frontiers | Frontiers in Energy Research

TYPE Methods
PUBLISHED 09 April 2025
DOI 10.3389/fenrg.2025.1472768

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EDITED BY
Mohammadreza Aghaei,
Norwegian University of Science and Technology, Norway

REVIEWED BY
Riccardo Mandrioli,
University of Bologna, Italy
Ali Fguiri,
Gabes University, Tunisia

*CORRESPONDENCE
Youssef Mhanni,
ymhanni@uae.ac.ma

RECEIVED 30 July 2024
ACCEPTED 07 February 2025
PUBLISHED 09 April 2025

CITATION
Mhanni Y and Lagmich Y (2025) Enhancing solar power harvesting with pinnacle multipoint optimization: a novel technique for maximum power point tracking.
Front. Energy Res. 13:1472768.
doi: 10.3389/fenrg.2025.1472768

Enhancing solar power harvesting with pinnacle multipoint optimization: a novel technique for maximum power point tracking

Youssef Mhanni* and Youssef Lagmich

Polydisciplinary Faculty, University of Abdelmalek Essaadi (UAE), Larache, Morocco

This study introduces a new technique called Pinnacle Multipoint Optimization (PMO) for Maximum Power Point Tracking (MPPT). The approach is specifically developed to improve the performance of photovoltaic (PV) systems in both regular and partially shaded settings. The PMO algorithm adaptively modifies three crucial tracking points to effectively traverse the power-voltage (P-V) curve, guaranteeing precise monitoring (GMPP). The PMO algorithm has been proven to surpass the classic Perturb and Observe (P&O) approach regarding efficiency, tracking speed, and resilience through comprehensive simulations conducted under diverse irradiation settings. More precisely, when there is partial shadowing, the PMO approach demonstrates significant enhancements compared to the P&O method, which only achieves an average efficiency of 54.71%. The PMO algorithm is proficient in optimizing energy output and minimizing power dissipation in photovoltaic systems.

KEYWORDS

maximum power point tracking (MPPT), pinnacle multi-point optimization (PMO), photovoltaic (PV) systems, partial shading conditions, GMPP tracking

1 Introduction

Solar energy, captured by photovoltaic (PV) systems, is an essential element of the renewable energy landscape, offering a sustainable alternative to fossil fuels (Akbari et al., 2017). Not only does this clean energy source not need much upkeep, but it has also become very popular because of worries about the environment and the fact that traditional energy sources are running out. The worldwide push for green energy has made wind and solar power much more important because they are easily accessible and do not produce many pollutants (Hossain and Hasan Ali, 2015). Of these, photovoltaic panels stand out because they can directly turn sunlight into power. They offer several benefits, including high availability and the ability to adjust their output based on available sunlight, without the need for fuel (Priyadarshi et al., 2020).

Despite these advantages, PV panels exhibit nonlinear characteristics, making them highly sensitive to fluctuations in light intensity, temperature, and load. This sensitivity complicates the process of achieving maximum power point tracking (MPPT) in diverse and variable environments (Dadkhah and Niroomand, 2021; Demirhan, 2022). Since the inception of silicon-based solar cells, significant advancements have been made in the materials and manufacturing methods used in PV technology (Pachauri et al., 2019; Saravanan and Babu, 2016; Mao et al., 2020).

In real-world scenarios, PV panels frequently experience partial shadowing from nearby buildings, trees, or other obstacles, resulting in uneven lighting and partial shading conditions (PSCs). Due to the fact that the power-voltage (P-V) curve has several local maxima under these conditions, it is difficult for conventional MPPT algorithms to determine the precise location of the GMPP. If we want to maximize energy production and make sure PV systems work reliably, we must solve the problem of partial shadowing (Kumar et al., 2023; Rezazadeh et al., 2023).

Under uniform irradiation, the P-V curve of a PV module or array exhibits a single peak representing the MPP. However, partial shading introduces multiple peaks in the current-voltage (I-V) characteristic curve. The number of peaks depends on the series and parallel configuration of the PV array and specific shading conditions affecting the PV strings (Ali et al., 2020). These peaks include multiple local maximum power points (LMPP) and a single GMPP (Katche et al., 2023). Operating at an LMPP instead of the GMPP can lead to significant energy losses, underscoring the need for MPPT controllers with rapid response times and high accuracy to optimize solar energy utilization under varying conditions.

To overcome these challenges, various MPPT algorithms have been developed. Traditional methods like the Perturb and Observe (P&O) algorithm (Liu et al., 2020; Manoharan et al., 2021) are popular due to their simplicity and ease of implementation. This method perturbs the voltage or current and observes the resulting change in power output to track the MPP. However, P&O often struggles under PSCs, where it can get trapped in local maxima. The Incremental Conductance (IC) method (Atharah Kamarzaman and Tan, 2014) offers improved accuracy by comparing incremental conductance (dI/dV) with instantaneous conductance (I/V), allowing for more precise voltage adjustments, especially under rapidly changing conditions. The Hill Climbing (HC) method (Alik and Jusoh, 2018), which adjusts voltage or current based on the power curve gradient, is another effective approach for tracking the MPP under varying irradiance levels. Recent advancements in MPPT techniques include the application of artificial intelligence and stochastic algorithms, which have shown exceptional performance in tracking the GMPP under PSCs (Saravanan and Babu, 2016; Mao et al., 2020). These advanced methods are designed to quickly and accurately locate the GMPP, thereby enhancing the overall efficiency of PV systems.

In this study, we present Pinnacle Multi-Point Optimization (PMO), a new method for Maximum Power Point Tracking (MPPT) that uses a special set of tracking points to effectively traverse the P-V curve in both fully and partially shaded environments. To find and keep the GMPP, the PMO approach dynamically changes these locations, greatly increasing the efficiency of PV systems.

The contributions of this paper are as follows:

- A detailed review of traditional MPPT algorithms, including P&O, IC, and HC methods, highlighting their strengths and limitations.
- Introduction of the novel PMO algorithm, which enhances GMPP tracking accuracy and efficiency under PSCs.
- Comparative analysis of the proposed PMO method against traditional MPPT techniques, demonstrating its superior performance in terms of efficiency, tracking speed, and effectiveness.
- Proposals for future research directions aimed at further improving MPPT performance in PV systems under diverse environmental conditions.

Following is the structure of the remaining parts of this paper: In the second section, we will explore the history of MPPT approaches as well as the associated research. The Perturb and Observe (P&O) Maximum Power Point Tracking (MPPT) approach is examined about its problems and limits in Section 3. In Section 4, the Pinnacle Multi-Point Optimization (PMO) method that has been suggested is discussed, along with its application to photovoltaic (PV) systems that are operating under partial shading conditions (PSCs). In the fifth section, the simulation setup is described, and an evaluation of the effectiveness of the suggested strategy is presented. In Section 6, the work is brought to a close and recommendations for further research are made.

