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# Performance Evaluation of P&O, improved Sliding Mode and Fuzzy Logic MPPT Methods in PV Systems: A Comparative Study under uniform and non-uniform conditions

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**Abstract**

This paper presents a comprehensive comparative analysis of three Maximum Power Point Tracking (MPPT) algorithms Perturb and Observe (P&O), improved Sliding Mode Control (SMC), and Fuzzy Logic Control (FLC) applied to photovoltaic (PV) systems operating under both uniform irradiance and partial shading conditions. While uniform irradiance allows straightforward MPPT operation, variations caused by shading introduce nonlinearities in the power–voltage (P–V) characteristics that degrade performance and energy yield. The three MPPT techniques are implemented and evaluated in a simulated PV system using MATLAB/Simscape. Their performance is assessed using key metrics, including tracking efficiency, power losses (at the PV and load levels), and output power ripple. Results show that under uniform conditions, intelligent controllers (SMC and FLC) outperform conventional P&O by achieving faster convergence and improved output stability. Under partial shading, the disparity in algorithm performance becomes more pronounced, with FLC achieving the highest tracking accuracy (up to 99.8%), minimal ripple, and negligible power losses. The results reveal critical insights into the strengths and limitations of each method, providing guidance for optimal MPPT strategy selection in real-world solar energy applications.

**Keywords:** Photovoltaic (PV) systems; Maximum Power Point Tracking (MPPT); Partial shading; Fuzzy Logic Control (FLC); Sliding Mode Control (SMC); Perturb and Observe (P&O).

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## 1. Introduction

Climate change remains one of the most pressing global challenges, driven largely by greenhouse gas emissions from fossil fuel consumption. These emissions have led to rising global temperatures and an increased frequency of extreme weather events, threatening ecosystems and long-term human development. As conventional energy sources dwindle and their environmental impact becomes increasingly unsustain- able, the transition to renewable energy is not only a necessity but a strategic imperative for global energy security and sustainable growth [1]. Among renewable technologies, photovoltaic (PV) systems stand out due to their modularity, declining costs, and environmental advantages. However, their power conversion efficiency remains highly dependent on external conditions—particularly solar irradiance. Under uniform irradiance (healthy conditions), PV systems typically exhibit a single, well-defined maximum on the power–voltage (P–V) curve, allowing conventional Maximum Power Point Tracking (MPPT) algorithms to operate effectively. In contrast, partial shading caused by clouds, buildings or trees introduces multiple local maxima on the P–V curve [2], significantly complicating the tracking of the Global Maximum Power Point (GMPP). This can result in suboptimal energy harvesting and even lead to module degradation due to hotspot formation. Given these challenges, this study investigates MPPT performance under both healthy and partially shaded conditions to provide a comprehensive analysis of system behavior across realistic scenarios. However, particular emphasis is placed on the partial shading case, due to its critical impact on system reliability and energy yield in real-world PV deployments. By examining both static and dynamic irradiance patterns, the paper aims to benchmark algorithmic effectiveness in overcoming the limitations of conventional MPPT strategies and enhancing overall system performance. MPPT algorithms are essential in PV systems to continuously adjust the operating point and ensure maximum energy extraction under both uniform and partial shading conditions. Conventional MPPT methods such as Perturb and Observe (P&O), hill climbing (HC) and Incremental Conductance (INC) are widely used for their simplicity and ease of implementation. However, under partial shading, their effectiveness is compromised due to their inability to distinguish local from global maxima on the P-V curve [3, 4]. To overcome these limitations, researchers have explored a range of intelligent and advanced control strategies. These include neuro-fuzzy structures [5],metaheuristic algorithms such as Particle Swarm Optimization (PSO) [6] and the Crow Search Algorithm (CSA),and hybrid methods like Grey Wolf Optimizer integrated with Fuzzy Logic Control (GWO- FLC) [7], GWO-PSO [8] and P&O-FLC [9].Deep Reinforcement Learning (DRL) has also emerged as a promising solution due to its capacity for adaptive learning in dynamic environments [10].Additionally, nonlinear and adaptive control strategies such as Sliding Mode Control (SMC) and Fuzzy Logic Control (FLC) have been employed for their robustness and precision. SMC offers strong resilience against model uncertainties and abrupt irradiance changes, whereas FLC provides an intuitive, human-like decision mechanism that adapts well to complex behaviors without requiring a detailed mathematical model [11].This paper presents a comprehensive evaluation of three Maximum Power Point Tracking (MPPT) algorithms Perturb and Observe (P&O), improved Sliding Mode Control (SMC), and Fuzzy Logic Control (FLC) applied to photovoltaic (PV) systems under uniform irradiance and partial shading conditions. The study is motivated by the performance limitations of traditional MPPT techniques in the presence of multiple local maxima on the power–voltage (P–V) curve caused by partial shading, which significantly complicates the tracking of the Global Maximum Power Point (GMPP). The modeling of the PV system and the analysis of its P–V characteristics under healthy and shaded conditions are presented in the second section. The third and fourth sections describe the simulation setup and provide a comparative performance evaluation of the three MPPT strategies under both static and dynamic irradiance patterns. Finally, the conclusion is presented in the last section, summarizing the key findings and proposing perspectives for future research.

