reliably track the maximum power point (MPP).

The key research problem addressed in this paper is the inherent limitations of maximum power point tracking (MPPT) techniques under dynamic environmental conditions. While traditional MPPT algorithms, such as perturb and observe (P&O) [3], and incremental conductance (InC) [4], while effective under stable conditions, often struggle to perform optimally under dynamic and unpredictable climatic situations. Leading to issues such as slow response, tracking errors, and Failure to achieve the optimal MPPT, In order to handle these issues, several MPPT algorithms have been developed recently; those can be divided into some categories such as conventional algorithms, meta-heuristic algorithms, hybrid algorithms, mathematics-based algorithms, artificial intelligence (AI) algorithm, algorithm based on a characteristic curve, and other miscellaneous algorithms [5]–[7].

This paper presents the modified fuzzy logic controller (MFLC), which is designed to overcome the limitations of the conventional MPPT techniques. The MFLC exploits the inherent strengths of fuzzy logic, its ability to handle uncertainties and non-linearities, while incorporating specific modifications to improve its performance under dynamic weather conditions. The proposed method addresses critical issues such as MPPT settling time delays and efficiency degradation under rapidly changing weather conditions. A boost DC-DC converter is integrated into photovoltaics to maximize energy transfer and stabilize the connection voltage, ensuring reliable operation in a variety of scenarios. The effectiveness of the MFLC-based MPPT approach is validated by comprehensive simulations performed in MATLAB/Simulink version 2024a. The results confirm the outstanding performance of the proposed method, with energy conversion efficiencies of up to 97.05% and a fast-settling time of less than 10 ms under all test conditions. These results highlight the potential of the MFLC technique to significantly improve the efficiency, stability, and settling time of PVs, making it a promising solution for renewable energy applications.

There are five portions in this work. The electrical modeling and properties of solar systems under changing conditions are examined in section 2. The suggested strategy is described in section 3. The simulation results and their analysis are shown in section 4. Lastly, the key findings are highlighted in the conclusion section.

2. ELECTRICAL MODELING OF A PVs

Figure 1 illustrates the block diagram of the PV system, comprising key components such as the PV panel, DC-DC boost converter, MPPT control, and load. The PV panel captures sunlight and converts it into electrical energy. The generated power, on the other hand, is regulated and supplied for consumption directly to the load, then the boost converter increases the voltage to as per the load requirement. The load is taken out of the boost converter output as shown below. This PVs operates in two distinct modes: Constant Voltage Control mode in which the inverter works to control the output voltage, while MPPT mode works to maximize energy extraction from the solar panel [8].

2.1. Photovoltaic cell model

The core components of PVs are PV cells and modules, which absorb photons from sunlight and release electron charges, thereby converting solar energy directly into electrical power [9]. Among the most commonly utilized models for describing PV behavior are the single-diode and double-diode models [10]. In this study, we employ the single diode model, where the diode (D) symbolizes the P-N junction, to accurately characterize the electrical properties of PV cells [11].

As shown in Figure 2, the single-diode model consists of a parallel diode (D), a shunt resistance (Rsh), and a series resistance (Rs). The governing equations for its electrical performance are sourced from prior studies [12], [13]. Using Kirchhoff's Law, (1) defines the current-voltage (I-V) relationship governing the circuit. This fundamental equation forms the basis for analyzing and optimizing PV cell performance.

$$I_{pv} = I_{ph} - I_d - I_{R_{sh}} \quad (1)$$

– Solar-generated current in the basic photovoltaic cell:

$$I_{ph} = (I_{cc} + K_i \Delta T) \quad (3)$$

– Current passing through the parallel-configured diode:

$$I_d = I_0 \left[\exp\left(\frac{q(V_{pv} + R_s I_{pv})}{AKT}\right) - 1\right] \quad (4)$$

– The shunt current through the resistance:

$$I_{Rsh} = \frac{V_{pv} + R_s I_{pv}}{R_{sh}} \quad (5)$$

I_0 Denotes the diode's reverse saturation current, while V_{pv} and I_{pv} represent the output voltage and current. Constants include q (electron charge, 1.602×10^{-19} C), A (ideality factor), and k (Boltzmann constant, 1.38×10^{-23} J/K).

