



Enhancing PV efficiency: A comparative study of FLC, SMC, and P&O MPPT algorithms using Matlab/Simscaper

Ahmed Chebri ^{a,*}, Fatima Zohra Boukahil ^a, Assala Mouffouk ^a, Boubekour Azoui ^a

^a Renewable Energies and New Technologies Department, HNS-RE2SD, Batna, Algeria

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ABSTRACT

The growing demand for sustainable energy has accelerated the development of efficient photovoltaic power conversion systems. However, the nonlinear behavior of photovoltaic generators and their strong dependence on solar irradiance and temperature significantly affect the amount of extractable power. Therefore, effective control strategies are required to ensure continuous operation at the optimal operating point where maximum power can be delivered. This study presents a comparative investigation of three maximum power point tracking techniques applied to a photovoltaic system: Perturb and Observe, Improved Sliding Mode Control, and Fuzzy Logic Control. A detailed simulation model of the photovoltaic energy conversion system is developed to evaluate the dynamic performance of each control strategy under varying irradiance conditions. The comparison focuses on key performance indicators including tracking speed, stability, power oscillations, and robustness. The obtained results demonstrate that intelligent and nonlinear control approaches significantly enhance the energy harvesting capability of photovoltaic systems compared with conventional methods. In particular, Fuzzy Logic Control provides superior tracking accuracy, faster dynamic response, and reduced steady-state oscillations, whereas Improved Sliding Mode Control offers strong robustness with reduced oscillatory behavior. These findings confirm the effectiveness of advanced control strategies in improving the efficiency and stability of photovoltaic energy conversion systems.

1. INTRODUCTION

The rapid digitalization of modern society and the continuous expansion of electrical infrastructures, combined with the growing global demand for energy, have significantly increased the need for reliable

* Corresponding author, E-mail address: chebri.ahmed.eng@gmail.com



and sustainable energy sources (Alhusseini et al., 2025). At the same time, the heavy dependence of conventional energy systems on fossil fuels has raised serious environmental concerns, including greenhouse gas emissions, global warming, and environmental degradation. These challenges have accelerated the transition toward cleaner and more efficient energy technologies. Consequently, the development and deployment of renewable and sustainable energy systems have become essential for ensuring long-term energy sustainability and reducing the carbon footprint of modern power systems (Chellakhi et al., 2025).

Among the available renewable resources, solar energy has become one of the most attractive solutions due to its vast availability, modularity, and low environmental impact. Photovoltaic (PV) technology, which directly converts solar radiation into electrical energy, has experienced remarkable technological progress and cost reduction over the last decade (Abdelmalek et al., 2025). These improvements have facilitated the widespread integration of PV systems in residential, industrial, and grid-connected applications. However, despite their potential, the energy conversion efficiency of photovoltaic systems remains relatively limited and highly dependent on environmental conditions such as solar irradiance and temperature (Salman et al., 2025).

The electrical characteristics of photovoltaic (PV) modules are inherently nonlinear and strongly influenced by environmental conditions such as solar irradiance and temperature. Consequently, the operating point of a PV system does not naturally remain at the optimal level where the maximum possible power can be extracted (Hasan et al., 2025). This optimal operating condition, referred to as the Maximum Power Point (MPP), corresponds to the specific voltage and current at which the photovoltaic generator delivers its highest power output. However, because atmospheric conditions change continuously throughout the day, the position of the MPP also varies dynamically (El Oussoul et al., 2025). To address this challenge, efficient Maximum Power Point Tracking (MPPT) techniques are employed to continuously monitor and adjust the operating point of the PV system (Bouksaim et al., 2025). These algorithms ensure that the system operates as close as possible to the MPP, thereby maximizing energy extraction and improving the overall efficiency and performance of photovoltaic power generation systems under varying environmental conditions.

Several Maximum Power Point Tracking (MPPT) algorithms have been proposed in the literature (Chandola et al., 2026) to enhance the performance and efficiency of photovoltaic systems. Among the classical techniques, the Perturb and Observe (P&O) method is one of the most commonly used due to its simplicity and ease of implementation. Another widely adopted conventional approach is the Incremental Conductance (INC) method (Maamar et al., 2025), which determines the position of the operating point by comparing the incremental conductance of the PV array with its instantaneous conductance. This technique is capable of identifying the exact location of the Maximum Power Point and generally provides better tracking accuracy under varying atmospheric conditions. In addition, methods such as the Hill Climbing algorithm (Benkirane et al., 2025), the Constant Voltage method, and the Open-Circuit Voltage technique are also frequently used in traditional MPPT control strategies because of their low computational requirements and straightforward implementation. However, despite their advantages, these classical methods still present certain limitations, including steady-state oscillations around the maximum power point, slow dynamic response, and reduced tracking performance under rapidly changing irradiance conditions. These drawbacks can result in energy losses and consequently reduce the overall efficiency of photovoltaic energy conversion systems.