## 2. PV system modeling and P-V characteristics

### 2.1 PV system architecture

To assess the effectiveness of different MPPT techniques in real-world operating conditions, a comprehensive simulation model of a PV energy conversion system is developed in MATLAB/Simscape. Figure 1 presents the overall architecture of a photovoltaic (PV) energy conversion system designed to evaluate and compare the performance of three MPPT algorithms Perturb and Observe (P&O), Fuzzy Logic Control (FLC), and an improved Sliding Mode Control (SMC) under both healthy and partial shading conditions.

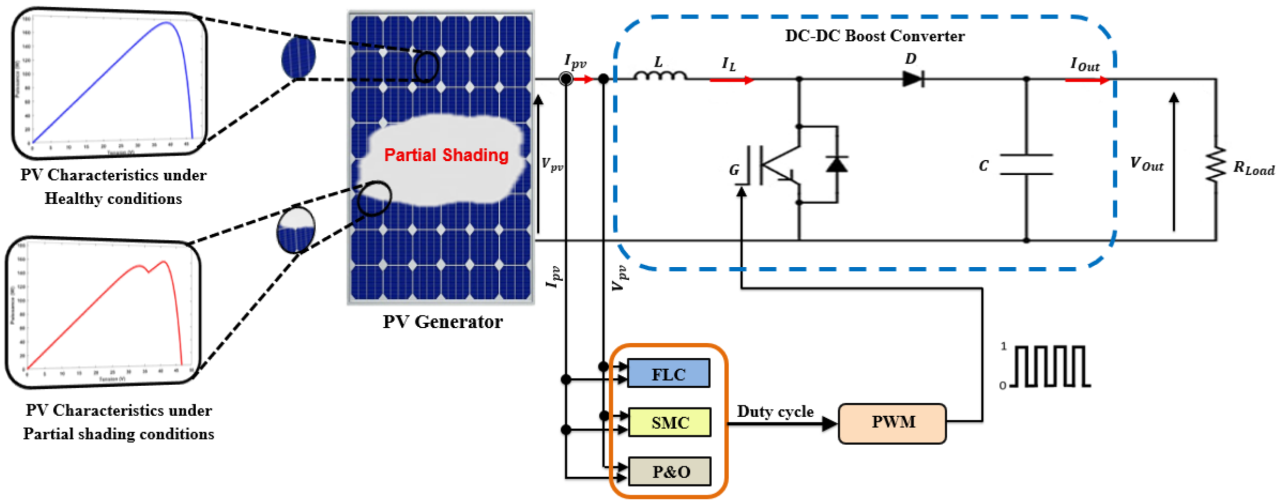


Figure 1. Block diagram of the PV system with MPPT control under healthy and partial shading conditions.