2 Background and related work

2.1 Traditional MPPT methods

One of the most popular approaches for Maximum Power Point Tracking (MPPT) in photovoltaic (PV) systems is the algorithm known as the Perturb and Observe (P&O) method. As a result of its straightforwardness and ease of execution, it is a well-liked option. In order to understand the fundamental concept, it is necessary to make changes to the voltage or current of the photovoltaic array and then observe the corresponding change in power production. In power production, if the power is rising, the perturbation will continue in the same direction; however, if the power is falling, the direction of the disturbance will shift in the opposite direction. The goal of this iterative procedure is to arrive at the Maximum Power Point (MPP) or the Maximum Power Point (Mohamed and Ibrahim, 2012).

There are a number of different approaches and techniques that are often utilized in photovoltaic (PV) systems in order to ascertain the Maximum Power Point Tracking (MPPT). The Perturb and Observe (P&O) method (Liu et al., 2020; Manoharan et al., 2021), for instance, adjusts the operating voltage iteratively and observes changes in power output. If the power increases, adjustments continue in the same direction; if the power decreases, the direction is reversed. This method is referenced in several studies (Atharah Kamarzaman and Tan, 2014; Alik and Jusoh, 2018).

The Incremental Conductance (IC) method calculates and compares incremental conductance (dI/dV) with instantaneous conductance (I/V) (Shengqing et al., 2020; Gupta et al., 2021). This comparison helps determine the direction of voltage adjustments, offering higher accuracy under rapidly changing conditions.

The Hill Climbing (HC) technique, which is comparable to the P&O method, is another strategy (Jately et al., 2021). By adjusting the voltage or current according to the power curve's gradient, the HC technique efficiently tracks the maximum power point regardless of the irradiance level.

These methods are essential to improve the efficiency of PV systems, increase their energy harvest, and ensure that they work well in a variety of environments.

Nevertheless, there are substantial restrictions on the use of P&O algorithms, especially when dealing with partial shading. Because some photovoltaic (PV) modules are partially shadowed while others are not, the power-voltage (P-V) curve has several local maxima due to partial shading from things like buildings and trees. Conventional P&O algorithms may become stuck in these local maximums and not be able to find the global maximum probability point. Furthermore, the PV system's total efficiency might be further diminished due to sluggish convergence and oscillations around the MPP caused by the fixed step size employed in P&O.

2.2 Advanced MPPT methods

Lots of sophisticated MPPT algorithms have been created to overcome the shortcomings of classic P&O algorithms:

2.2.1 Particle swarm optimization (PSO)

Particle Swarm Optimization (PSO) is a population-based optimization algorithm inspired by the social behavior of fish schools and bird flocks. In PSO, particles represent potential solutions and adjust their positions based on personal and shared experiences, enabling efficient exploration of complex search spaces. PSO's key advantages include its ability to handle multi-modal optimization problems, such as partial shading in solar systems, and its robustness to initial conditions. These features make PSO particularly effective for Maximum Power Point Tracking (MPPT), offering reliable power extraction in challenging environments (Águila-León et al., 2024; Chinedu Odo and Chinedozi Ejiogu, 2024; Zitouni et al., 2024).

2.2.2 Grey wolf optimization (GWO)

Grey Wolf Optimization (GWO) is another population-based algorithm inspired by the hunting behavior and social hierarchy of grey wolves. The algorithm simulates the hunting process and leadership structure to find optimal solutions. GWO is effective in exploring the search space and avoiding local maxima, making it a promising approach for (MPPT) applications, particularly in challenging environments (Zhao and Zhang, 2024; Águila-León et al., 2024).

2.2.3 Pelican optimization algorithm (POA)

The Pelican Optimization Algorithm (POA) is a bio-inspired method based on the cooperative foraging behavior of pelicans. In POA, solutions collaborate to explore the search space, balancing exploration and exploitation to find the global maximum. This makes POA effective for Maximum Power Point Tracking (MPPT) in solar systems. The Improved Pelican Optimization Algorithm (IPOA) enhances POA by accelerating convergence and improving accuracy (Mhanni and Lagmich, 2024b).

Particle Swarm Optimization (PSO) converges quickly to the Global Maximum Power Point (GMPP), making it highly efficient for MPPT. Grey Wolf Optimization (GWO), while effective in finding the GMPP, does not converge as rapidly as PSO. On the other hand, the Pelican Optimization Algorithm (POA) is slower in convergence but offers greater stability, making it reliable for MPPT in varying conditions (Mhanni and Lagmich, 2024a).

2.2.4 Fuzzy logic control (FLC)

FLC uses fuzzy logic to handle uncertainty and imprecision associated with MPPT. It applies a set of fuzzy rules to determine the control action based on the current state of the PV system. FLC can adapt to changing environmental conditions and has been effective in improving the performance of MPPT under partial shading (Kumar and Balakrishna, 2024; Sharma et al., 2023).

2.2.5 Neural networks (NN)

Neural networks can model the non-linear characteristics of PV systems and predict MPP based on historical data. NN-based MPPT methods can quickly adapt to varying conditions and provide accurate MPP tracking (Ncir and El Akchioui, 2024).

2.3 Research gap

Although there has been progress made in MPPT techniques, there is still a need for a solution that is more robust and efficient, and that is able to track the global MPP in a reliable manner even when partial shading is present. This is despite the fact that there has been development made in MPPT approaches. Despite their simplicity and ease of implementation, conventional P&O algorithms have issues in dealing with local maxima and fixed step size limits. This is despite the fact that these algorithms are simple. Advanced techniques such as PSO, GWO, FLC, NN, and POA can be challenging to apply and need a large amount of processing power. Furthermore, despite the fact that they bring benefits, these techniques can be difficult to execute.

A unique modification to the P&O algorithm that involves multiple tracking points and dynamic step size adjustment is proposed in this research as a means of addressing the gap that has been identified. In order to provide a solution that is more dependable and effective for photovoltaic (PV) systems, the suggested technique intends to enhance the accuracy and convergence speed of maximum power point tracking (MPPT) under partial shadowing. The purpose of this method is to provide a balanced approach that is both successful and practical for applications that are used in the real world. This is accomplished by harnessing the strengths of both conventional practice and modern approaches.

3 Challenges and limitations of perturb and observe MPPT

(MPPT) in (PV) systems is commonly accomplished using the Perturb and Observe (P&O) approach since it is straightforward and easy to use. But it has a number of problems, particularly in different environments and when there is partial shading (PSCs).

