International Journal of Applied Power Engineering (IJAPE)
Vol. 15, No. 2, June 2026, pp. 590~599
ISSN: 2252-8792, DOI: 10.11591/ijape.v15.i2.pp590-599

Adaptive P&O algorithm for fast and acurate maximum power point tracking for PV system

Fathurrahman[1,2], Rika Sri Utami[1], Akhyar[1,3], Khairun Saddami[1,4]
[1]Department of Electrical and Computer Engineering, Faculty of Engineering, Universitas Syiah Kuala, Aceh, Indonesia
[2]Department of Electrical Engineering, King Fahd University of Petroleum and Minerals, Saudi Arabia
[3]Department of Electrical, Electronic, and System Engineering, Faculty of Engineering and Built Environment, Universiti Kebangsaan Malaysia, Selangor, Malaysia
[4]AI Research Group, Universitas Syiah Kuala, Aceh, Indonesia

Article Info

Article history:

Received Dec 11, 2024
Revised Dec 25, 2025
Accepted Mar 12, 2026

Keywords:

Adaptive P&O
Maximum power point tracking
Partial shading
Photovoltaic
PV system

ABSTRACT

In this study, we proposed an adaptive perturb and observe (P&O) algorithm designed for efficient maximum power point tracking (MPPT) in photovoltaic (PV) systems. This method addresses key challenges in solar energy systems, including variability in solar irradiation and partial shading conditions. The proposed method introduced a dynamic and adaptive in adjusting the step size of the P&O as it nears the maximum power point (MPP), enhancing tracking precision and reducing energy losses. To show the ability of the proposed, we compared it with the conventional P&O and GWO & P&O. The proposed adaptive P&O MPPT algorithm consistently maintains near-ideal tracking efficiency of ≈99.7% across various irradiance scenarios, significantly outperforming conventional P&O, which drops to 74.45% under partial shading. Overall, it achieves an average efficiency of 99.71%, surpassing hybrid P&O-GWO (99.52%) and conventional P&O (91.30%), demonstrating superior reliability and energy harvesting performance. The results indicated that the proposed could reduce power deviations and obtain greater accuracy in detecting MPP. The study confirms the method's potential for optimizing energy extraction and suggests further refinement for broader applicability. This advancement represents a significant step in enhancing the reliability and efficiency of PV systems in both grid-connected and off-grid applications.

Corresponding Author:

Khairun Saddami
Department of Electrical and Computer Engineering, Universitas Syiah Kuala
Street Syekh Abdurrauf No. 7, Banda Aceh 23111, Aceh, Indonesia
Email: khairun.saddami@usk.ac.id

1. INTRODUCTION

Maximum power point tracking (MPPT) is a crucial aspect of photovoltaic (PV) systems, as it enables the extraction of maximum power from the solar array under varying environmental conditions. The MPPT algorithm plays a vital role in optimizing energy yield, reducing energy losses, and increasing the overall efficiency of the PV system. Recent studies have shown that these limitations can result in significant energy losses, ranging from 5% to 20% of the total energy yield [1]-[3]. Furthermore, the increasing adoption of PV systems in grid-connected and off-grid applications has created a growing need for more efficient and reliable MPPT techniques. To address these challenges, researchers have explored various advanced MPPT algorithms, such as model predictive control, artificial neural networks, and fuzzy logic control [4]. However, these approaches often require complex computations, high-resolution sensors, and precise modelling of the PV system, which can increase the overall cost and complexity of the system.

The increasing adoption of PV systems in both grid-connected and off-grid applications has intensified the demand for more efficient, accurate, and reliable MPPT techniques. Recent studies have explored advanced algorithms to address the shortcomings of conventional methods. For instance, model predictive control (MPC) has been highlighted for its ability to anticipate system dynamics and optimize control actions [5], while artificial neural networks (ANNs) have demonstrated exceptional adaptability in learning nonlinear PV characteristics [6]. Similarly, fuzzy logic control has been employed for its robustness in handling uncertainties and variations in environmental conditions [4].

Despite their advantages, these advanced methods often come with increased involve high computational requirements and complexity, reliance on high-resolution sensors, and the need for precise modelling of PV systems, which can drive up costs and complicate implementation. Hybrid approaches, such as combining perturb and observe (P&O) with machine learning [7], have attempted to balance simplicity and performance. However, achieving a cost-effective solution with high accuracy and adaptability remains a challenge. Furthermore, real-world issues such as the need for fast response to irradiance changes, resilience under partial shading, and low dependency on precise sensor data highlight gaps in the current state of MPPT research [8], [9].

In this context, our study introduces a lightweight yet robust solution to two core challenges in conventional P&O: i) fixed step sizes that result in overshooting or slow convergence near the maximum power point (MPP) and ii) poor adaptability under rapid irradiance changes or partial shading. The proposed method enhances traditional P&O by introducing a gradient-based, normalized, and bounded step size—computed using the power-voltage slope. This dynamic mechanism accelerates convergence when far from the MPP and improves precision near the peak without increasing system complexity. While several advanced adaptive MPPT methods have been proposed—such as fuzzy logic controllers, artificial neural networks, and hybrid AI-based approaches—they often require complex tuning procedures, high-resolution sensor inputs, and substantial computational overhead [10]-[13]. These factors limit their practicality in low-cost or real-time embedded PV controllers.