The PV generator is analysed under two separate irradiance scenarios: uniform irradiance (healthy case) the blue curve, where the power-voltage (P–V) curve exhibits a single, well-defined peak; and non-uniform irradiance (partial shading case) the red curve, where shaded cells introduce multiple local maxima, complicating the tracking of the global maximum power point (GMPP). A DC-DC boost converter is used to regulate the PV output, while the MPPT algorithms dynamically adjust the duty cycle signal applied to a PWM controller, enabling real- time adaptation to varying irradiance conditions for efficient power harvesting.

### 2.2 P–V characteristics under uniform irradiance

The P–V characteristics of the photovoltaic system under three uniform irradiance levels—1000 W/m² (blue), 900 W/m² (brown), and 800 W/m² (red)—are illustrated in Figure 2. In all cases, the curves maintain a single MPP, reflecting a healthy and uniformly irradiated PV array. As the irradiance level decreases, the output power drops proportionally, highlighting the strong dependency of PV performance on solar input. This reduction in irradiance leads to lower power generation, which must be considered during energy yield analysis and system design.

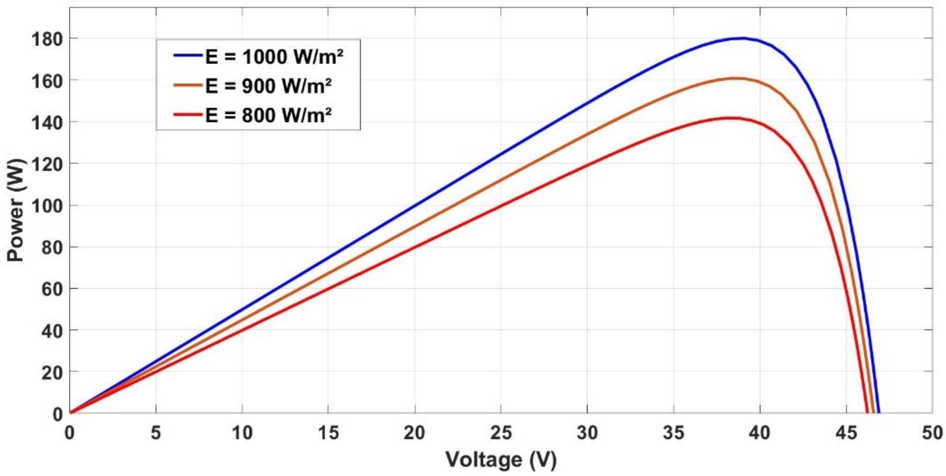


Figure 2. P–V Characteristics under Varying Irradiance Levels (Healthy Condition).

### 2.3 P–V characteristics under partial shading

The power–voltage (P–V) characteristics of the photovoltaic system under three distinct operating scenarios—a healthy uniform irradiance condition (blue curve) and two partial shading cases—are shown in Figure 3. Under healthy conditions, the curve exhibits a single, well-defined Maximum Power Point (MPP), indicating optimal operation without mismatch losses. In contrast, partial shading leads to multiple local peaks in the P–V curves due to uneven irradiance distribution across the PV modules, resulting in the formation of Local MPPs (LMPPs) and a Global MPP (GMPP). These multiple peaks highlight the challenges faced by conventional MPPT algorithms, which may become trapped at a local maximum, thereby reducing energy harvesting efficiency. A noticeable reduction in the maximum extractable power is observed when comparing the GMPPs of the shaded cases with the healthy condition, quantifying the power losses induced by partial shading.