To mitigate the drawbacks of classical MPPT techniques, modern research has increasingly emphasized the adoption of nonlinear and intelligent control strategies. Among these methods, Sliding Mode Control (SMC) has emerged as a prominent control strategy, offering high robustness in the presence of system uncertainties, external disturbances, and parameter variations. SMC is a nonlinear control technique that

ensures system stability by forcing the system trajectory to reach and remain on a predefined sliding surface. This approach offers fast dynamic response and high robustness, which are highly desirable characteristics for photovoltaic systems operating under rapidly changing environmental conditions. However, despite its advantages, classical SMC methods may suffer from the well-known chattering phenomenon, characterized by high-frequency oscillations in the control signal, which can negatively affect system performance and may cause additional stress on power electronic components.

Another promising approach for MPPT applications is Fuzzy Logic Control (FLC). Unlike conventional model-based controllers, fuzzy logic controllers rely on a set of linguistic rules and expert knowledge rather than requiring an accurate mathematical model of the system. This feature makes FLC particularly suitable for photovoltaic systems, which exhibit highly nonlinear behavior and operate under uncertain and variable environmental conditions. By using fuzzy inference mechanisms to determine the appropriate control action, FLC-based MPPT techniques can effectively handle system nonlinearities and parameter variations. As a result, these methods have demonstrated improved dynamic performance, enhanced tracking accuracy, and greater robustness compared to traditional MPPT techniques.

Motivated by these considerations, this paper presents a comparative study of three MPPT techniques applied to a photovoltaic energy conversion system: the conventional Perturb and Observe (P&O) algorithm, an improved Sliding Mode Control (ISMC) strategy, and a Fuzzy Logic Controller (FLC). These algorithms are used to regulate the duty cycle of a DC–DC boost converter in order to ensure optimal power extraction from the PV generator under varying irradiance conditions.

The main contributions of this work can be summarized as follows:

- Development of a detailed photovoltaic system model including a PV generator and a DC–DC boost converter using MATLAB/Simscape.
- Implementation and analysis of three MPPT algorithms: conventional P&O, improved SMC, and fuzzy logic control.
- Comparative evaluation of these algorithms based on key performance indicators such as response time, steady-state error, efficiency, and power ripple.
- Identification of the most effective MPPT strategy for enhancing the performance and energy extraction capability of photovoltaic systems.

The structure of this paper is outlined as follows. Section II focuses on the mathematical modeling of the photovoltaic system and the DC–DC boost converter. Section III describes the MPPT control strategies used in this study. Section IV discusses the simulation results and comparative performance analysis. Finally, Section V concludes the paper and outlines possible directions for future research.

2. PHOTOVOLTAIC SYSTEM MODELING

The photovoltaic system considered in this study is illustrated in Fig. 1. It consists of a photovoltaic (PV) generator connected to a DC–DC boost converter, which supplies a resistive load. The boost converter operates as an interface between the PV module and the load, allowing the adjustment of the operating voltage of the PV generator in order to ensure optimal energy extraction. The duty cycle of the converter is regulated by the MPPT controller based on the measured PV voltage and current. This configuration enables the system to operate close to the maximum power point (MPP) despite variations in solar irradiance and temperature.

2.1 Photovoltaic generator model

The electrical behavior of the photovoltaic generator is described using the single-diode equivalent circuit model, which provides a reliable representation of the nonlinear characteristics of PV modules

while maintaining reasonable computational complexity. In this model, the PV cell is represented by a current source in parallel with a diode, while the internal losses are modeled by a series resistance R_s and a shunt resistance R_p .