In contrast, the proposed algorithm maintains the simplicity and low-resource profile of the conventional P&O, making it highly suitable for low-power microcontroller-based systems used in rural, remote, or off-grid PV applications. Its novelty lies not in complexity, but in the effective balance it strikes between tracking accuracy, responsiveness, and implementation simplicity. Moreover, it does not rely on heuristics, pre-trained models, or rule-based logic, making it more predictable and easier to standardize.

This article proposes a new MPPT technique that aims to improve the tracking accuracy and efficiency under various operating conditions. The proposed technique combines the benefits of existing MPPT algorithms with an advanced fast searching method to provide a more accurate and reliable method for optimizing energy yield. Therefore, the main contributions are:

i) Development of an adaptive P&O MPPT algorithm that adaptively changes the step-size to approach the MPP, significantly reducing power deviation and improving tracking accuracy.
ii) Demonstration of superior performance over both conventional P&O and hybrid P&O-GWO methods through simulation under uniform and partial shading conditions, validating faster convergence and enhanced reliability.

The rest of this article will provide a detailed description of the proposed method and the simulation setting in Section 2. Section 3 discussed the simulation results and how that impact of the research. Section 4 concluded the key findings and highlights the practical relevance of the proposed method for improving MPPT efficiency in real-world PV systems.

2. METHOD

2.1. Characteristics system

A solar PV system consists of one or more interconnected solar panels, arranged in series and parallel or combined, with power electronic devices acting as an interface to the load. A cell in a PV system is typically modelled as a single-diode equivalent circuit. The current-voltage characteristic of the cell equivalent circuit is described as (1) [14]-[16].

$$I_{PV} = I_{ph} - I_0 \left[\exp\left(\frac{V_{PV}+I_{PV}R_S}{nV_T}\right) - 1\right] - \frac{V_{PV}+I_{PV}R_S}{R_{sh}} \tag{1}$$

The power electronic device is employing MPPT algorithm to ensure the system extract maximum power in every working condition. The change in solar irradiation is the most contributing factor in PV power generation. Two irradiation conditions must be taken into account. The first is when PV modules receive uniform irradiation, known as the uniform irradiation condition (UIC). The second is when certain modules of the PV array are shaded by passing clouds, or other objects, this referred partial shading condition (PSC).

Figure 1 shows the illustration of PV under UIC conditions with varied solar irradiance range from 1000 W/m^2 to 700 W/m^2 [17]-[20].

2.2. The proposed method

The proposed MPPT technique that was proposed in this study focused an improved of the conventional P&O technique as outlined in previous research [21]-[23]. The main improvement of the proposed method lies in the dynamic adjustment of the perturbation step size based on the proximity to the MPP [24]. While the conventional P&O method maintains a constant step size throughout the search, the proposed method proposed a new adaptive size of steps by slowing down the steps as it approaches the MPP [25], [26]. This adaptive step size addresses a critical limitation of the conventional P&O method. When the step size is too large, the search may overshoot the MPP, reducing accuracy. Conversely, a smaller step size improves precision but significantly slows the search process. By dynamically adjusting the step size, the proposed method ensures efficient and accurate convergence to the MPP. Figure 1 depicts the proposed method's workflow and its adaptive step-size strategy, showcasing improved tracking precision and efficiency near the MPP.