The power-voltage (P-V), and current-voltage (I-V) curves presented in Figure 3 are based on results obtained using the advanced solar hydro wind power API156P-200 photovoltaic module. The array configuration includes a single series module with one parallel string. Figures 3(a) and 3(b) illustrate the properties of PV cells under different environmental conditions, such as temperature and irradiance. Solar radiation and temperature alterations critically impact PV behavior owing to the system's nonlinear operational dynamics. As a result, variations in these parameters can significantly influence the performance and efficiency of PV cells [14].

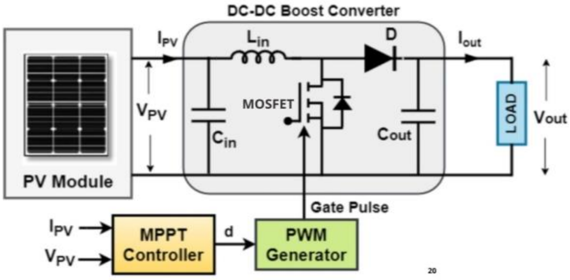


Figure 1. Photovoltaic system with MPPT control

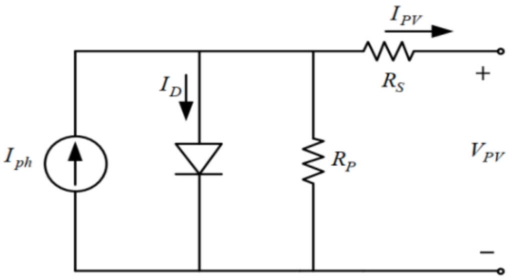
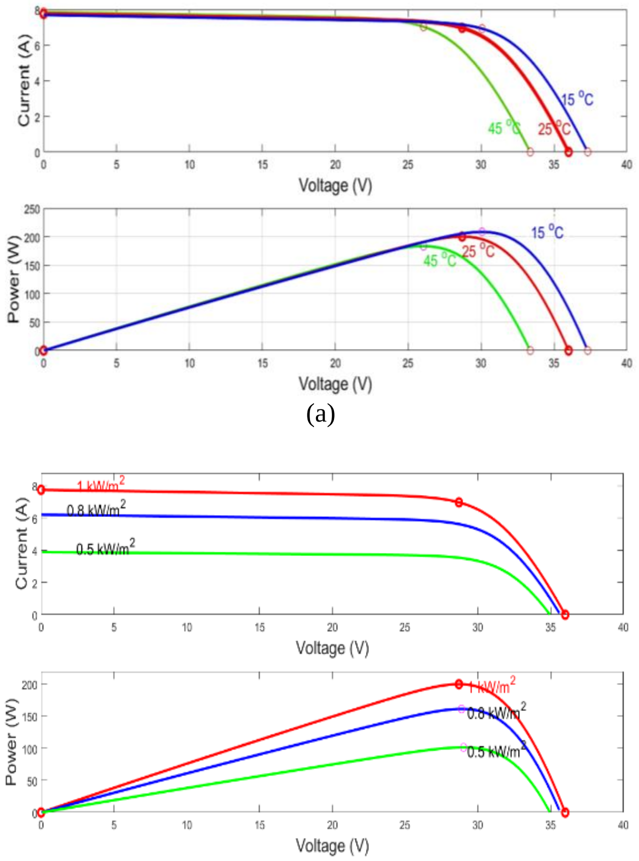


Figure 2. PV cell equivalent circuit



(a)

(b)

Figure 3. Properties of PV cells under different variable weather conditions (VWC): (a) different temperatures and (b) different irradiations