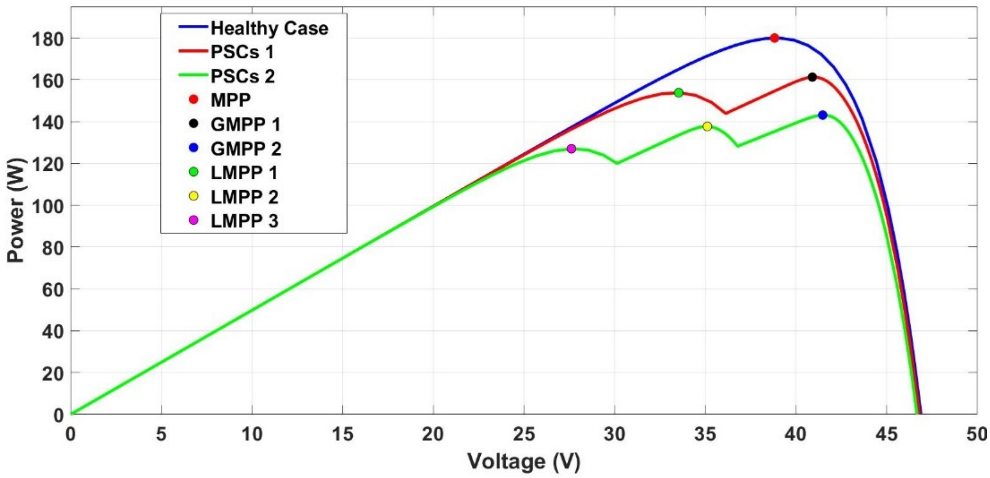


Figure 3. P–V characteristics of the PV system under uniform (healthy) and partial shading conditions.

## 3. Simulation framework and performance evaluation metrics

The performance of the proposed Maximum Power Point Tracking (MPPT) algorithms—Perturb and Observe (P&O), improved Sliding Mode Control (SMC), and Fuzzy Logic Control (FLC)—is evaluated through detailed simulations carried out in the MATLAB/Simscape environment. The photovoltaic (PV) energy conversion system consists of two BlueSolar SPP04090120 modules connected in series. The electrical characteristics of the PV module used in the simulations are summarized in Table 1.

Table 1. Electrical Parameters of the 90 W PV Module under Standard Test Conditions (STC).

| **Parameter** | **Value** |
|---|---|
| Maximum Power ($\boldsymbol{P}_{\mathbf{MPP}}$) | 90 W |
| Voltage at MPP ($\boldsymbol{V}_{\mathbf{MPP}}$) | 19.5 V |
| Current at MPP ($\boldsymbol{I}_{\mathbf{MPP}}$) | 4.61 A |
| Open-Circuit Voltage ($\boldsymbol{V_{OC}}$) | 23.44 V |
| Short-Circuit Current ($\boldsymbol{I_{SC}}$) | 4.98 A |

To assess the robustness and effectiveness of the MPPT techniques, two operating scenarios are considered: uniform irradiance (healthy condition) and non-uniform irradiance (partial shading condition). These scenarios allow a comprehensive evaluation of the tracking capability, stability, and efficiency of each algorithm under realistic operating conditions.

Several key performance indicators are defined and calculated under both operating conditions to enable a quantitative comparison of the MPPT algorithms.

### 3.1 Tracking efficiency

Tracking efficiency quantifies the ability of the algorithm to deliver power close to the theoretical maximum available from the PV generator. It is calculated using the following expression:

$$\eta(\%) = \left(\frac{P_{Load}}{P_{PV}}\right) \times 100 \quad (1)$$

where ($P_{Load}$) is the power delivered to the load, and ($P_{PV}$) represents the measured PV power, defined as the maximum power point (MPP) under uniform conditions and the global MPP (GMPP) under partial shading.

### 3.2 Power losses

Power losses are evaluated in two stages to distinguish between tracking accuracy and conversion efficiency. Two types of losses are considered:

- **PV-side power losses,** defined as the difference between the theoretical maximum PV power and the tracked PV power:

$$P_{Loss,PV} = P_{PV(theoretical)} - P_{PV(tracked)} \quad (2)$$

- **Load-side power losses,** defined as the difference between the tracked PV power and the power delivered to the load:

$$P_{Loss,Load} = P_{PV(tracked)} - P_{Load} \quad (3)$$

### 3.3 Power ripple

Power ripple is used to measure the fluctuations in the output power during steady-state operation. It provides an indication of the stability and precision of the power extraction process. The formula for calculating power ripple is:

$$Power\ Ripple\ (\%) = \frac{P_{Max} - P_{Min}}{P_{Max}} \times 100 \quad (4)$$

Where ($P_{Max}$) and ($P_{Min}$) denote the maximum and minimum power values observed during steady-state operation, respectively. These performance indicators provide a comprehensive basis for evaluating the dynamic response, stability, and overall effectiveness of the MPPT algorithms under both uniform and partial shading conditions.