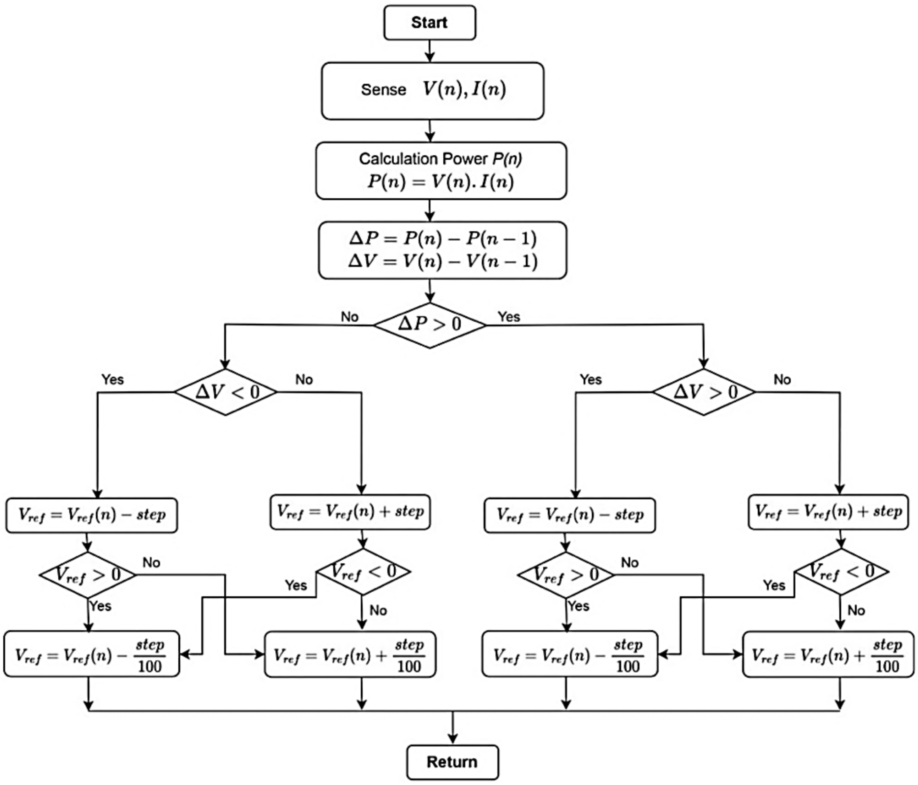


Figure 1. The proposed adaptive P&O

As shown in Figure 1, the proposed MPPT method is based on the conventional P&O approach but introduces an adaptive behaviour as it nears the MPP. When the power output is increasing, and the tracking point is far from the peak, the proposed method operates similarly to the standard P&O algorithm, using a consistent step size to expedite the search. However, as the tracking point approaches the MPP, the proposed method significantly slows down its movement. This deliberate reduction in step size ensures precise convergence to the MPP, preventing overshooting or deviation from the optimal point. This adaptive mechanism enhances both the accuracy and stability of the tracking process. This adaptive strategy optimizes energy extraction while minimizing the drawbacks of conventional P&O methods.

In a conventional P&O method, the step size ΔD for the duty cycle is constant. In the proposed method, the step size becomes a function of the power difference, enabling finer tuning as the algorithm nears the MPP. The perturbation step size is dynamically scaled based on the rate of change in power as (2).

$$\Delta D(k) = \alpha . \left|\frac{\Delta P}{\Delta V}\right| \tag{2}$$

Where ΔD is a perturbation in duty cycle, $D(k)$ is duty cycle at iteration at k, α is a gain factor, ΔP refers to the change in power output between two consecutive measurement points or iterations, and ΔV refers to the change in voltage over the same time interval. To ensure stability, it is capped using (3).

$$\Delta D(k) = \min(\Delta D(k), \Delta D_{max}) \quad (3)$$

Where ΔD_{max} is maximum allowable perturbation. This rule makes the perturbation become large when far from the MPP (high value of $\left|\frac{\Delta P}{\Delta V}\right|$) and small while near the MPP (low value of $\left|\frac{\Delta P}{\Delta V}\right|$) which prevent from oscilation.

The direction of the update follows the P&O principle, which is calculated using (4).

$$\begin{aligned} &if\ \Delta P > 0 \Rightarrow D(k+1) = D(k) + \Delta D(k) \\ &if\ \Delta P < 0 \Rightarrow D(k+1) = D(k) - \Delta D(k) \end{aligned} \quad (4)$$

This ensures the algorithm continues moving in the direction of increasing power but slows down adaptively as it converges to the MPP. The algorithm converges to the MPP more accurately than conventional P&O due to: i) Reduction in overshoot: smaller ΔD as MPP is approached, and ii) Faster stabilization: larger ΔD when far from MPP. This strategy leads to improved tracking accuracy, reduced steady-state oscillation, and shorter settling time. Algorithm 1 shows the simulation implementation of the proposed method.

Algorithm 1. Adaptive perturb and observe MPPT
Input:
  Initial duty cycle (D_0)
  Maximum step size (ΔD_{max})
  Adaptive gain factor (α)
Output: updated duty cycle D for MPPT control
Steps:
1. Initialization:
   Set initial voltage V_{prev}, current I_{prev}, and power $P_{prev} = V_{prev} \times I_{prev}$
   Set initial duty cycle $D \leftarrow D_0$
2. Repeat for each sampling interval
   Measure current voltage V, current I; compute current power: $P = V \times I$
   Calculate change in power: $\Delta P = P - P_{prev}$; calculate change in voltage: $\Delta V = V - V_{prev}$
3. Compute adaptive step size
   if $\Delta V \neq 0$, compute:
     $\Delta D(k) = \alpha . \left|\frac{\Delta P}{\Delta V}\right|$
   else,
     Set ΔD to a small constant
   limit ΔD to (ΔD_{max}
4. Update duty cycle D based on power change
   If $\Delta P > 0$ and $\Delta V > 0$:
     $D \leftarrow D + \Delta D$
   If $\Delta P > 0$ and $\Delta V < 0$:
     $D \leftarrow D - \Delta D$
   If $\Delta P < 0$ and $\Delta V > 0$:
     $D \leftarrow D - \Delta D$
   If $\Delta P < 0$ and $\Delta V < 0$:
     $D \leftarrow D + \Delta D$
5. Update previous values
   $P_{prev} \leftarrow P$
   $V_{prev} \leftarrow V$
6. Apply new D to the converter and repeat from step 2

2.3. Simulation setting

Figure 2 shows simulation system of the proposed adaptive P&O. The simulation was designed on two conditions, including UIC and partial shading. The performance of the proposed MPPT method was tested through simulations using MATLAB Simulink under both uniform irradiance and partial shading conditions.