2.2. The DC-DC boost converter

The Boost converter steps up the input DC voltage to a higher output level. Its design in Figure 4 includes a DC source V_A, inductor (L), MOSFET, diode (D), and capacitors (C_{int}, C_{out}), as parameterized in Table 1. By leveraging (6) and (7), it dynamically adjusts the PV panel's operating point to achieve MPPT, ensuring optimal load matching [15], [16].

$$\frac{dI_L}{dt} = \frac{V_A}{L} \quad (6)$$

$$\frac{dV_0}{dt} = -\frac{V_0}{C_{out}R_L} \quad (7)$$

A PWM pulse generator provides duty pulses. When t is within the interval [αT, T], the transistor is inactive. Here, T represents the period of the static converter, while α indicates the duty cycle. The converter's behavior is described by (8) and (9). The converter's functioning is controlled by a switch, commonly a MOSFET, which switches between open and closed states dependent on the duty cycle generated by the MPPT process [17], [18].

$$\frac{dV_0}{dt} = \frac{i_L}{C_{out}} - \frac{V_0}{C_{out}R_L} \quad (8)$$

$$\frac{dI_L}{dt} = \frac{V_A - V_0}{L} \quad (9)$$

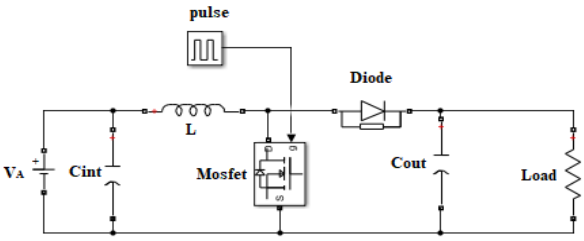


Figure 4. DC-DC boost converter

Table 1. DC-DC boost converter specifications

Parameter	Value
Inductance(L)	10 mH
Capacity (Cint)	4 µF
Capacity (Cout)	20 µF
Frequency (fs)	20 kHz
Load	60 Ω

3. PROPOSED METHOD
3.1. The MPPT-based fuzzy logic controller

The fuzzy logic controller is increasingly applied in various renewable energy systems due to their simplicity and effectiveness. Over the past decade, the demand for FLC has grown significantly, largely because it can manage imprecise inputs without needing an accurate mathematical model [19]–[21]. FLC is particularly adept at handling nonlinear conditions, making it an excellent choice for maximizing power output from PV modules. It can operate effectively under diverse weather conditions and adapt to changes in temperature and light intensity. Three criteria can be used to classify FLC processes: a) fuzzification, b) evaluation of rules, and c) defuzzification as depicted in Figure 5.

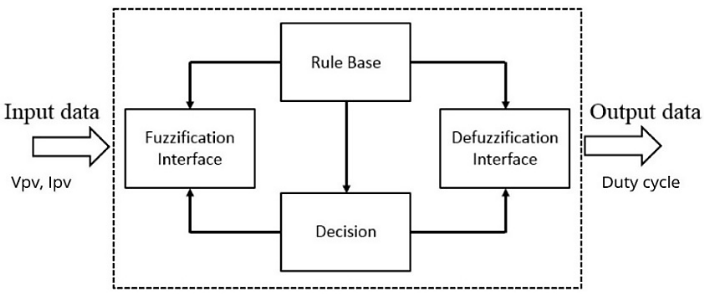


Figure 5. The framework of a fuzzy logic controller

3.2. The MPPT-based fuzzy logic controller

The fuzzification process is the first stage of an MFLC, and it is a big deal. The reason for this is that it is the first stage of an MFLC, because this is the part where clear, precise inputs are transformed into fuzzy values. It involves taking data such as voltage level changes and running them through predefined membership functions to transform them into error sets. This step is crucial as it establishes a framework for the controller to deal with uncertainty and make better decisions.