## 4. Simulation results and discussion

This section discusses the performance of the three MPPT algorithms—Perturb and Observe (P&O), improved Sliding Mode Control (SMC), and Fuzzy Logic Control (FLC)—applied to the photovoltaic system under both uniform irradiance and partial shading conditions. The objective is to interpret the dynamic and steady-state responses of each controller in terms of tracking accuracy, power stability, ripple magnitude, and energy losses, in order to identify the most suitable MPPT strategy for reliable and efficient photovoltaic energy conversion under realistic operating conditions.

### 4.1 Performance under uniform irradiance conditions

The dynamic behavior of the PV output power under variable irradiance conditions for the three evaluated MPPT algorithms—Fuzzy Logic Control (FLC), improved Sliding Mode Control (SMC), and Perturb and Observe (P&O)—is illustrated in Figure 4. The FLC method exhibits the most favorable response, characterized by fast convergence to the maximum power point and minimal oscillations, indicating strong dynamic performance and high tracking precision. The improved SMC algorithm also demonstrates robust operation, maintaining effective tracking with moderate oscillatory behavior. In contrast, the P&O algorithm displays inferior tracking stability, with evident power fluctuations and a tendency to deviate from the global maximum, reflecting limited adaptability to rapidly changing conditions.

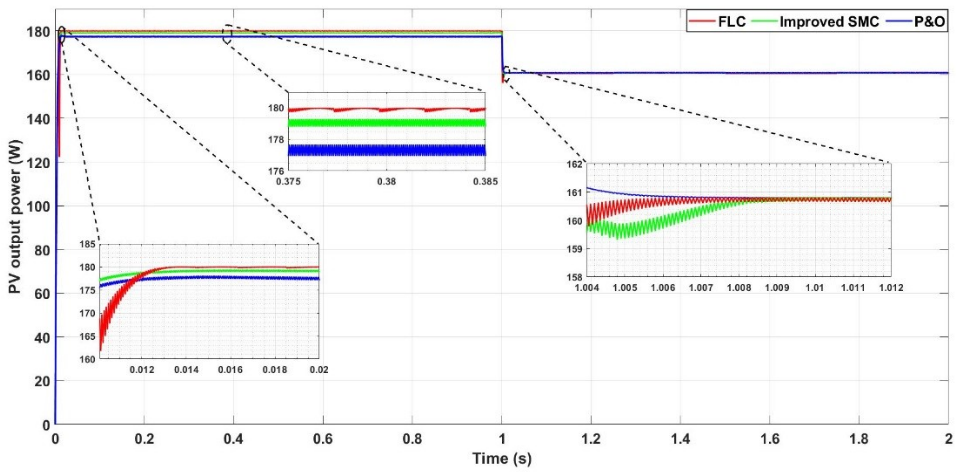


Figure 4. The PV output power of the three algorithms under varying irradiance conditions.

Figure 5 presents the corresponding load power profiles for the same MPPT strategies. Consistent with the PV output analysis, FLC ensures the most stable and reliable power delivery to the load, highlighting its superior capability in maintaining consistent operation under varying irradiance. While SMC and P&O both exhibit fluctuations in load power, the improved SMC achieves slightly enhanced steadiness compared to P&O, confirming its relatively better performance. Overall, FLC emerges as the most effective technique in ensuring both accurate MPPT and stable power output, followed by improved SMC, with P&O showing the most pronounced limitations.