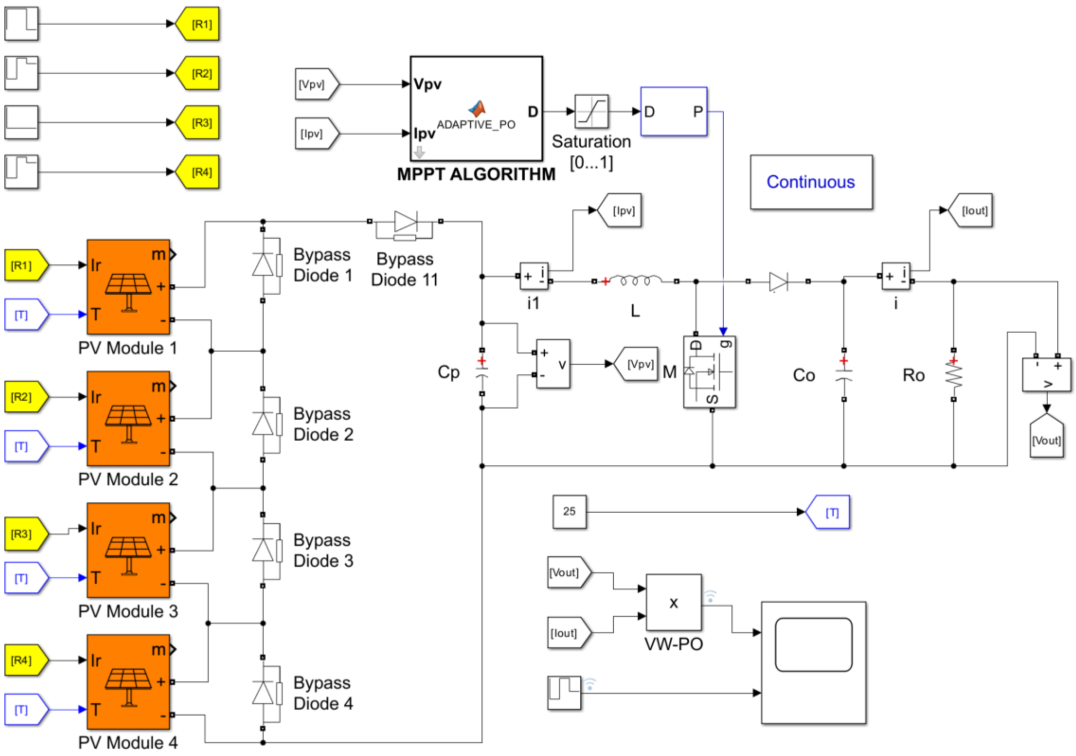


Figure 2. MPPT Simulink: (a) PV system and (b) overall MPPT simulation system

Table 1 presents the main specifications of the PV module and boost converter circuit used in the MPPT system testing. The solar panel used is a Tata Power Solar System TP250MBZ with a maximum power pmax of 249 W, an open circuit voltage (Voc) of 36.8 V, a short circuit current (Isc) of 8.83 A, a voltage at maximum power of 30 V, and a current at maximum power of 8.3 A. This information is displayed in Table 1 to provide an overview of the module's electrical characteristics, which form the basis for calculating the system's power performance.

Furthermore, Table 2 also describes the specifications of the boost converter used to regulate the PV module's output voltage. The main components consist of a 1.2 mH inductor, a 468 µF capacitor, and a 53 Ω resistive load. The selection of these component values is based on the need to maintain voltage stability and maximize power transfer during the MPPT process.

The MPPT system test scenario involved varying irradiation intensity at a constant temperature, as shown in Table 3. Four PV modules were arranged, each subjected to varying light intensity to simulate partial shading and uniform insolation conditions. PSC pattern 1 represents partial shading conditions, with irradiance of 1000 W/m² on modules 1 and 3, and 600 W/m² on modules 2 and 4. PSC pattern 2 depicts a transition to uniform conditions, with all modules receiving 1000 W/m². Uniform insolation represents conditions approaching uniformity but with irradiance variations decreasing to 700–1000 W/m².

Table 1. The specifications of the photovoltaic (PV)

No.	Item	Specifications
1.	Modules	Tata Power Solar System TP250MBZ
2.	Max power	249 W
3.	Open circuit voltage	36.8 V
4.	Short circuit current	8.83 A
5.	Voltage at max power	30 V
6.	Current at max power	8.3 A

Table 2. Boost converter specifications

No.	Description	Nominal values
1.	Inductor	L = 1.2 mH
2.	Capacitor	C = 468 µF
3.	Resistive load	R_{Load} = 53 Ohm

Table 3. Irradiation changes the scenario with temperature constant

No.	Module number	PSC pattern 1 (W/m^2)	PSC pattern 2 (kW/m^2)	Uniform insolation (kW/m^2)
1.	Module 1	1000	1000	700
2.	Module 2	600	1000	900
3.	Module 3	1000	1000	1000
4.	Module 4	600	1000	900

The effectiveness of an MPPT system is evaluated based on the deviation of the actual output power from the maximum reference power. The effectiveness calculation is performed using (5).

$$P_{eff} = \frac{P_{ref} - P_{mppt}}{P_{ref}} \times 100\% \tag{5}$$

Where P_{ref} is the solar panel's reference power obtained from the maximum power curve under the current irradiation conditions, while P_{mppt} is the output power obtained from the MPPT algorithm being tested. The P_{eff} value indicates the percentage of power loss relative to the reference power, so a smaller value indicates better MPPT tracking performance. Next, the average MPPT effectiveness over the test period is calculated by averaging the P_{eff} values for each data sample taken, using (6).

$$MPPTef = \frac{1}{N} \sum_{i=1}^{N} P_{eff_i} \tag{6}$$

Where N is the total number of measurement samples during the test period. This equation provides an average effectiveness value that represents the overall performance of the MPPT algorithm in maintaining the PV system output close to maximum power under various irradiation and load conditions.