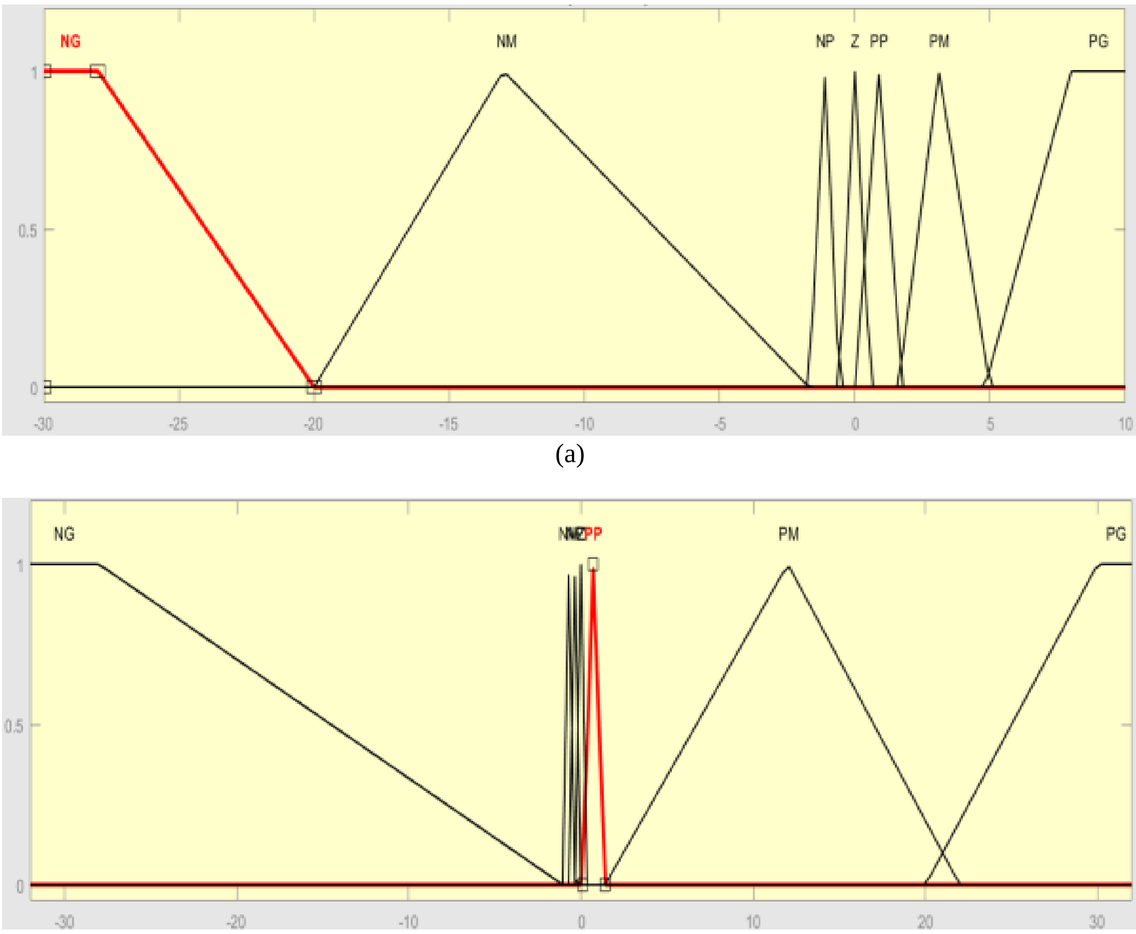
3.2.1. Fuzzification

The fuzzification unit is responsible for converting real variables into fuzzy variables [22]. In this case, the inputs to the MFLC represented as $E(k)$ and $CE(k)$, are calculated using (10) and (11) respectively. The error signal $E(k)$ and its derivative CE (at time step k) serve as the dual inputs to the MFLC, which computes the duty cycle modification (dD) as its output.

$$E(k) = \frac{P(k)-P(k-1)}{V(k)-V(k-1)} \tag{10}$$

$$CE(k) = E(k) - E(k-1) \tag{11}$$

Figures 6(a)-(b), and 7 show the fuzzy variables E, CE, and dD membership functions. Among the several types of membership functions accessible, the symmetric triangular function was chosen for its simplicity and ease of implementation. To correctly reflect real signals, the fuzzy variables' range limitations are often adjusted between -1 and +1 using a gain factor. For this investigation, the symmetric triangular membership functions were utilized, with range limitations of ([-30, 10], [-30, 30], and [0, 1]) for E, CE, and dD, respectively.