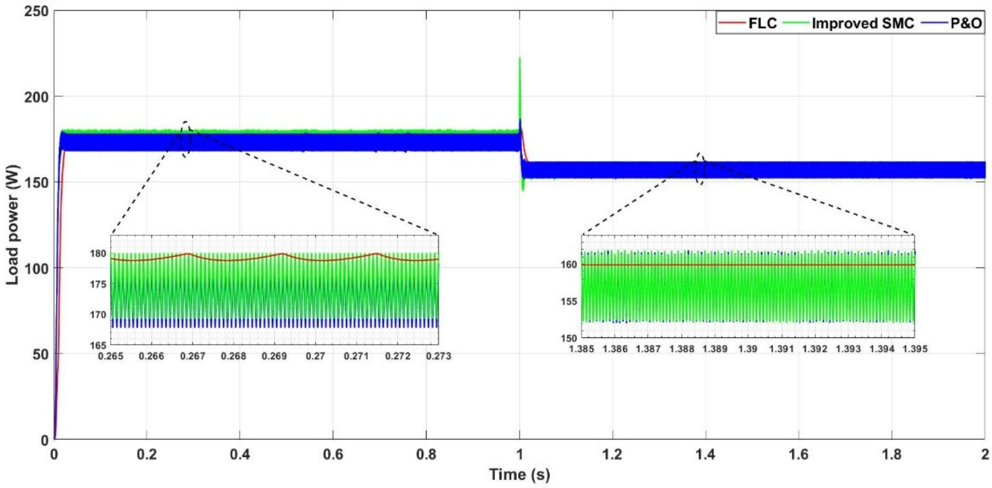


Figure 5. Load power response under partial shading conditions using P&O, FLC, and improved SMC algorithms.

### 4.2 Performance under partial shading conditions

Partial shading introduces multiple local maxima in the power–voltage characteristic, making MPPT significantly more challenging and increasing the risk of convergence to suboptimal operating points. The PV output power under partial shading is shown in Figure 6. The results indicate that both FLC and improved SMC effectively track the Global Maximum Power Point (GMPP), ensuring maximum energy ex- traction under non-uniform irradiance conditions. In contrast, the conventional P&O algorithm fails to reach the GMPP and instead settles near a Local Maximum Power Point (LMPP), resulting in reduced output performance.

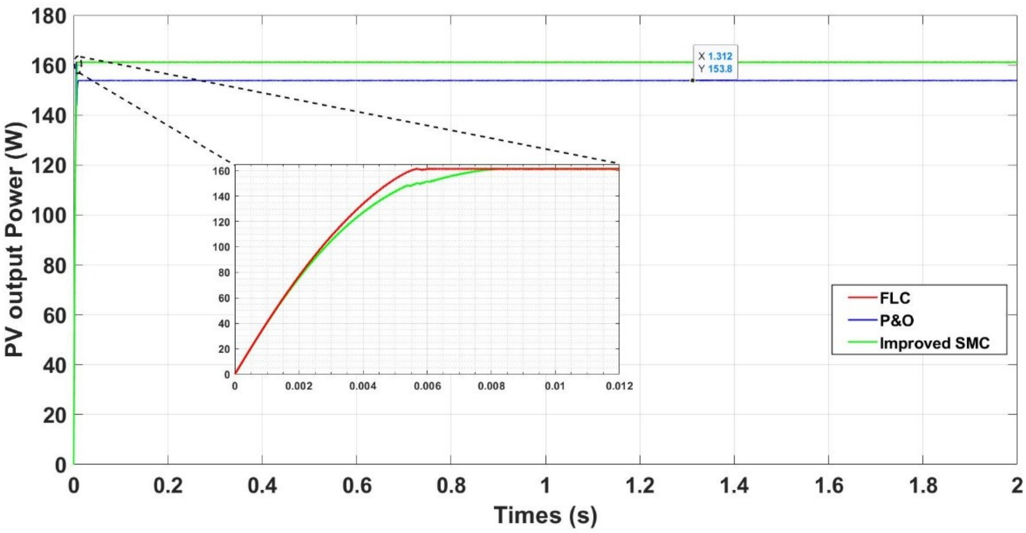


Figure 6. PV output power response under partial shading using P&O, FLC, and improved SMC.

The load power responses under partial shading are depicted in Figure 7. The FLC method maintains highly stable and smooth power delivery, with minimal oscillations around the steady state, confirming its accuracy and robustness in tracking the GMPP. The improved SMC algorithm also converges reliably to the GMPP, although minor power fluctuations are observed. On the other hand, the P&O approach exhibits noticeable oscillatory behavior and a lower average power output, reflecting its limitations in dynamic response and reduced efficiency under partial shading conditions.