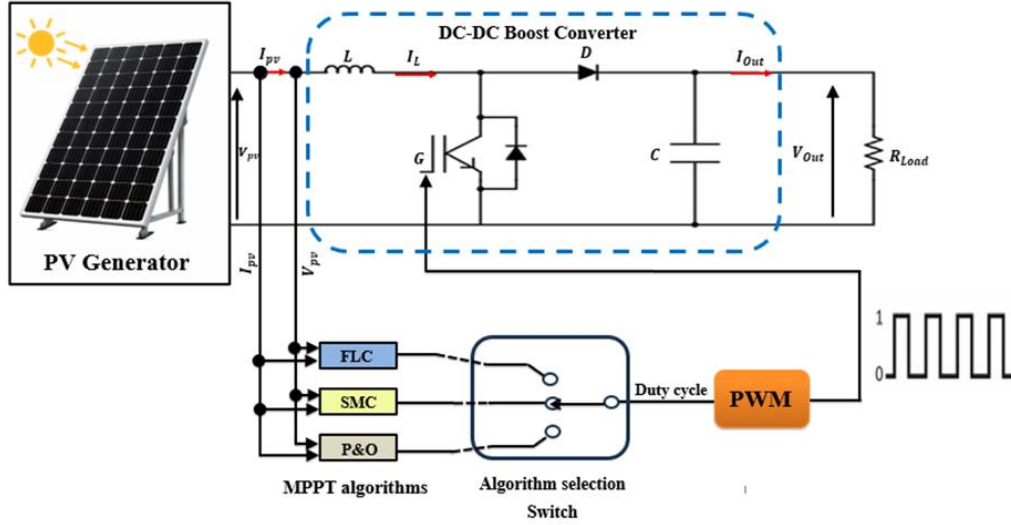


Fig 1. General structure of the photovoltaic system including the PV generator, MPPT controller, DC–DC boost converter, and load

The output current of the PV generator can be expressed as follows (Ghazi et al., 2024):

$$I_{pv} = N_p I_{ph} - N_p I_s \left[\exp \left(\frac{q \left(\frac{V_{pv}}{N_s} + I_{pv} R_s \right)}{AKT_c} \right) - 1 \right] - \frac{N_p \left(\frac{V_{pv}}{N_s} + I_{pv} R_s \right)}{R_p} \quad (1)$$

Where I_{pv} and V_{pv} represent the output current and voltage of the photovoltaic module, respectively. N_s and N_p denote the number of cells connected in series and parallel. I_{ph} is the photocurrent generated by solar irradiance, while I_s represents the diode reverse saturation current. The parameters R_s and R_p correspond to the series and shunt resistances, respectively. Furthermore, q is the electron charge, k is Boltzmann's constant, T_c denotes the cell temperature, and A represents the diode ideality factor.

This nonlinear equation accurately describes the (I–V) characteristics of the photovoltaic generator and allows the analysis of its dynamic behavior under different environmental conditions.

2.2 DC–DC boost converter model

To efficiently transfer the generated power to the load and regulate the operating point of the PV generator, a DC–DC boost converter is employed. The boost converter increases the PV output voltage to the level required by the load and enables impedance matching between the PV generator and the load.

The dynamic model of the boost converter can be expressed using a state-space representation. Considering the inductor current and the output capacitor voltage as state variables, the system dynamics can be written as (Khan et al., 2024):

$$\begin{bmatrix} \dot{x}_1 \\ \dot{x}_2 \end{bmatrix} = \begin{bmatrix} 0 & -\frac{(1-\alpha)}{L} \\ \frac{(1-\alpha)}{C} & -\frac{1}{C \cdot R_{load}} \end{bmatrix} \begin{bmatrix} x_1 \\ x_2 \end{bmatrix} + \begin{bmatrix} 1 \\ 0 \end{bmatrix} \frac{1}{L} V_{pv} \quad (2)$$

Where $x_1 = I_{pv}$ represents the inductor current and $x_2 = V_{out}$ denotes the output voltage of the converter. L and C are the inductance and capacitance of the converter, respectively, R_{load} is the load resistance, and α represents the duty cycle of the switching device.

The duty cycle plays a crucial role in controlling the energy transfer between the PV generator and the load. By modifying the duty cycle, the boost converter effectively adjusts the input impedance seen by the PV module.

2.3 Impedance matching condition

For optimal energy extraction, the equivalent input resistance of the converter must match the resistance corresponding to the MPP of the photovoltaic generator. This relationship can be expressed as (Ayop & Tan, 2018):

$$\frac{V_{MPP}}{R_{MPP}} = \left(\frac{V_{MPP}}{1-\alpha} \right)^2 \cdot \frac{1}{R_{load}} \quad (3)$$

which can be simplified as:

$$R_{load} = \frac{R_{MPP}}{(1-\alpha)^2} \quad (4)$$

This relationship highlights the importance of the duty cycle in achieving impedance matching between the PV generator and the load, thereby ensuring that the system operates at the maximum power point.

3. MPPT CONTROL ALGORITHMS

In this study, three MPPT strategies are investigated and compared: the conventional Perturb and Observe (P&O) algorithm, Improved Sliding Mode Control (ISMC), and Fuzzy Logic Control (FLC). These algorithms determine the optimal duty cycle of the DC–DC boost converter in order to regulate the operating voltage of the PV generator and maintain operation near the maximum power point (MPP).

3.1 Perturb and observe (P&O) algorithm

The Perturb and Observe (P&O) method is one of the most widely used MPPT techniques due to its simplicity and ease of implementation. The basic principle of this algorithm is based on periodically perturbing the operating voltage of the PV generator and observing the resulting variation in output power (Khaleel et al., 2025).

At each sampling instant, the PV voltage is slightly increased or decreased, and the corresponding change in power is evaluated. If the perturbation leads to an increase in power, the algorithm continues to perturb the voltage in the same direction. Otherwise, the direction of perturbation is reversed (Ayoubi et al., 2025).