3. RESULTS AND DISCUSSION

This section presents the simulation results and analysis of the proposed adaptive P&O. The performance is evaluated under various irradiance conditions, including uniform and partial shading scenarios. The objective is to assess the accuracy, responsiveness, and robustness of the method in tracking the MPP, and to compare its behavior against conventional P&O and hybrid P&O-GWO methods. Evaluation metrics such as convergence speed, steady-state stability, and power deviation are used to validate the effectiveness and practical applicability of the proposed approach.

Figure 3(a) illustrates the effectiveness of the proposed adaptive P&O method in accurately tracking the MPP under varying irradiance conditions. The red curve represents the tracked MPP using the proposed method, while the blue curve indicates the actual MPP derived from system parameters. The simulation is divided into three regions to evaluate performance. In region 1 (Figure 3(b)), the power deviation is minimal at approximately 5 W, increasing slightly to 9 W in region 2 (Figure 3(c)) and 15 W in region 3 (Figure 3(d)), where partial shading introduces more complex dynamics. These deviations remain well within acceptable limits, demonstrating robust detection and tracking capability. The algorithm effectively adapts to changing operating conditions, maintaining stable convergence and minimizing energy loss. Even under non-uniform irradiance, deviations remain below 20 W, confirming its reliability and adaptability. Overall, the proposed method consistently maintains close alignment with the actual MPP, outperforming conventional P&O by ensuring faster convergence and improved energy extraction in dynamic PV environments.

Figure 4(a) compares the performance of the conventional P&O method and the proposed MPPT approach. The dashed blue line represents the proposed method, while the brown line corresponds to conventional P&O. In region 1, the conventional P&O method exhibits a deviation of nearly 200 W between the tracked MPP and the actual maximum power, whereas the proposed method achieves a deviation of only ~5 W—demonstrating roughly a 40-fold improvement in accuracy. This discrepancy arises because conventional P&O with a large step size suffers from overshooting and undershooting, resulting in poor precision and energy loss. The proposed method mitigates this by adaptively reducing its step size near the MPP, ensuring precise convergence. In regions 2 and 3, both methods perform comparably, but the superior accuracy in region 1 highlights the robustness of the proposed approach.

Figure 4(b) further compares the proposed method with the hybrid P&O GWO technique. The hybrid method exhibits substantial deviation during the initial tracking stage, particularly in regions 1 and 3, before stabilizing after approximately one second. In contrast, the proposed method delivers accurate MPP detection from the outset, emphasizing its reliability in dynamic conditions. Overall, these results confirm that the proposed method consistently outperforms conventional and hybrid alternatives in maximizing PV energy extraction.

Figure 5 compares the proposed MPPT method with the hybrid P&OGWO and conventional P&O approaches. The proposed method consistently demonstrates accurate maximum power (MP) detection across all regions, maintaining stable and reliable tracking. In contrast, the P&OGWO method struggles during the initial phase in regions 1 and 3, exhibiting significant deviations before stabilizing after approximately one second. The conventional P&O method shows a different pattern, failing in region 1 due to its sensitivity to large step sizes but performing adequately in regions 2 and 3 where the power curve is less complex. Overall, the results highlight the superiority of the proposed method, which combines fast convergence with consistent accuracy, effectively overcoming the limitations of both P&OGWO and conventional P&O for robust energy extraction.

Table 4 compares the performance of three MPPT methods—conventional P&O, hybrid GWO & P&O, and the proposed method—across PSC pattern 1, PSC UIC, and PSC pattern 2. Efficiency represents the ratio of tracked maximum power to P_{ref}. under PSC pattern 1, P&O achieved only 74.45%, while GWO & P&O and the proposed method reached 99.38% and 99.70%, respectively. In uniform and Pattern 2 conditions, all methods exceeded 99.7%. The average efficiencies were 91.30% for P&O, 99.52% for GWO & P&O, and 99.71% for the proposed method. These results confirm the proposed method's superior and consistent performance, particularly under challenging partial shading conditions. The simulation results demonstrate that the proposed adaptive P&O algorithm outperforms both conventional P&O and hybrid P&O-GWO methods in accuracy and convergence speed. Its dynamic step-size mechanism minimizes overshoot near the MPP, reducing energy loss and ensuring smooth power regulation under varying irradiance. While P&O-GWO eventually achieves good accuracy, its delayed response limits early energy harvesting, and conventional P&O shows large deviations under partial shading. The proposed method balances simplicity and precision, making it suitable for real-time, low-cost embedded PV systems. In future work, integrating this adaptive method with global optimization logic may help it detect global MPPs in complex shading conditions. Moreover, experimental validation on hardware platforms could further establish its real-world applicability.