(a)

(b)

Figure 6. The fuzzy variables: (a) Input variable error E and (b) Variable change in error CE

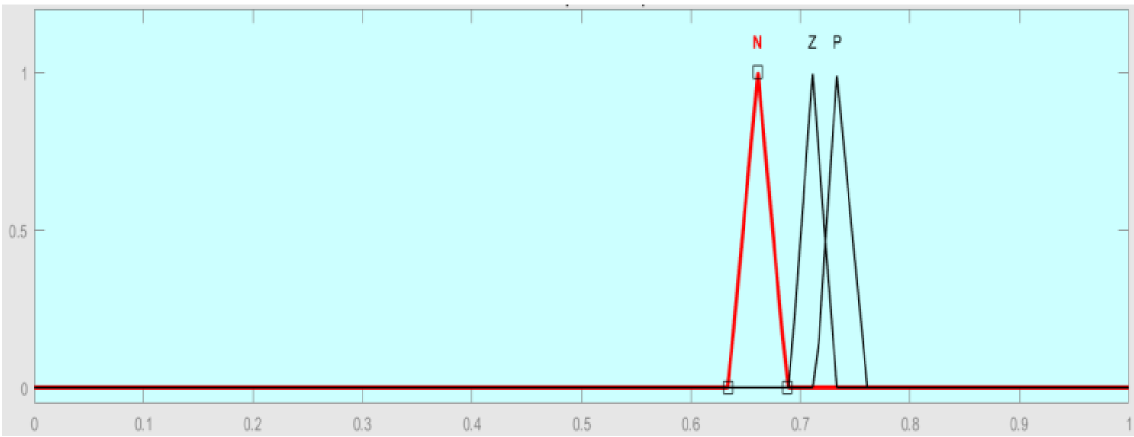


Figure 7. The fuzzy variables: Output variable dD

3.2.2. Evaluation of rules

The most important part of the fuzzy inference, normally referred to as the 'heart,' consists of the basic set of "IF-THEN" rules that contribute to a fuzzy inference. Such rules can be defined using the experience and knowledge of specialists in the natural language processing domain [23]. The final fuzzy conclusion is derived by considering the membership degrees of the input variables in the fuzzy sets along with the applied fuzzy rules. Several approaches can be used to perform fuzzy inference and such a number of approaches can yield different results. Employing the Max-Min compositional approach, the Mamdani inference system is a cornerstone of FLC and decision analysis. The inference rule table is presented in Table 2.

Table 2. Table of inference rules

E \ CE	GP	PM	PP	Z	NP
GP	P	P	P	P	P
PM	Z	Z	Z	Z	Z
PP	N	N	N	Z	Z
Z	Z	Z	Z	P	N
NP	Z	Z	Z	P	P

3.2.3. Defuzzification

The defuzzification step transforms the fuzzy output into a precise, non-fuzzy value, which is crucial for controlling the process. This process takes a fuzzy set as input and produces a single numeric value that can be used as the final control output. Since the system requires a non-fuzzy control output for effective operation, defuzzification is a critical component of process control. For the given sample data, the arithmetic mean is obtained via (12). The defuzzification results are multiplied by a gain factor, yielding the control signal in Figure 6 that refines the fuzzy logic MPPT mechanism.