The operating principle can be summarized as follows:

- If $\Delta P > 0$ and $\Delta V > 0$, the operating point moves toward the MPP.
- If $\Delta P > 0$ and $\Delta V < 0$, the perturbation direction is maintained.
- If $\Delta P < 0$, the perturbation direction is reversed.

Although the P&O algorithm is simple and requires minimal computational effort, it suffers from steady-state oscillations around the maximum power point and may exhibit reduced tracking performance under rapidly changing environmental conditions. The flowchart of the P&O algorithm used in this work is illustrated in Fig. 2.

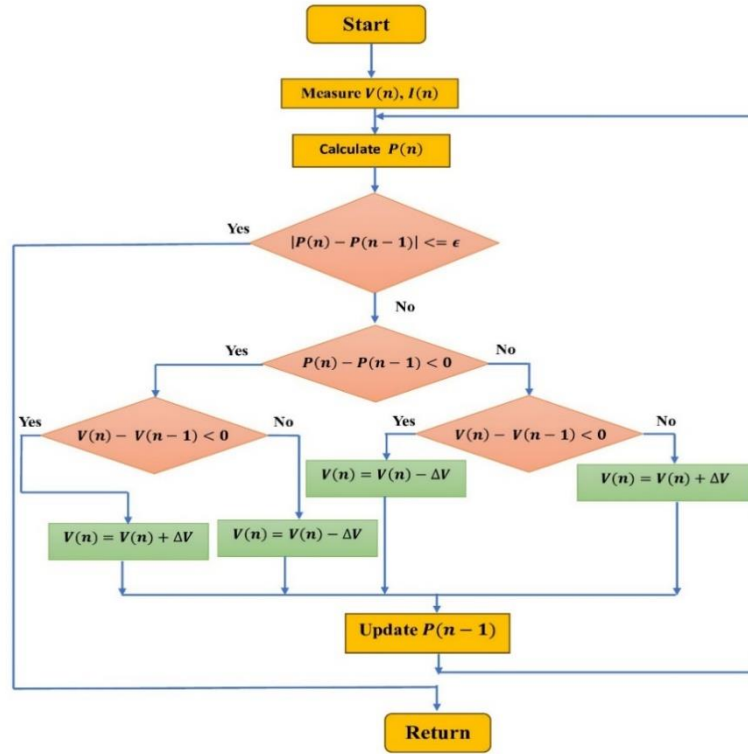


Fig 2. Flowchart of the P&O Algorithm

3.2 Improved sliding mode control (ISMC)

Sliding Mode Control (SMC) is a nonlinear control technique widely used in photovoltaic applications due to its strong robustness against parameter variations and external disturbances. In the context of Maximum Power Point Tracking (MPPT), SMC enables fast convergence toward the optimal operating point while maintaining stable system behavior under varying irradiance and temperature conditions (Bollipo et al., 2020).

However, conventional SMC strategies often suffer from the chattering phenomenon, which results from the high-frequency switching of the control signal around the sliding surface. This effect may lead to undesirable oscillations in the system response and can negatively affect the stability of the converter and the accuracy of maximum power point tracking.

To overcome this limitation, an improved Sliding Mode Control approach is adopted in this work. The improvement primarily focuses on refining the design of the sliding surface in order to reduce the chattering effect while preserving the inherent robustness of the SMC strategy. By introducing a more appropriate formulation of the sliding surface, the switching behavior of the controller becomes

smoother, leading to reduced oscillations around the Maximum Power Point (MPP) and improved dynamic performance of the PV system. Following the method proposed by Slotine (1984), the sliding surface can be expressed as :

$$S = \left(\frac{d}{dt} + \gamma \right)^{r-1} e(x) \quad (5)$$

Where $e(x)$ represents the tracking error, γ is a positive constant that determines the convergence rate, and r denotes the relative degree of the system.

For photovoltaic MPPT applications, the sliding surface is defined based on the derivative of the PV power with respect to the PV voltage. This formulation allows the controller to directly drive the operating point toward the maximum power condition. The sliding surface is therefore expressed as:

$$S = \frac{dP_{PV}}{dV_{PV}} = I_{PV} + V_{PV} \frac{dI_{PV}}{dV_{PV}} \quad (6)$$

The maximum power point is reached when the derivative of the PV power with respect to the voltage becomes zero ($S = 0$).