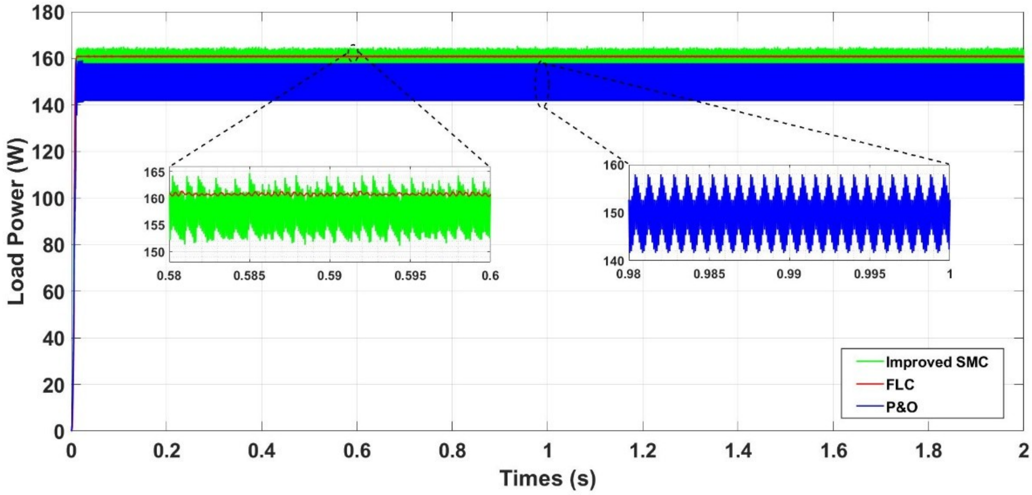


Figure 7. Load power performance under partial shading conditions using the P&O, improved SMC, and FLC algorithms.

### 4.3 Comparative performance evaluation

The comparative performance of the three MPPT algorithms is summarized in Table 2. Under healthy irradiance conditions, the classical P&O method records the lowest efficiency (90.24%) with significant power ripple (6%) and higher load losses (17.3 W), indicating its limitations in fast convergence and steady-state stability. In contrast, the intelligent FLC method achieves 99.6% efficiency, with negligible PV losses and a substantially reduced ripple of 0.6%, showcasing its superior ability to track the MPP with minimal dynamic fluctuations. The improved SMC approach also demonstrates strong performance, balancing high efficiency (97.5%) with moderate ripple (5.88%) and lower total losses compared to P&O. Under non-uniform irradiance conditions, which emulate realistic partial shading effects, the performance divergence becomes even more pronounced. The P&O algorithm fails to track the Global Maximum Power Point (GMPP) effectively, resulting in considerable PV power losses (7.6 W) and a decline in efficiency to 92.78%. Meanwhile, improved SMC maintains strong performance with 97.9% efficiency, moderate power losses, and controlled ripple. Once again, FLC exhibits the most robust and consistent behavior, sustaining 99.8% efficiency, virtually eliminating PV and load-side losses, and producing an exceptionally low ripple (0.18%), confirming its adaptability and high precision under rapidly changing and shaded conditions. This comprehensive evaluation clearly highlights the limitations of conventional MPPT techniques like P&O in dynamic and shaded environments, while confirming the potential of intelligent controllers—particularly FLC—as powerful algorithms for maximizing energy extraction and ensuring system reliability in modern PV applications.

Table 2. Comparative performance of MPPT Algorithms under Healthy and Shaded Conditions.

| | MPPT Algorithm | Efficiency (%) | Load Power (W) | Output PV Power (W) | Power loses (W) | | Power ripple (%) |
|---|---|---|---|---|---|---|---|
| | | | | | PV loses | Load loses | |
| Healthy case | P&O | 90.24 | 160 | 177.3 | 2.7 | 17.3 | 6 |
| | Improved SMC | 97.5 | 174.65 | 179.05 | 0.95 | 4.4 | 5.88 |
| | FLC | 99.6 | 179.35 | 180 | Negligible | 0.65 | 0.6 |
| Shaded Case | P&O | 92.78 | 149.75 | 153.8 | 7.6 | 4.05 | 0.03 |
| | Improved SMC | 97.9 | 158 | 161.3 | 0.1 | 3.3 | 0.14 |
| | FLC | 99.8 | 161 | 161.3 | 0.1 | 0.3 | 0.18 |