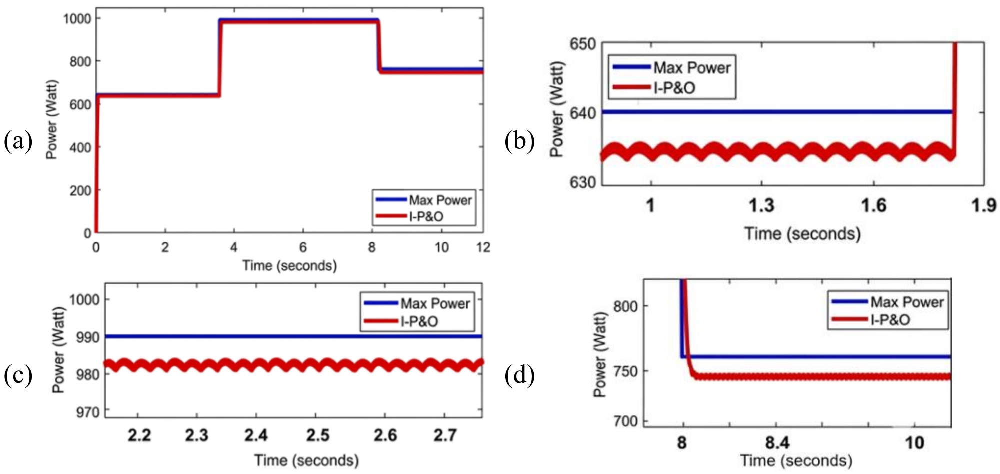


Figure 3. Tracking the result of maximum point using the proposed method: (a) overall response, (b) region 1, (c) region 2, and (d) region 3

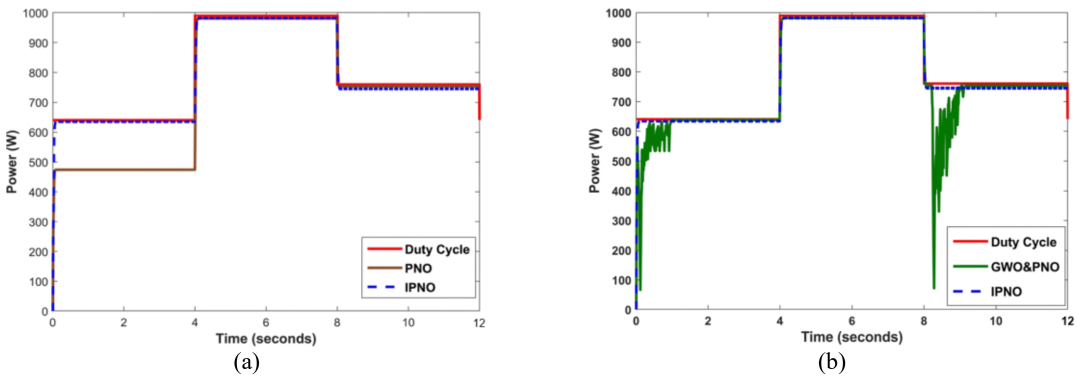


Figure 4. Comparison results between the proposed improved P&O with (a) P&O conventional and (b) GWO and P&O

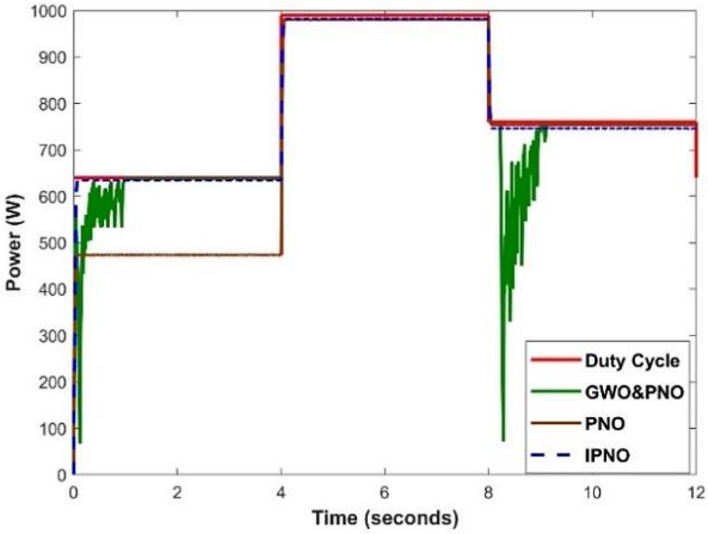


Figure 5. Comparison between the proposed method, P&O, and combination GWO and P&O

Table 4. Simulation results

Test case	P ref	Methods	MPP	Efficiency (%)
Psc pattern 1	642	P&O	478	74.45
		GWO and P&O	638 (2 s delay)	99.38
		Proposed	640	99.70
Psc UIC	989	P&O	986	99.70
		GWO and P&O	986 (2 s delay)	99.70
		Proposed	986	99.70
Psc pattern 2	762	P&O	760	99.74
		GWO and P&O	758 (2 s delay)	99.70
		Proposed	760	99.74

4. CONCLUSION

This study proposes an adaptive method to enhance the P&O algorithm for MPPT. The proposed method proposed a new mechanism for the step size used in the detection process to become more adaptive and dynamic. Unlike conventional P&O, where the step size remains constant throughout, the improved method dynamically reduces the step size as it approaches the MPP. This adaptive step adjustment allows for more precise tracking near the MPP, minimizing overshooting and improving detection accuracy. The key advantage of this approach is its ability to detect the MPP with higher precision, especially in scenarios where subtle variations in power output can lead to inaccuracies in conventional P&O. However, the method has a limitation: it struggles to identify the global maximum when the initial peak is lower than subsequent peaks, such as in cases of partial shading. This shortcoming could lead to the algorithm converging on a local maximum rather than the true global MPP. Despite this limitation, the proposed method offers better mechanisms in MPPT technology by addressing the inefficiencies of constant-step P&O. Future work could focus on the ability to differentiate between local and global peaks and improving on complex scenarios like partial shading.