The stability of the proposed control strategy is validated using the Lyapunov-based stability condition (Gursoy et al., 2021):

$$\dot{V} = S \cdot \dot{S} < 0 \quad (7)$$

The control law of the sliding mode controller consists of two components: the equivalent control u_{eq} and the discontinuous control u_n , which together determine the duty cycle applied to the boost converter:

$$u = u_{eq} + u_n \quad (8)$$

where the discontinuous component is defined as:

$$u_n = -k_{eq} \operatorname{sgn}(S) \quad (9)$$

and the equivalent control is expressed as:

$$u_{eq} = 1 - \frac{V_{PV}}{V_{Out}} \quad (10)$$

Through this improved SMC formulation, the controller ensures rapid convergence toward the sliding surface while reducing undesirable oscillations around the maximum power point. Consequently, the proposed approach provides enhanced MPPT performance, improved stability, and better robustness under rapidly changing environmental conditions.

3.3 Fuzzy logic control (FLC)

Fuzzy Logic Control (FLC) is widely adopted in photovoltaic applications owing to its ability to handle nonlinear dynamics and uncertainties without requiring an explicit mathematical model of the system

(Zongo, 2021). Unlike conventional control methods, fuzzy logic relies on linguistic rules and human expertise to determine the appropriate control action, which makes it particularly suitable for photovoltaic applications where operating conditions change continuously.

The fuzzy logic MPPT controller implemented in this study operates through three principal stages: fuzzification, rule-based inference, and defuzzification, as illustrated in Fig. 3. The fuzzification process converts the numerical input variables into linguistic variables using predefined membership functions. The inference engine then applies a set of fuzzy rules to determine the appropriate control action. Finally, the defuzzification stage converts the fuzzy output into a crisp value that is used to update the duty cycle of the DC–DC boost converter (Hu et al., 2022).

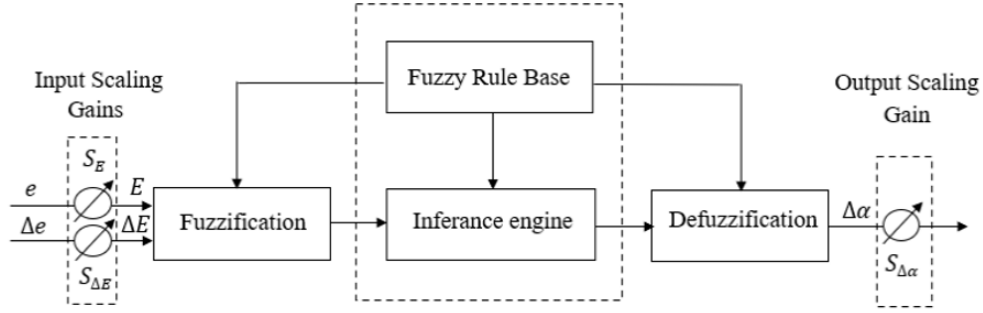


Fig 3. Structure of the fuzzy logic controller used for MPPT

At each sampling instant k , the fuzzy controller receives two input variables: the error E and the change in error ΔE . These variables are defined based on the slope of the PV power–voltage characteristic and are expressed as follows:

$$E(k) = \frac{P_{PV}(k) - P_{PV}(k-1)}{V_{PV}(k) - V_{PV}(k-1)} \quad (11)$$

$$\Delta E(k) = E(k) - E(k-1) \quad (12)$$

The error $E(k)$ represents the slope of the PV power curve, indicating the relative position of the operating point with respect to the maximum power point. The change in error ΔE reflects the dynamic variation of this slope and helps determine the direction and magnitude of the duty cycle adjustment.

The input and output variables are described using seven linguistic terms, namely:

- NB (Negative Big), NM (Negative Medium), NS (Negative Small), ZE (Zero), PS (Positive Small), PM (Positive Medium), and PB (Positive Big).

Triangular membership functions are adopted for both input and output variables in order to simplify the implementation and reduce computational complexity while maintaining effective control performance, as illustrated in Figs. 4, 5, and 6.

The fuzzy inference system uses a rule base consisting of 49 control rules, which define the relationship between the input variables E and ΔE and the output control variable $\Delta\alpha$, as presented in Table. These rules determine how the duty cycle of the boost converter should be adjusted to drive the operating point toward the maximum power point.