## 5. Conclusion and future work

This paper presented a comparative assessment of P&O, improved SMC, and FLC MPPT algorithms for photovoltaic systems under uniform and partial shading conditions. Simulation results demonstrated that intelligent controllers significantly outperform conventional P&O, particularly in shaded environments. Among the evaluated methods, FLC achieved the highest tracking efficiency (up to 99.8%), with negligible power losses and minimal ripple, ensuring fast convergence and excellent stability. Improved SMC also showed robust performance but with slightly higher oscillations. Overall, the findings confirm FLC as a highly effective and reliable MPPT solution for real-world PV applications, especially under complex and dynamic irradiance conditions. Future work will focus on experimental validation using real-time hardware platforms such as DSP or microcontroller-based systems, as well as the development of hybrid or adaptive MPPT strategies to further enhance performance under rapidly changing and complex shading conditions.

## References

[1] G. Upreti, "Climate change and its threat to humanity in the Anthropocene," in *Ecosociocentrism: The earth first paradigm for sustainable living*: Springer, 2023, pp. 137-162.

[2] M. Ben Smida, A. T. Azar, A. Sakly, and I. A. Hameed, "Analyzing grid connected shaded photovoltaic systems with steady state stability and crow search MPPT control," *Frontiers in Energy Research,* vol. 12, p. 1381376, 2024.

[3] D. Mazumdar, C. Sain, P. K. Biswas, P. Sanjeevikumar, and B. Khan, "Overview of solar photovoltaic MPPT methods: a state of the art on conventional and artificial intelligence control techniques," *International Transactions on Electrical Energy Systems,* vol. 2024, no. 1, p. 8363342, 2024.

[4] S. A. Sarang *et al.*, "Maximizing solar power generation through conventional and digital MPPT techniques: a comparative analysis," *Scientific Reports,* vol. 14, no. 1, p. 8944, 2024.

[5] I. Sajid *et al.*, "Optimizing photovoltaic power production in partial shading conditions using dandelion optimizer (DO)-based MPPT method," *Processes,* vol. 11, no. 8, p. 2493, 2023.

[6] H. Ahessab, A. Gaga, and B. Elhadadi, "Enhanced MPPT controller for partially shaded PV systems using a modified PSO algorithm and intelligent artificial neural network, with DSP F28379D implementation," *Science Progress,* vol. 107, no. 4, p. 00368504241290377, 2024.

[7] A. M. Eltamaly and H. M. Farh, "Dynamic global maximum power point tracking of the PV systems under variant partial shading using hybrid GWO-FLC," *Solar Energy,* vol. 177, pp. 306-316, 2019.

[8] S. A. Taha, Z. S. Al-Sagar, M. A. Abdulsada, M. Alruwaili, and M. A. Ibrahim, "Design of an efficient MPPT topology based on a grey wolf optimizer-particle swarm optimization (GWO-PSO) algorithm for a grid-tied solar inverter under variable rapid-change irradiance," *Energies,* vol. 18, no. 8, p. 1997, 2025.

[9] H. Karimi, A. Siadatan, and A. Rezaei-Zare, "A Hybrid P&O-Fuzzy-Based Maximum Power Point Tracking (MPPT) Algorithm for Photovoltaic Systems under Partial Shading Conditions," *IEEE Access,* 2025.

[10] B. C. Phan, Y.-C. Lai, and C. E. Lin, "A deep reinforcement learning-based MPPT control for PV systems under partial shading condition," *Sensors,* vol. 20, no. 11, p. 3039, 2020.

[11] M. H. Ali, M. Zakaria, and S. El-Tawab, "A comprehensive study of recent maximum power point tracking techniques for photovoltaic systems," *Scientific Reports,* vol. 15, no. 1, p. 14269, 2025.