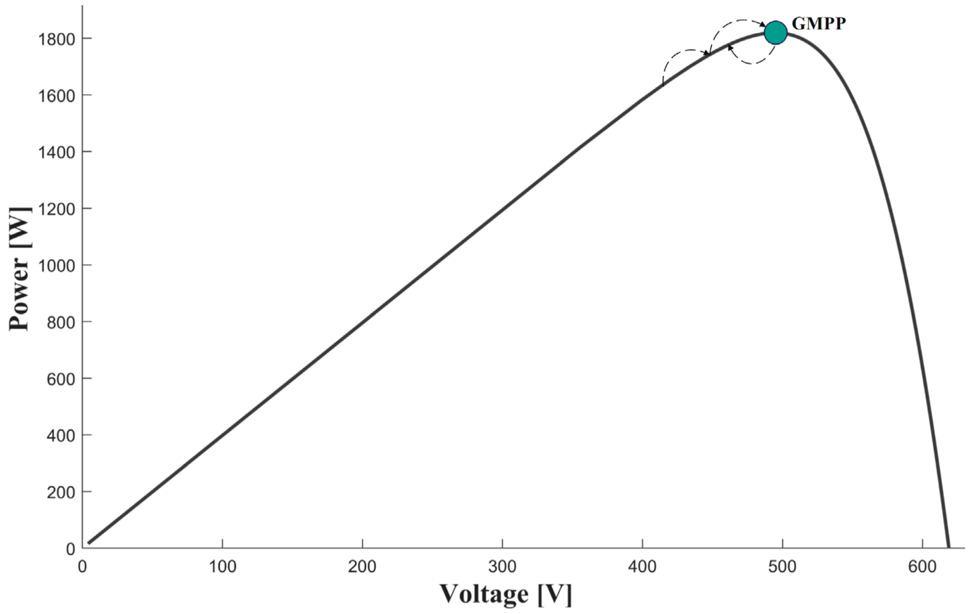

FIGURE 1
P-V curve showing a single MPP under uniform irradiation conditions.

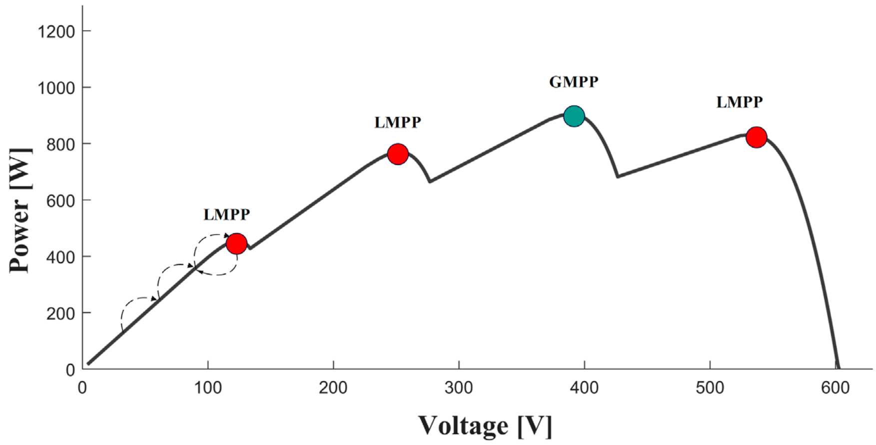

FIGURE 2
P-V curve showing multiple peaks under partial shading conditions.

Taking into account the sign of the most recent PV power increase, the P&O algorithm's basic idea is to change or alter the solar PV operating point. When PV power increases, the disturbance will also increase; when PV power decreases, it will decrease in the opposite manner (Surya Kumari et al., 2012).

3.1 Under uniform irradiation conditions

A photovoltaic (PV) module or array's power-voltage (P-V) curve shows a single peak, which represents the maximum power point (MPP), under conditions of uniform irradiance. In order to get the most out of the PV module or array, the P&O algorithm can successfully follow this one MPP.

The Figure 1 above illustrates the P-V curve under normal irradiation conditions, where the P&O algorithm can efficiently detect and track the MPP.

3.2 Under partial shading conditions

PV panels in practical scenarios sometimes encounter partial shadowing caused by impediments like as trees, buildings, or other structures. The presence of shading causes uneven distribution of irradiance over the surface of the panel, leading to the formation of several peaks in the power-voltage (P-V) characteristic curve. The P&O algorithm may encounter difficulty in differentiating between local maximum power points (LMPPs) and the global

TABLE 1 Summary of MPPT techniques.

Method	Key advantage	Limitation	Suitability
Perturb and Observe (P&O)	Simple and easy to implement	Struggles under partial shading, local maxima problems	General use, but not effective under shading
Incremental Conductance (IC)	More accurate under changing conditions	Computationally more complex than P&O	Moderate shading conditions, dynamic environments
Particle Swarm Optimization (PSO)	Handles multi-modal optimization, fast convergence	Requires more computational resources	Complex conditions with partial shading
Grey Wolf Optimization (GWO)	Effective at avoiding local maxima	Slower convergence than PSO	Shading scenarios, multi-peak power curves
Pelican Optimization Algorithm (POA)	Stable, effective collaboration between solutions	Slower convergence compared to PSO	Varying environmental conditions
Fuzzy Logic Control (FLC)	Adapts well to uncertainties and changing conditions	Needs careful tuning of fuzzy rules	Unstable environments, partial shading
Neural Networks (NN)	Fast adaptation to changing conditions	Requires significant training data	Rapidly changing conditions, dynamic systems

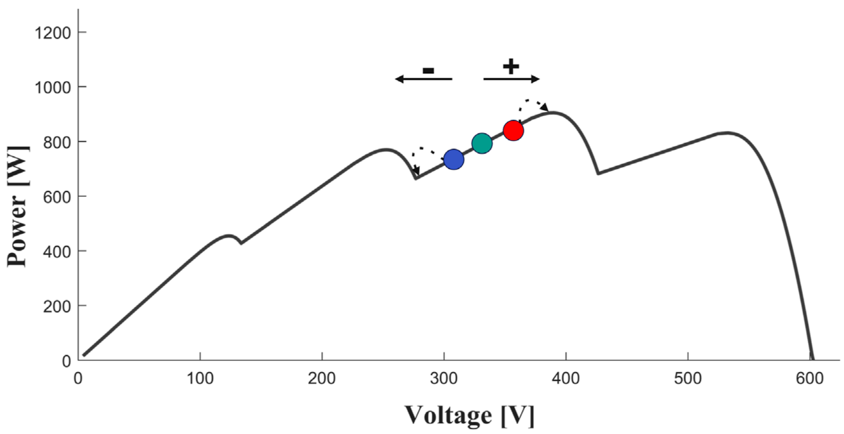

FIGURE 3
Illustration of the PMO algorithm under partial shading conditions.

maximum power point (GMPP). This constraint can result in the system becoming stuck at an LMPP, resulting in substantial energy depletion.

The provided diagram Figure 2 illustrates the P-V curve in the presence of partial shading, depicting numerous Local Maximum Power Points (LMPPs) and a single (GMPP). The P&O algorithm may erroneously classify an LMPP as the GMPP, resulting in poor performance.

3.3 Response to rapidly changing conditions

The performance of the P&O approach is significantly diminished when exposed to rapidly fluctuating irradiance and temperature conditions. The program manipulates the voltage and monitors the resulting change in power in order to determine the subsequent perturbation direction. In dynamic settings, this might result in erroneous choices, leading to fluctuations around the maximum power point (MPP) and further diminishing effectiveness.