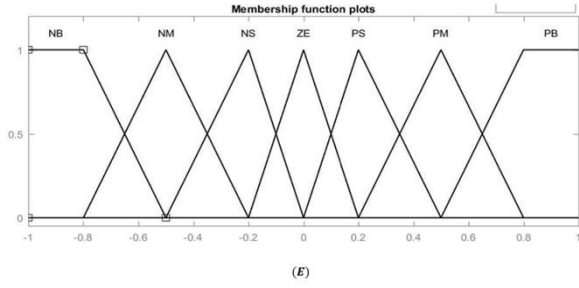


Fig 4. Membership functions of the input variable E

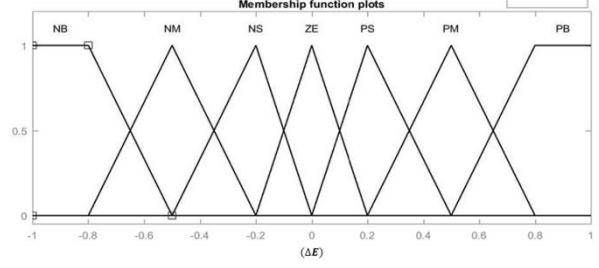


Fig 5. Membership functions of the input variable ΔE

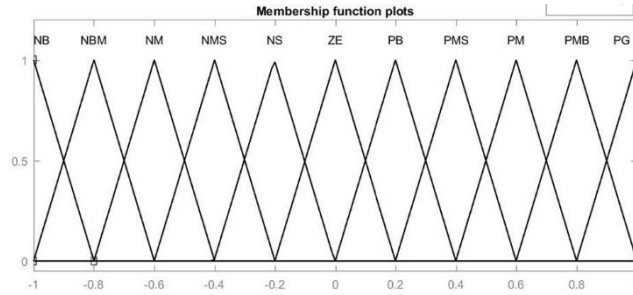


Fig 6. Membership functions of the output variable $\Delta\alpha$

Table 1. Fuzzy rule base used in the FLC controller

$\Delta\alpha$		ΔE							
E		NB	NM	NS	ZE	PS	PM	PB	
	NB	NB	NB	NBM	NM	NMS	NS	ZE	
	NM	NB	NBM	NM	NMS	NS	ZE	PS	
	NS	NBM	NM	NMS	ZE	PS	PM	PMS	
	ZE	NM	NMS	ZE	ZE	PS	PMS	PM	
	PS	NMS	NS	ZE	PS	PMS	PM	PMB	
	PM	NS	ZE	PMS	PMS	PM	PMB	PB	
	PB	ZE	PS	PMS	PM	PMB	PB	PB	

During the defuzzification stage, the fuzzy output is converted into a crisp control signal using the center of gravity (COG) method, which is widely used due to its accuracy and smooth control response. The defuzzified output is calculated as follows (Ullah et al., 2023):

$$\Delta\alpha = \frac{\sum_{j=1}^n \mu(\alpha_j) - \alpha_j}{\sum_{j=1}^n \mu(\alpha_j)} \quad (13)$$

4. SIMULATION RESULTS AND DISCUSSION

To evaluate the effectiveness of the proposed MPPT techniques, the photovoltaic system described in Section II was implemented in the MATLAB/Simulink simulation environment. The objective of the simulation is to analyse and compare the dynamic and steady-state performance of the three MPPT algorithms, namely Perturb and Observe (P&O), Improved Sliding Mode Control (ISMC), and Fuzzy Logic Control (FLC), under varying irradiance conditions.

The photovoltaic generator considered in this study is composed of two BlueSolar SPP040901200 modules connected in series, each rated at 90 W under standard test conditions (STC) defined by an irradiance of 1000 W/m^2 and a temperature of 25°C . Consequently, the total maximum power of the PV generator reaches approximately 180 W under nominal conditions.

To evaluate the influence of solar irradiance on the photovoltaic system performance, simulations were conducted under three irradiance levels: 1000 W/m^2 , 900 W/m^2 , and 800 W/m^2 , while the temperature was maintained constant at 25°C . These conditions allow the assessment of the MPPT algorithms in terms of tracking accuracy, response time, power ripple, and stability.

4.1 Photovoltaic generator characteristics

The electrical behavior of the PV generator under different irradiance levels is illustrated through the power–voltage (P–V) characteristics, as shown in Fig. 7.

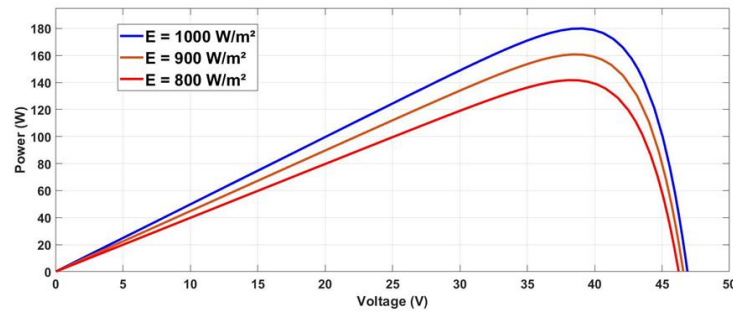


Fig 7. P–V characteristics of the photovoltaic generator under different irradiance levels

As observed in Fig. 7, the maximum power point varies with the irradiance level. When the irradiance decreases from 1000 W/m^2 to 800 W/m^2 , the maximum generated power decreases, while the voltage at the MPP remains nearly constant. This behavior is consistent with the typical characteristics of photovoltaic modules, where irradiance mainly affects the output current.