FUNDING INFORMATION

Author thanks to LPPM Universitas Syiah Kuala as funder of our research under Penelitian Lektor scheme 2024 with contract number 304/UN11.2.1/PG.01.03/SPK/PTNBH/2024.

AUTHOR CONTRIBUTIONS STATEMENT

This journal uses the Contributor Roles Taxonomy (CRediT) to recognize individual author contributions, reduce authorship disputes, and facilitate collaboration.

Name of Author	C	M	So	Va	Fo	I	R	D	O	E	Vi	Su	P	Fu
Fathurrahman	✓	✓	✓	✓	✓	✓	✓	✓	✓		✓			
Rika Sri Utami		✓			✓			✓		✓	✓			
Akhyar			✓			✓	✓			✓				
Khairun Saddami	✓	✓	✓	✓	✓				✓	✓	✓	✓		

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

CONFLICT OF INTEREST STATEMENT

Authors state no conflict of interest.

DATA AVAILABILITY

The data that support the findings of this study are available from the corresponding author, [KS], upon reasonable request.

REFERENCES

[1] I. N. Syamsiana, R. N. A. Wijaya, A. D. W. Sumari, R. N. Amalia, and H. Sungkowo, "Maximization of battery charging efficiency in photovoltaic systems through PI controlled SEPIC converter with P&O MPPT," *Results in Engineering*, vol. 26, p. 105469, Jun. 2025, doi: 10.1016/j.rineng.2025.105469.

[2] N. A. Windarko, M. N. Habibi, B. Sumantri, E. Prasetyono, M. Z. Efendi, and Taufik, "A new MPPT algorithm for photovoltaic power generation under uniform and partial shading conditions," *Energies*, vol. 14, no. 2, p. 483, Jan. 2021, doi: 10.3390/en14020483.

[3] N. Winanti, A. Purwadi, B. Halimi, and N. Heryana, "Study and design of energy-saving solar lamp for small island in Indonesia: Matakus Island," in *2018 Conference on Power Engineering and Renewable Energy (ICPERE)*, Oct. 2018, pp. 1–5, doi: 10.1109/ICPERE.2018.8739672.

[4] S. R. Kiran and F. Alsaif, "A novel advanced hybrid fuzzy MPPT controllers for renewable energy systems," *Scientific Reports*, vol. 14, no. 1, p. 21104, Sep. 2024, doi: 10.1038/s41598-024-72060-4.

[5] N. Kacimi, A. Idir, S. Grouni, and M. S. Boucherit, "Improved MPPT control strategy for PV connected to grid using inccond-PSO-MPC approach," *CSEE Journal of Power and Energy Systems*, 2023, doi: 10.17775/CSEEJPES.2021.08810.

[6] R. B. Roy *et al.*, "A comparative performance analysis of ANN algorithms for MPPT energy harvesting in solar PV system," *IEEE Access*, vol. 9, pp. 102137–102152, 2021, doi: 10.1109/ACCESS.2021.3096864.

[7] S. Mohanty, B. Subudhi, and P. K. Ray, "A grey wolf-assisted perturb & observe MPPT algorithm for a PV system," *IEEE Transactions on Energy Conversion*, vol. 32, no. 1, pp. 340–347, Mar. 2017, doi: 10.1109/TEC.2016.2633722.

[8] A. I. M. Ali and H. R. A. Mohamed, "Improved P&O MPPT algorithm with efficient open-circuit voltage estimation for two-stage grid-integrated PV system under realistic solar radiation," *International Journal of Electrical Power & Energy Systems*, vol. 137, p. 107805, May 2022, doi: 10.1016/j.ijepes.2021.107805.

[9] A. I. M. Ali *et al.*, "An enhanced P&O MPPT algorithm with concise search area for grid-tied PV systems," *IEEE Access*, vol. 11, pp. 79408–79421, 2023, doi: 10.1109/ACCESS.2023.3298106.

[10] M. N. Ali, K. Mahmoud, M. Lehtonen, and M. M. F. Darwish, "Promising MPPT methods combining metaheuristic, fuzzy-logic and ANN techniques for grid-connected photovoltaic," *Sensors*, vol. 21, no. 4, p. 1244, Feb. 2021, doi: 10.3390/s21041244.

[11] M. Fathi and J. A. Parian, "Intelligent MPPT for photovoltaic panels using a novel fuzzy logic and artificial neural networks based on evolutionary algorithms," *Energy Reports*, vol. 7, pp. 1338–1348, Nov. 2021, doi: 10.1016/j.egyr.2021.02.051.

[12] M. I. S. Guerra, F. M. U. de Araújo, J. T. de Carvalho Neto, and R. G. Vieira, "Survey on adaptative neural fuzzy inference system (ANFIS) architecture applied to photovoltaic systems," *Energy Systems*, vol. 15, no. 2, pp. 505–541, May 2024, doi: 10.1007/s12667-022-00513-8.