3.4 Fixed step size issues

Another notable concern with the P&O method is its utilization of a constant step size for perturbations. An excessively large step size can result in oscillations around the Maximum Power Point (MPP), whereas a very tiny step size might impede the convergence process, leading to ineffective tracking.

Table 1 summarizes key MPPT techniques used in photovoltaic systems, highlighting their advantages, limitations, and suitability for various environmental conditions.

4 Problem statement and objective

Despite the significant progress in Maximum Power Point Tracking (MPPT) techniques for photovoltaic (PV) systems, each existing method presents certain limitations, especially when it comes to handling partial shading and fluctuating environmental conditions, such as changing irradiance and temperature. Traditional methods like Perturb and Observe (P&O) and Incremental Conductance (IC) work well under ideal conditions, but they struggle when the system encounters partial shading or rapid environmental changes.

4.1 Limitations of existing methods

- Partial Shading: When PV panels are partially shaded due to obstacles like buildings, trees, or clouds, the power-voltage (P-V) curve can exhibit multiple peaks. Conventional MPPT algorithms, such as P&O, often get trapped in local maxima, leading to suboptimal power extraction and reduced efficiency.
- Climate Variability: Rapid changes in irradiance and temperature due to dynamic weather conditions can disrupt the performance of MPPT methods. Fixed-step algorithms, such as P&O, often fail to quickly adapt to such changes, causing oscillations around the maximum power point (MPP) and delaying convergence.
- Complexity: While more advanced methods, such as Particle Swarm Optimization (PSO) or Neural Networks (NN), offer better performance under complex conditions, they come with high computational costs and increased implementation complexity.

4.2 Objective

The objective of this work is to develop a novel MPPT technique that effectively addresses these challenges. We aim to design a method that:

- Is **resilient to partial shading**, avoiding the problem of getting stuck in local maxima.
- Can **adapt to rapidly changing climatic conditions** (irradiance and temperature) without compromising tracking speed or efficiency.
- Is **simple and efficient**, avoiding the high computational cost associated with more complex algorithms, making it suitable for real-world PV applications.

By focusing on these key objectives, the proposed method strives to provide a practical, reliable, and efficient solution for MPPT in diverse environmental conditions, ensuring that PV systems consistently operate at or near their global maximum power point (GMPP).

5 The new proposal method for optimal power extraction in shaded solar panels

The Pinnacle Multi-Point Optimization (PMO) method seeks to improve the (MPPT) capacities of (PV) systems, especially in situations when there is partial shadowing. The main goal is to precisely monitor the (GMPP) while preventing local maxima (LMPP), to optimize the energy output.

5.1 Overview of the proposed algorithm

The Pinnacle Multi-Point Optimization (PMO) method successfully manages the power-voltage (P-V) curve by utilizing three monitoring points, regardless of whether the conditions are typical or partially shaded. These points enhance the efficiency of the PV system by dynamically adjusting to locate and sustain the (GMPP).

By gradually reducing the voltage at a certain point, it becomes possible to investigate the lower P-V curve. This facilitates the identification of potential maximum power points that may remain undiscovered if only higher voltages are considered. To accommodate environmental changes affecting the curve's upper range, the voltage of the second point is gradually increased to encompass the higher voltage range.

The primary monitoring point compares and continuously monitors the power outputs at the voltages that the other two points have identified. Using this feedback, the system makes adjustments to its location to optimize power generation. This application can respond immediately to changes in irradiation and shading due to its dynamic adjustment feature. This feature optimizes energy production.

The PMO algorithm mitigates the risk of the system being trapped at a local maximum power point (LMPP) by utilizing a multi-point method. The PMO algorithm is highly effective in improving the performance of PV systems under diverse environmental conditions due to its adaptability and comprehensive coverage.

The (Figure 3) Demonstrates the PMO Algorithm in the presence of partial shading. The system demonstrates the dynamic adjustment of three tracking points along the power-voltage (P-V) curve to effectively locate and sustain the (GMPP). This enhances the performance of the photovoltaic (PV) system by avoiding local maxima and improving energy production under different situations.

5.2 Algorithm description

The PMO method utilizes three essential tracking points to efficiently navigate the power-voltage (P-V) curve, guaranteeing excellent performance in both regular and partial shading scenarios:

- Decreasing Point: This point decreases its value incrementally with each iteration, serving as a dynamic guide towards the Maximum Power Point (MPP).
- Increasing Point: This point increases its value incrementally with each iteration, also acting as a guide towards the MPP.
- Tracking Point: The tracking point, also known as the green point, is the primary tracking point that is responsible for listening for the best power output and updating its location

whenever it discovers a power output that is superior to the value it is currently at. In the event that the decreasing and rising points are unable to locate a power output that is superior to the tracking point, the algorithm will continue to alter the tracking point by performing adjustments using conventional techniques.

5.3 Algorithm steps

The algorithm follows these steps:

1. **Initialization:**
   - Initialize the voltage values for the decreasing point (V_{mpo1}), the increasing point (V_{mpo2}), and the tracking point (V_{mpo}) to the same starting voltage.
   - Set the initial step sizes (*step_size* and *step_size*1).
2. **Measurement:**
   - Measure the initial power at V_{mpo}, V_{mpo1}, and V_{mpo2}.
3. **Simultaneous Adjustments:**
   - Adjust V_{mpo} by using the P&O method, which involves:
     - If the current power at V_{mpo} is greater than the previous power, increase V_{mpo} by *step_size*.
     - If the current power at V_{mpo} is less than the previous power, decrease V_{mpo} by *step_size*, halve *step_size*, and reverse its direction.
   - Adjust V_{mpo1} by adding *step_size*1.
   - Adjust V_{mpo2} by subtracting *step_size*1.
4. **Power Measurement:**
   - Measure the power at V_{mpo}, V_{mpo1}, and V_{mpo2}.
5. **Evaluation and Update:**
   - If the power at V_{mpo1} is greater than the maximum power, update V_{mpo} to V_{mpo1} and set *step_size* to *step_size*1.
   - If the power at V_{mpo2} is greater than the maximum power, update V_{mpo} to V_{mpo2} and set *step_size* to *step_size*1.
   - If neither V_{mpo1} nor V_{mpo2} provides a better power output than V_{mpo}, continue adjusting V_{mpo} using traditional methods.
6. **Iteration:**
   - Repeat the above steps for each iteration until the GMPP is accurately tracked.

5.4 Advantages of the PMO algorithm

The PMO algorithm offers several advantages over traditional P&O methods:

- Improved Accuracy: By simultaneously adjusting multiple voltage points and comparing their power outputs, the algorithm reduces the likelihood of getting trapped in local maxima.
- Faster Convergence: The dynamic adjustment of step sizes ensures quicker convergence to the GMPP.
- Enhanced Performance under PSCs: The algorithm effectively handles the multi-peak P-V curve characteristic of PSCs, ensuring optimal power extraction.