$$dD = \frac{\sum_{j=1}^{n} \mu(Dj) - Dj}{\sum_{j=1}^{n} \mu(Dj)} \tag{12}$$

4. SIMULATION RESULTS AND DISCUSSION

In this Simulation, an API156P200 photovoltaic panel was used, and a simulation model that incorporates an enhanced MPPT control method based on MFLC. A boost converter, shown in Figure 8, was employed to manage the load. The particular specifications of the photovoltaic modules were described in Table 3, and simulations were carried out at a constant temperature of 25 °C. This research focuses on validating the performance of solar PVs, with particular attention to their impact on output power and stabilization time. Table 4 provides a summary of the simulation results. Additionally, Table 5 presents a comparative analysis of the system's stabilization time and efficiency relative to three other techniques, demonstrating the superiority of the proposed MFLC method in achieving high efficiency and rapid stabilization. The proposed technique aims to ensure fast and stable tracking of the MPPT. The voltage and current from the PV panel are used as inputs to compute the E and EC, which are then processed by the MFLC, as depicted in Figure 9.

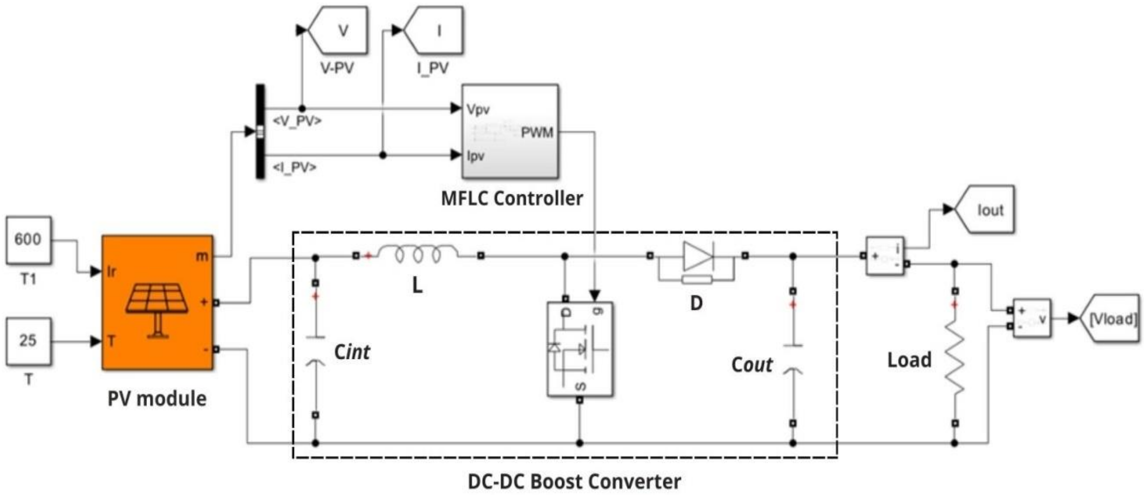


Figure 8. The comprehensive system model in MATLAB/Simulink

Table 3. Technical specifications of the API156P200 PV module and DC-DC boost converter

Parameter	Value
API156P200 solar PV module	
Number of cells per module	60
V_{oc} (V)	36 V
I_{SC} (A)	7.75 A
V_{Mpp} (V)	28.7 V
I_{Mpp} (A)	6.97 A
P_{Mpp} (W)	200.039 W

Table 4. Outcomes of the three case studies

Irradiance (w/m^2)	$P_{GMPP}(w)$	$I_{out}(A)$	$V_{out}(V)$	$P_{out}(w)$	Settling time (ms)	Efficiency (%)
600	121.225	1.396	83.771	116.989	12	97.02
800	161.416	1.613	96.88	156.37	8	97.00
1000	200.010	1.799	107.862	194.00	10	97.05