The corresponding electrical parameters of the PV generator are summarized in Table 2.

These results confirm that the available photovoltaic power is strongly dependent on solar irradiance, which emphasizes the importance of efficient MPPT techniques to continuously extract the maximum available energy.

Table 2. Electrical characteristics of the photovoltaic generator under different irradiance levels

$E (\text{W/m}^2)$	1000	900	800
$P_{MPP} (\text{W})$	180	160.8	141.93
$V_{MPP} (\text{V})$	38.91	38.38	38.36
$I_{MPP} (\text{A})$	4.63	4.19	3.70

4.2 PV output power analysis

The performance of the three MPPT algorithms is evaluated by analyzing the PV output power under varying irradiance conditions.

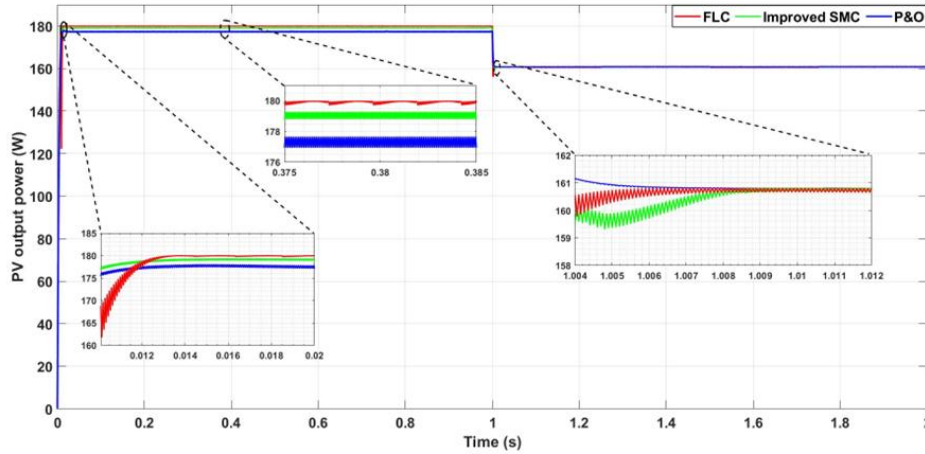


Fig 8. PV output power obtained using P&O, improved SMC, and FLC algorithms

As illustrated in Fig. 8, all three algorithms are capable of tracking the maximum power point; however, significant differences in dynamic response and steady-state behavior can be observed.

The Fuzzy Logic Controller (FLC) demonstrates the best overall performance. It rapidly converges toward the maximum power point with a response time of approximately 0.013 s, while exhibiting negligible steady-state error and very low power ripple (0.6%). This behavior highlights the ability of fuzzy logic control to effectively handle the nonlinear characteristics of the photovoltaic system.

The Improved Sliding Mode Control (SMC) also shows a fast dynamic response with a response time of about 0.014 s. Thanks to the improved sliding surface design; the chattering phenomenon is significantly reduced compared to conventional SMC methods. However, a small steady-state error of approximately 0.6 W and a moderate power ripple of 5.88% can still be observed.

In contrast, the P&O algorithm exhibits the lowest tracking performance among the three methods. Although it maintains a similar response time of 0.014 s, it suffers from larger oscillations around the maximum power point, resulting in a steady-state error of approximately 3.1 W and a power ripple of about 6%. These oscillations are inherent to the perturbation mechanism used by this algorithm.

4.3 Load power performance

To further analyse the performance of the evaluated MPPT techniques, the power delivered to the load is examined.

The results presented in Fig. 9 confirm the observations obtained from the PV output power analysis. The FLC algorithm provides the most stable power delivery to the load, reaching approximately 180 W under standard irradiance conditions, with minimal oscillations.

The improved SMC algorithm also demonstrates stable performance, delivering approximately 173 W with lower oscillations compared to the conventional P&O method. The refinement introduced in the SMC control strategy contributes to reducing chattering effects and improving overall system stability.

On the other hand, the P&O algorithm exhibits noticeable fluctuations around 175 W, indicating less stable operation due to its inherent perturbation process.