6 Flowchart

Figure 4 shows the PMO algorithm's sequential steps, including initialization, power measurement, and repeated performance optimization changes.

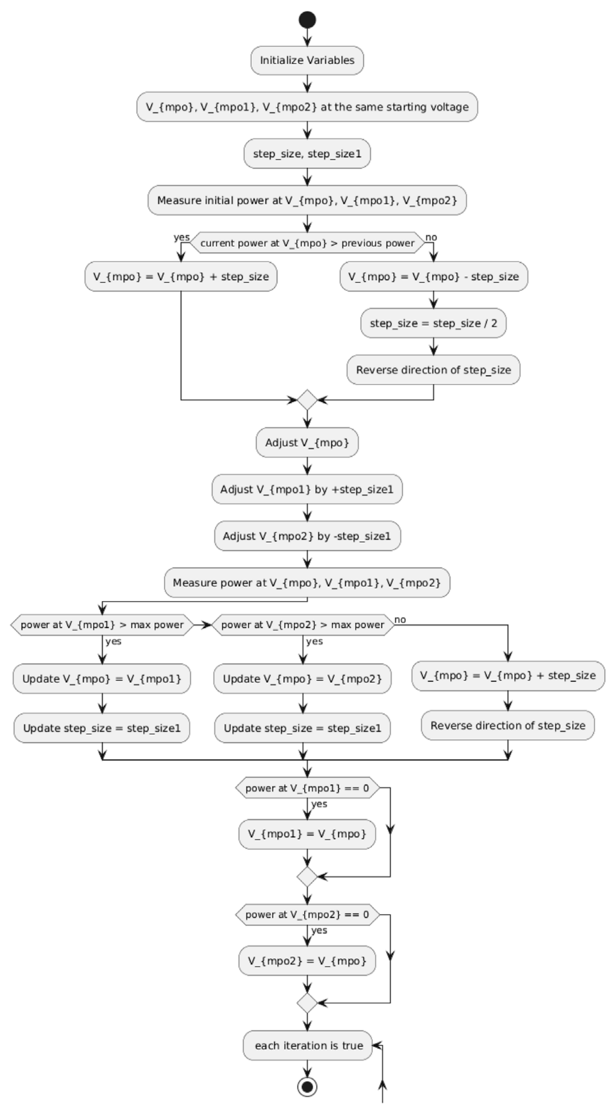

FIGURE 4
Flowchart of the PMO algorithm.

6.1 Pseudocode

```
Initialize: V_mpo, V_mpo1, V_mpo2 at the same starting
voltage, step_size, step_size1
for each iteration do
  Measure initial power at V_mpo, V_mpo1, V_mpo2
  Adjust V_mpo using PO method:
  if current power at V_mpo > previous power then
    V_mpo = V_mpo + step_size
  else
     V_mpo = V_mpo − step_size
    step_size = step_size/2
    step_size = −step_size
  end if
   Adjust V_mpo1 by +step_size1
   Adjust V_mpo2 by −step_size1
   Measure power at V_mpo, V_mpo1, V_mpo2
   if power at V_mpo1 > max power then
    V_mpo = V_mpo1
    step_size = step_size1
   else if power at V_mpo2 > max power then
    V_mpo = V_mpo2
    step_size = step_size1
   end if
   if power at V_mpo1 = 0 then
    V_mpo1 = V_mpo
   end if
   if power at V_mpo2 = 0 then
    V_mpo2 = V_mpo
   end if
end for
```

Algorithm 1. Proposed PMO Algorithm.

7 Results and discussion

7.1 Simulation setup

The effectiveness of the proposed Pinnacle Multipoint Optimization (PMO) system was evaluated using comprehensive simulations conducted in MATLAB/Simulink. The effectiveness of the PMO technique with the standard Perturb and Observe (P&O) strategy was evaluated by modeling the photovoltaic (PV) system under various partial shadow conditions. The primary evaluation criteria were of efficiency, power output, and convergence speed.

7.2 Simulation results

7.2.1 Scenario 1: guided by increasing point (red point)

In this process, the red guiding point progressively increases its value with each repetition, steering the system toward the Maximum Power Point (MPP) as shown in Figure 5.

7.2.2 Scenario 2: guided by decreasing point (blue point)

In this scenario, the blue guiding point increases its value with each iteration, effectively guiding the system towards the Maximum Power Point (MPP), as illustrated in Figure 6.

The simulations were performed using four different partial shade situations, specifically designed to test the MPPT algorithms under varying levels of irradiance. The findings demonstrate the convergence characteristics and effectiveness of the PMO algorithm in comparison to the conventional P&O technique.

This Tables 2, 3 present iteration details for every five iterations, comparing the traditional PO method with the proposed methods guided by red and blue points, respectively. The tables show the corresponding voltage and power values at each iteration, illustrating the convergence process and performance improvements achieved by the proposed methods in each case.

7.2.3 Voltage output

The Figure 7 Demonstrates the efficacy of several (MPPT) techniques in maintaining high voltage output under instances of partial shade. Pinnacle Multipoint Optimization (PMO) methodology, incorporating blue and red guiding points, is being contrasted to the existing P&O approach. The PMO's exceptional performance in adaptively finding the GMPP is emphasized, in contrast to the traditional P&O approach which tends to remain stuck at a local maximum power point (LMPP).

Table 4 presents the performance metrics of different MPPT algorithms, including the initial and final voltage values, convergence time in iterations, and tracking error in watts. The proposed methods (red guiding and blue guiding) show faster convergence and zero tracking error compared to the traditional P&O method.

Table 5 provides an overview of different MPPT algorithms, including the traditional Perturb and Observe (P&O) method and the proposed hybrid methods (red guiding and blue guiding). Each algorithm's description highlights its approach, and characteristics emphasize its strengths and potential limitations.

7.2.4 Power output

Power output is a critical metric for evaluating the performance of MPPT algorithms. The ability to maintain high power output under varying conditions directly impacts the overall efficiency and energy yield of the PV system.

The Figure 8 illustrates the power output over time for different MPPT methods under partial shading conditions. The proposed PMO method, guided by blue and red points, effectively navigates towards the GMPP. Unlike the traditional P&O method, which often stabilizes at an LMPP, the PMO method continues to adjust and optimize, ensuring higher power output and better energy harvest from the PV system.