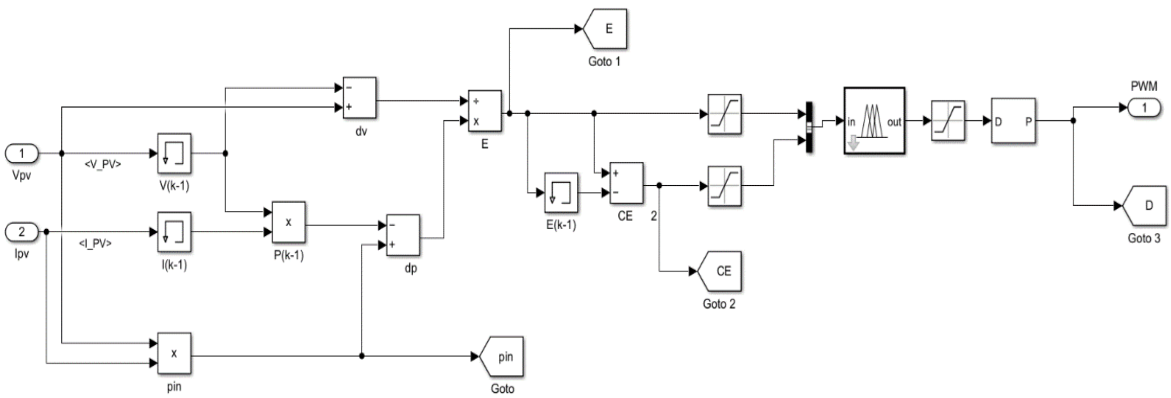
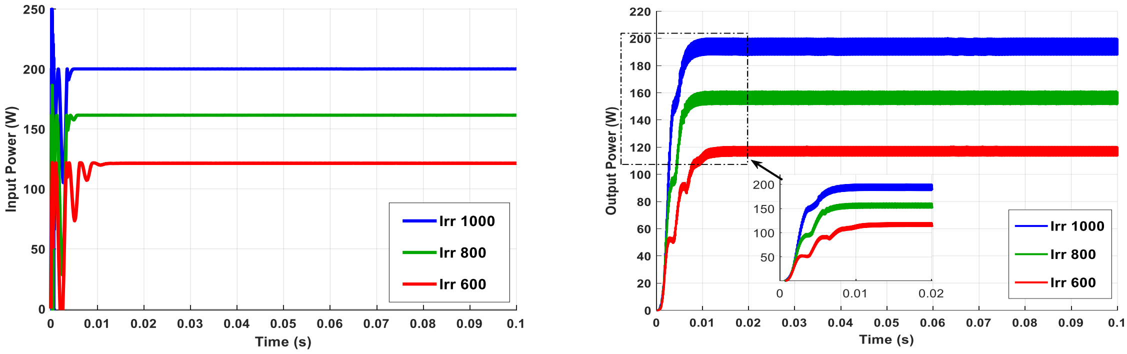


Figure 9. The MFLC calculator

4.1. Results and discussion

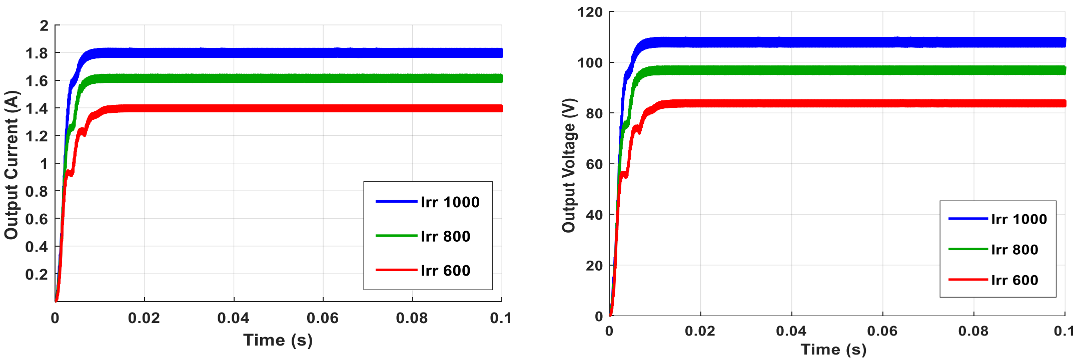
The MFLC's capability to optimize PV systems is confirmed by simulations, excelling in rapid, high-accuracy MPPT. At varying irradiance levels of 600, 800, and 1000 W/m², the MFLC showcased its ability to quickly stabilize the system and maintain efficiency. For instance, Figure 10(a) indicates a rapid response time of 4.6 milliseconds for input power, with minimal overshoot and weak ripple in steady-state conditions. This performance highlights the controller's capability to swiftly and precisely reach the MPP, ensuring optimal energy harvesting.