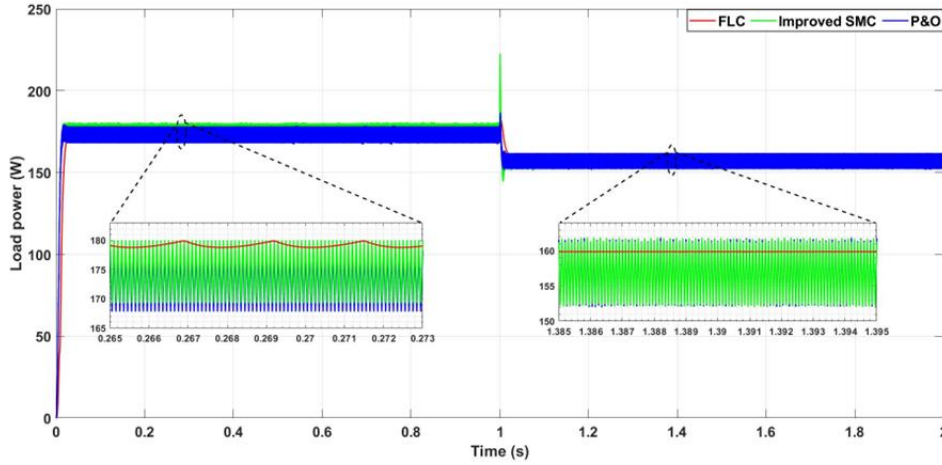


Fig 9. Load power obtained using P&O, improved SMC, and FLC algorithms

4.4 Comparative Performance Analysis

To quantitatively compare the performance of the three MPPT techniques, several key performance indicators are considered, including response time, steady-state error, tracking efficiency, power ripple, and implementation complexity.

A detailed analysis of the results summarized in Table 3 highlights that the Fuzzy Logic Controller provides the highest efficiency and the lowest power ripple, making it the most effective technique among the evaluated methods. The Improved SMC algorithm offers a good compromise between performance and control robustness, while the P&O algorithm, despite its simplicity, shows limited performance under dynamic conditions.

Overall, these results demonstrate that intelligent control techniques such as FLC and nonlinear strategies like improved SMC significantly enhance the dynamic performance and stability of photovoltaic systems compared to conventional MPPT approaches.

Table 3. Comparative performance of the MPPT algorithms

MPPT Algorithm	Response time (s)	Steady-state error (W)	Efficiency (%)	Power ripple (%)	Complexity
FLC	0.013	Negligible	99.6	0.6	High
Improved SMC	0.014	0.6	97.8	5.88	Medium
P&O	0.014	3.1	97.3	6	Low

5. CONCLUSION AND FUTURE WORK

This paper presented a comprehensive comparative analysis of three Maximum Power Point Tracking (MPPT) techniques—Perturb and Observe (P&O), Improved Sliding Mode Control (ISMC), and Fuzzy Logic Control (FLC)—applied to a photovoltaic system modelled in the MATLAB/Simscap simulation framework. The proposed system comprises a photovoltaic generator interfaced with a DC–DC boost converter, whose duty cycle is regulated by the MPPT controller to ensure optimal power extraction under varying irradiance conditions.

Simulation results were conducted under different solar irradiance levels in order to evaluate the dynamic performance of the considered algorithms in terms of response time, tracking accuracy, steady-

state error, power ripple, and overall efficiency. The obtained results demonstrate that the Fuzzy Logic Controller exhibits the best overall performance, achieving the fastest convergence toward the maximum power point, minimal steady-state oscillations, and the highest energy conversion efficiency. The improved Sliding Mode Control approach also shows strong robustness and good tracking capability while effectively reducing the chattering phenomenon typically observed in conventional SMC strategies. In contrast, the conventional P&O algorithm, while simple and easy to implement, exhibits pronounced power fluctuations near the maximum power point and reduced tracking accuracy under dynamic conditions.

Overall, the results highlight the advantages of intelligent and nonlinear control strategies in improving the performance and stability of photovoltaic energy conversion systems. In particular, the fuzzy logic-based MPPT method demonstrates a high capability to handle nonlinearities and environmental variations, making it a promising solution for efficient photovoltaic energy harvesting in practical applications. Future work could involve experimental validation of the proposed approaches, coupled with the implementation of advanced intelligent optimization techniques to further improve MPPT performance under partial shading conditions.

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ABBREVIATIONS

FLC	Fuzzy Logic Controller	PV	Photovoltaic
I-V	Current-Voltage characteristic	P-V	Power-Voltage characteristic
MPP	Maximum Power Point	PWM	Pulse Width Modulation
MPPT	Maximum Power Point Tracking	SMC	Sliding Mode Control
P&O	Perturb and observe	STC	Standard Test Conditions

NOMENCLATURE

A	Diode ideality factor	P_{PV}	Output power of the PV generator
C	Output capacitance of the boost converter	q	Electron charge
E	Error used in the fuzzy controller	R_{load}	Load resistance
I_{ph}	Photocurrent generated by solar irradiance	R_p	Shunt resistance
I_{pv}	Photovoltaic output current	R_s	Series resistance
I_s	Diode saturation current	T_c	PV cell temperature
k	Boltzmann constant	V_{out}	Output voltage of the converter
L	Inductance of the boost converter	V_{PV}	Photovoltaic output voltage
N_p	Number of PV cells connected in parallel	α	Duty cycle of the DC-DC converter
N_s	Number of PV cells connected in series	ΔE	Change in error

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