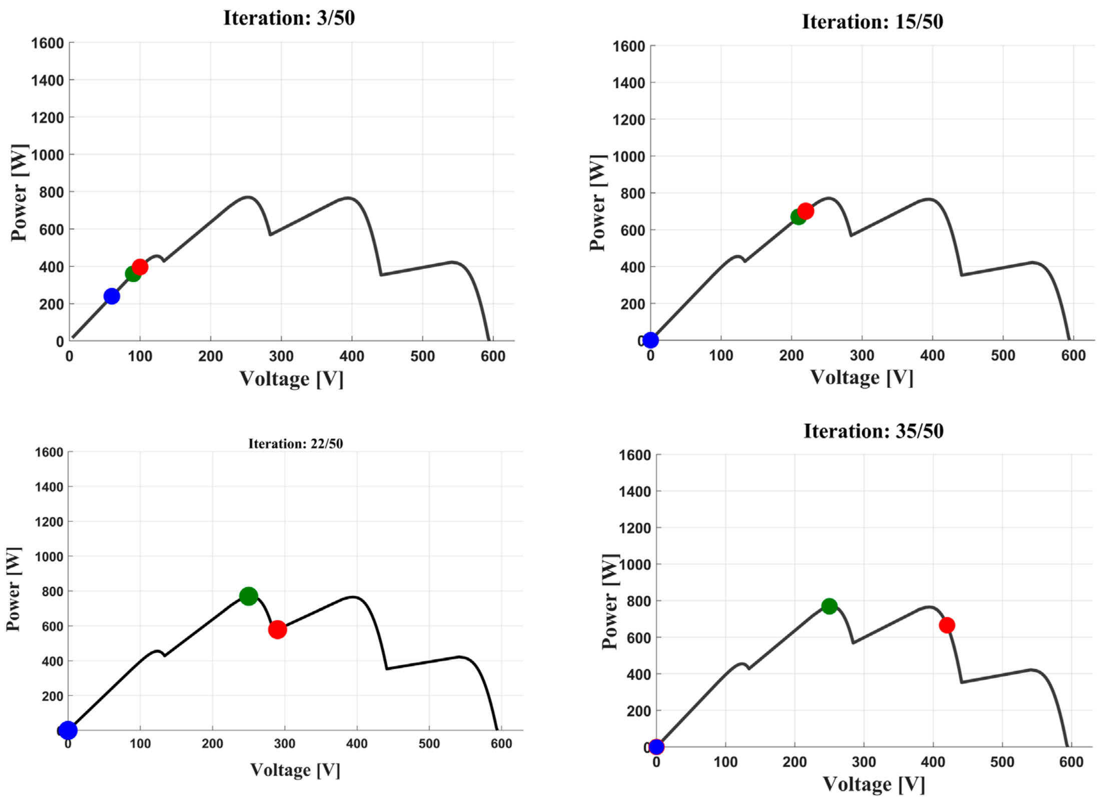

FIGURE 5
Convergence to maximum power point for scenario 1 (guided by red point).

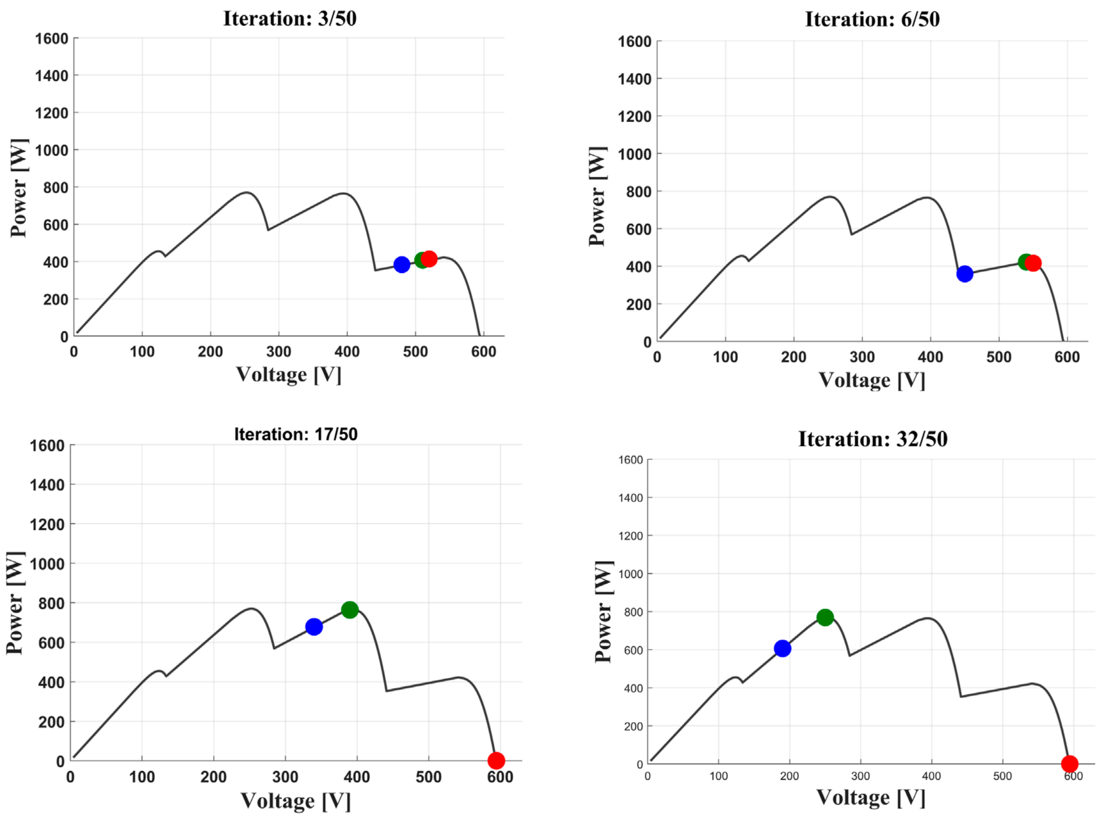

FIGURE 6
Convergence to maximum power point for scenario 2 (guided by blue point).

TABLE 2 Iteration details for red guiding method and traditional P&O.

Iteration	Voltage (V) (P&O)	Power (W) (P&O)	Voltage (V) (red guiding)	Power (W) (red guiding)
1	10.1	40.3	90	358.1
5	50.1	199.9	110.016	429.9
10	100.1	396.3	160	510.7
15	115.1	443.6	210	669.8
20	121.4	453.9	250	769.1
25	123.9	454.8	250	769.1
30	123.6	454.9	250	769.1
35	123.6	454.9	250	769.1
40	123.6	454.9	250	769.1
45	123.5	454.9	250	769.1
50	123.6	454.9	250	769.1

TABLE 3 Iteration details for blue guiding method and traditional P&O.

Iteration	Voltage (V) (P&O)	Power (W) (P&O)	Voltage (V) (blue guiding)	Power (W) (blue guiding)
1	10.1	40.3	510	406.6
5	50.1	199.9	530.016	419.7
10	100.1	396.3	420.048	665.6
15	115.1	443.6	390	763.6
20	121.4	453.9	390	763.6
25	123.9	454.8	390	763.6
30	123.6	454.9	250	769.1
35	123.6	454.9	250	769.1
40	123.6	454.9	250	769.1
45	123.5	454.9	250	769.1
50	123.6	454.9	250	769.1

7.3 Comparison under varying irradiation conditions

To evaluate the performance of the PMO algorithm under different environmental conditions, we tested the algorithm with various irradiation levels. These scenarios are designed to represent typical variations in real-world conditions, including partial shading and uniform irradiation.