The power output analysis, presented in Figure 10(b), shows that stabilization occurred within 8 milliseconds under normal conditions, with a slight increase to 12 milliseconds at reduced irradiance levels (G = 600 W/m²). Figures 11(a) and 11(b) further validate the stability of output voltage and current, where the MFLC effectively minimized oscillations. Overall, the MFLC achieved an MPPT efficiency of 97.05% with a fast stabilization time of 10 milliseconds, demonstrating its robustness and suitability for dynamic environmental conditions. MFLC can significantly improve the operation of photovoltaic systems in non-linear operating situations by providing fast and accurate tracking of the MPP, unlike conventional methods, with minimal energy losses, making it one of the most suitable options for real-world renewable energy applications.



(a) (b)

Figure 10. The simulation result for: (a) the input power and (b) the output power



(a) (b)

Figure 11. The simulation results for: (a) the output current and (b) the output voltage

4.2. Comparison of test results

Simulation results evaluated the MFLC's performance relative to P&O and INC, highlighting its precision and adaptability in dynamic conditions. This comparative study was conducted using a photovoltaic panel under various irradiation levels. The comparison examined several key aspects, including efficiency, accuracy, settling time, and robustness, as summarized in Table 5. The outstanding results obtained by the MFLC approach, particularly in terms of efficiency, precision, and stabilization time, highlight its clear superiority over the other optimization methods. These findings underscore the MFLC method's effectiveness for MPPT in photovoltaic power systems.

Table 5. Results of the comparison between FLC and three other techniques

Techniques	P&O [24]	InC [24]	INC [25]	FLC
Efficiency (%)	96.07	96.95	96,85	97,02
Settling time (ms)	293	300	77.6	10
Tracking speed	Very slow	Very slow	Slow	Very fast
Tracking accuracy	Moderate	Moderate	Moderate	Good

5. CONCLUSION

This study shows that an MFLC is effective in optimizing the performance of PVs. The MFLC consistently demonstrated quick response times, minimal overshoot, and stable operation even under varying environmental conditions, as shown in simulations conducted at different irradiation levels of 600, 800, and 1000 W/m². The MFLC achieved a high MPPT efficiency of 97.05% and demonstrated fast stabilization, with a performance of just 10 milliseconds in reaching the MPP. The simulation results confirm that the proposed MFLC provides a robust and precise control strategy for PVs, with particular strength in maintaining system stability and optimizing energy harvest across a wide range of operating conditions. Its ability to reduce oscillations and ensure smooth transitions between states makes it highly suitable for real-world applications. Overall, the MFLC offers a powerful solution for increasing the efficiency and reliability of PVs, contributing to the development of renewable energy technologies.

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AUTHOR CONTRIBUTIONS STATEMENT

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Yassine El Moujahid		✓				✓		✓	✓	✓	✓	✓		
Chafik El Idrissi Mohamed	✓		✓	✓			✓			✓	✓		✓	✓
Abdessamad Benlafkih					✓		✓			✓		✓		✓

C : **C**onceptualization
M : **M**ethodology
So : **So**ftware
Va : **Va**lidation
Fo : **Fo**rmal analysis
I : **I**nvestigation
R : **R**esources
D : **D**ata Curation
O : Writing -**O**riginal Draft
E : Writing - Review &**E**diting
Vi : **Vi**sualization
Su : **Su**pervision
P : **P**roject administration
Fu : **Fu**nding acquisition

CONFLICT OF INTEREST STATEMENT

Authors state no conflict of interest.

INFORMED CONSENT

We have obtained informed consent from all individuals included in this study.

ETHICAL APPROVAL

This research does not require ethical approval as it does not involve human participants, animal subjects, or sensitive data.

DATA AVAILABILITY

The data supporting this study's findings are available from the corresponding author, BS, upon reasonable request.

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