- Scenario 1: Irradiance levels: $ir_1 = 1$, $ir_2 = 0.8$, $ir_3 = 0.5$, $ir_4 = 0.2$
- Scenario 2: Irradiance levels: $ir_1 = 0.6$, $ir_2 = 0.3$, $ir_3 = 0.8$, $ir_4 = 1$
- Scenario 4: Irradiance levels: $ir_1 = 1$, $ir_2 = 1$, $ir_3 = 1$, $ir_4 = 1$

The examples demonstrate the algorithm's capacity to adjust to various shade patterns and offer a distinct contrast between the PMO and classic P&O approaches. The PMO algorithm's success in locating the (GMPP) is demonstrated in each situation, even in the presence of several local maxima. The comparison emphasizes the PMO algorithm's better ability in adapting to changing irradiation levels and maximizing power output.

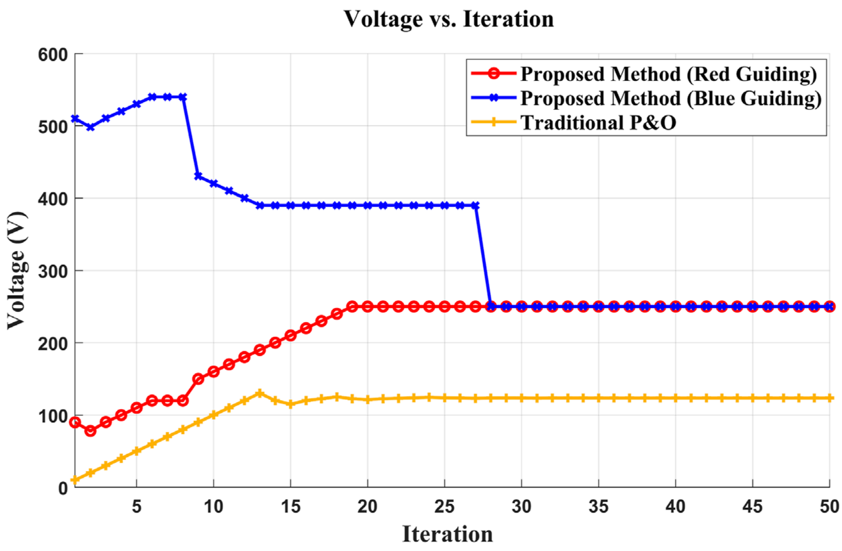

FIGURE 7
Tracking efficiency of various MPPT methods under partial shading conditions.

TABLE 4 Performance metrics.

Algorithm	Initial voltage (V)	Final voltage (V)	Convergence time (iterations)	Tracking error (W)
Traditional P&O	10.1	123.5501	50	0.8564
Proposed Method (Red Guiding)	90	250	19	0
Proposed Method (Blue Guiding)	510	250	27	0

TABLE 5 Algorithm details.

Algorithm	Description	Characteristics
Traditional P&O	Perturb and Observe method	Simple, fast, but may get stuck in local maxima
Proposed Method (Red Guiding)	Hybrid method using three points, with red guiding	Improved convergence to global MPP, reduces local maxima issues
Proposed Method (Blue Guiding)	Hybrid method using three points, with blue guiding	Enhanced tracking performance, efficient in finding global MPP

Table 6 presents the summary of results for each scenario, comparing the final power output, efficiency, and tracking speed of the proposed PMO algorithm against the traditional P&O method.

7.4 Gain comparison

Table 7 and Figure 9 illustrate the gain and percentage gain comparison for each scenario, showing the improvement in power output achieved by the proposed PMO algorithm compared to the traditional P&O method.

7.4.1 Improvements in tracking efficiency

The proposed method's ability to maintain higher tracking efficiency is attributed to its comprehensive exploration of the P-V curve. By using multiple points, the algorithm effectively identifies the GMPP, avoiding the pitfalls of local maxima that commonly trap traditional P&O methods.

This Table 8 compares the efficiency and effectiveness of the traditional Perturb and Observe (P&O) algorithm and the proposed PMO method across different scenarios. The PMO method consistently shows higher efficiency and better effectiveness in tracking the Maximum Power Point (MPP) under varying shading conditions.

The Figure 10 illustrates the tracking efficiency of different MPPT methods under partial shading conditions. It highlights the superior performance of the PMO method in accurately tracking the global maximum power point compared to the traditional P&O method.

The study indicates that the suggested strategy consistently exhibits great efficiency and effectiveness in all cases. In comparison to the conventional P&O technique, it substantially decreases power dissipation and improves the overall efficiency of the photovoltaic (PV) system. The PSO algorithm consistently outperforms other algorithms, demonstrating superior power output and efficiency in all cases.

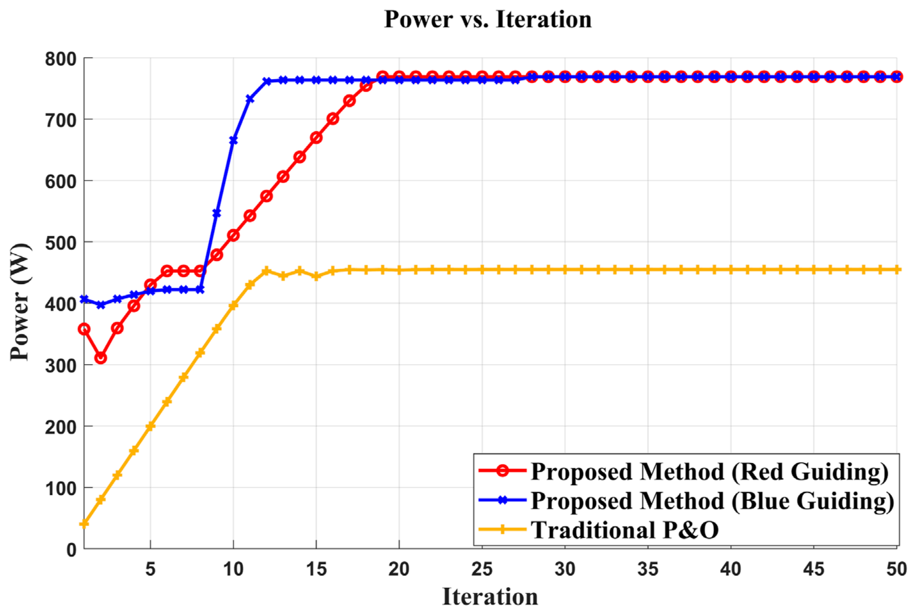

FIGURE 8
Power output of various MPPT methods under partial shading conditions.

TABLE 6 Summary of results for each scenario.

Scenario	Irradiation conditions	Algorithm	Final power (W)	Efficiency (%)	Tracking speed
1	$ir_1 = 1$, $ir_2 = 0.8$, $ir_3 = 0.5$, $ir_4 = 0.2$	Proposed	769.06	100.00	Fast
		Traditional P&O	454.86	59.14	Slow
2	$ir_1 = 0.6$, $ir_2 = 0.3$, $ir_3 = 0.8$, $ir_4 = 1$	Proposed	904.44	100.00	Fast
		Traditional P&O	454.86	50.27	Slow
3	$ir_1 = 1$, $ir_2 = 1$, $ir_3 = 1$, $ir_4 = 1$	Proposed	1819.31	100.00	Fast
		Traditional P&O	1819.24	99.98	Moderate

TABLE 7 Gain and percentage gain comparison.

Scenario	GMPP (W)	P&O power (W)	Gain (W)	Percentage gain (%)
1	769.06	454.86	314.20	69.06
2	904.44	454.86	449.58	98.84
3	1819.31	1819.24	0.07	0.004

By integrating these tables and analyses into your research paper, you can offer a thorough synopsis of the effectiveness of different MPPT algorithms in diverse partial shading scenarios. The

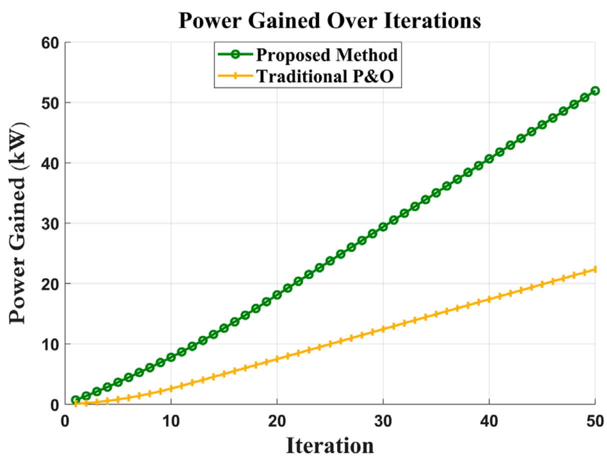

FIGURE 9
Gain of various MPPT methods under partial shading conditions.

comprehensive analysis emphasizes the benefits of the suggested approach and showcases its potential to enhance energy generation in photovoltaic systems.

7.4.2 Limitations and future work

Although the suggested approach demonstrates significant enhancements, there are aspects that warrant more investigation. Potential future research might investigate the incorporation of this technique with real-time hardware implementations and evaluate its efficacy in the face of significant environmental fluctuations. Moreover, integrating this method with additional

TABLE 8 Efficiency and effectiveness across scenarios.

Scenario	Algorithm	Max power (W)	Efficiency (%)	Effectiveness
1	P&O	454.86	59.14	High power loss in partial shading conditions
	PMO	769.06	100.00	Excellent tracking, minimizes power loss
2	P&O	454.86	50.27	High power loss in partial shading conditions
	PMO	904.44	100.00	Excellent tracking, minimizes power loss
3	P&O	1819.24	99.98	Moderate tracking efficiency
	PMO	1819.31	100.00	Highly efficient, effective in dynamic conditions

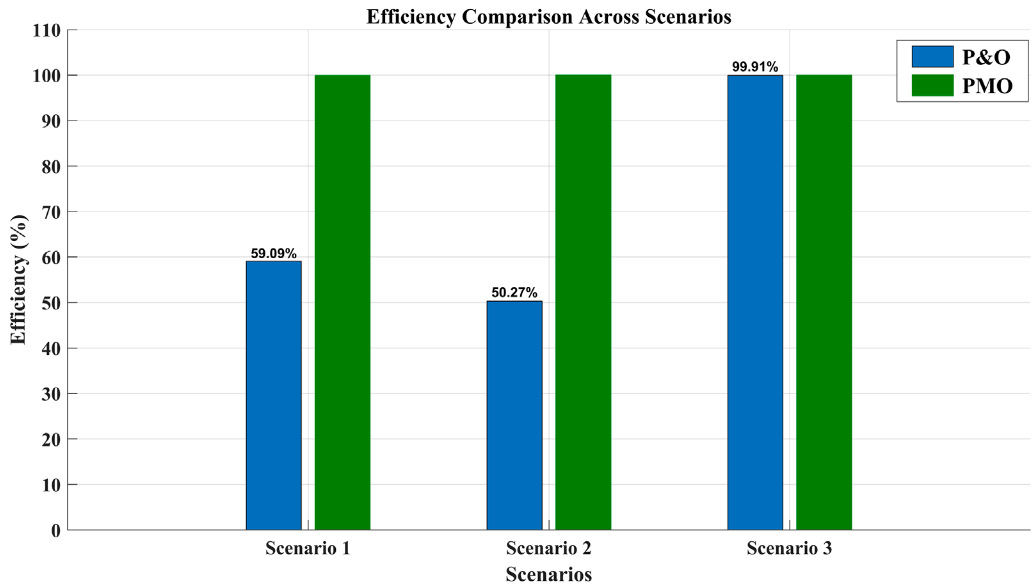

FIGURE 10
Tracking efficiency of various MPPT methods under partial shading conditions.

optimization strategies might significantly improve the performance of MPPT.

8 Conclusion

This study presents the Pinnacle Multi-Point Optimization (PMO) algorithm, a new method for achieving (MPPT) in (PV) systems. The technique is highly efficient in both normal and partial shade scenarios. The PMO method utilizes three essential tracking points that dynamically adapt to precisely discover and sustain the Global Maximum Power Point (GMPP).

The simulation results clearly showed that the PMO algorithm beats the classic Perturb and Observe (P&O) approach to a substantial extent. More precisely, when there is partial shade, the Perturb and Observe (P&O) approach performs significantly better than the Perturb and Observe (P&O) method, which only achieves an average efficiency of 54.71%. The results highlight the strong, fast, and precise nature of the PMO algorithm in optimizing the energy output of PV systems.

The utilization of the PMO algorithm presents a viable approach to improve the effectiveness and dependability of solar energy collection, rendering it well-suited for practical photovoltaic (PV) uses. Subsequent research will concentrate on enhancing the algorithm and investigating its efficacy in varied climatic circumstances and bigger photovoltaic arrays.

Data availability statement

The original contributions presented in the study are included in the article/supplementary material, further inquiries can be directed to the corresponding author.

Author contributions

YM: Conceptualization, Data curation, Formal Analysis, Methodology, Validation, Writing–original draft, Project administration, Writing–review and editing. YL: Supervision, Validation, Writing–original draft.

Funding

The author(s) declare that no financial support was received for the research, authorship, and/or publication of this article.

Conflict of interest

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Nomenclature

P_{max}	Maximum Power
V_{mp}	Voltage at Maximum Power Point
I_{mp}	Current at Maximum Power Point
η	Efficiency
G	Solar Irradiance
T	Temperature
GMMP	Global Maximum Power Point
MPPT	Maximum Power Point Tracking
PV	Photovoltaic
PSO	Particle Swarm Optimization
GWO	Grey Wolf Optimization
POA	Pelican Optimization Algorithm
IPOA	Improved Pelican Optimization Algorithm