[13] R. Koche and S. Lall, "Enhancing solar PV efficiency: a comprehensive review of ANFIS-based MPPT strategies," in *2024 IEEE 2nd International Conference on Innovations in High Speed Communication and Signal Processing (IHCSP)*, Dec. 2024, pp. 1–6, doi: 10.1109/IHCSP63227.2024.10959845.

[14] T. Le, H. Colin, F. Al Shakarchi, and T. T. Quoc, "Improved MATLAB/Simulink two-diode model of PV module and method of fast large-scale PV system simulation," in *2018 7th International Conference on Renewable Energy Research and Applications (ICRERA)*, Oct. 2018, pp. 982–985, doi: 10.1109/ICRERA.2018.8566792.

[15] K. Basaran, N. S. Cetin, and S. Borekci, "Energy management for on-grid and off-grid wind/PV and battery hybrid systems," *IET Renewable Power Generation*, vol. 11, no. 5, pp. 642–649, Apr. 2017, doi: 10.1049/iet-rpg.2016.0545.

[16] A. Chouder, S. Silvestre, B. Taghezouit, and E. Karatepe, "Monitoring, modelling and simulation of PV systems using LabVIEW," *Solar Energy*, vol. 91, pp. 337–349, May 2013, doi: 10.1016/j.solener.2012.09.016.

[17] M. N. Dehedkar and S. V. Murkute, "Optimization of PV system using distributed MPPT control," in *2018 International Conference on System Modeling & Advancement in Research Trends (SMART)*, Nov. 2018, pp. 216–220, doi: 10.1109/SYSMART.2018.8746931.

[18] A. Attou, A. Massoum, and M. Saidi, "Photovoltaic power control using MPPT and boost converter," *Balkan Journal of Electrical & Computer Engineering*, vol. 2, pp. 23–27, 2014. [Online]. Available: http://www.bajece.com/.

[19] B. N. Nguyen, V. T. Nguyen, M. Q. Duong, K. H. Le, H. H. Nguyen, and A. T. Doan, "Propose a MPPT algorithm based on thevenin equivalent circuit for improving photovoltaic system operation," *Frontiers in Energy Research*, vol. 8, Feb. 2020, doi: 10.3389/fenrg.2020.00014.

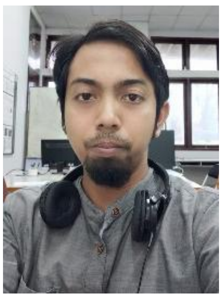
[20] A. A. Elbaset, H. Ali, M. Abd-El Sattar, and M. Khaled, “Implementation of a modified perturb and observe maximum power point tracking algorithm for photovoltaic system using an embedded microcontroller,” *IET Renewable Power Generation*, vol. 10, no. 4, pp. 551–560, Apr. 2016, doi: 10.1049/iet-rpg.2015.0309.
[21] H. H. H. Mousa, A.-R. Youssef, and E. E. M. Mohamed, “State of the art perturb and observe MPPT algorithms based wind energy conversion systems: A technology review,” *International Journal of Electrical Power & Energy Systems*, vol. 126, p. 106598, Mar. 2021, doi: 10.1016/j.ijepes.2020.106598.
[22] M. Büyük and M. İnci, “Improved drift-free P&O MPPT method to enhance energy harvesting capability for dynamic operating conditions of fuel cells,” *Energy*, vol. 267, p. 126543, Mar. 2023, doi: 10.1016/j.energy.2022.126543.
[23] A. Saberi, M. Niroomand, and B. M. Dehkordi, “An improved P&O based MPPT for PV systems with reduced steady-state oscillation,” *International Journal of Energy Research*, vol. 2023, pp. 1–15, Jul. 2023, doi: 10.1155/2023/4694583.
[24] M. Y. A. Khan, H. Liu, S. M. Hashemzadeh, and X. Yuan, “A novel high step-up DC–DC converter with improved P&O MPPT for photovoltaic applications,” *Electric Power Components and Systems*, vol. 49, no. 9–10, pp. 884–900, Jun. 2021, doi: 10.1080/15325008.2022.2049649.
[25] C. B. N. Fapi, H. Tchakounté, M. A. Hamida, P. Wira, and M. Kamta, “Enhanced P&O MPPT algorithm based on fuzzy logic for PV system: brief review and experimental implementation,” *International Journal of Engineering Science and Application*, vol. 7, no. 4, pp. 105–116, 2023.
[26] N. Ncir, N. El Akchioui, and A. El Fathi, “Enhancing photovoltaic system modeling and control under partial and complex shading conditions using a robust hybrid DE-FFNN MPPT strategy,” *Renewable Energy Focus*, vol. 47, p. 100504, Dec. 2023, doi: 10.1016/j.ref.2023.100504.

BIOGRAPHIES OF AUTHORS

Fathurrahman received the B.E. degree in power system engineering from the Department of Electrical Engineering, Syiah Kuala University, Indonesia, in 2010. In 2014, Fathurrahman obtained his master degree in energy system from School of Electrical Engineering and Telecommunication, University of New South Wales (UNSW), Australia. He joined Syiah Kuala University in March 2019. His research interest in area of energy systems engineering and renewable energy concentrating on solar, hydro, wind and waste energy system, energy efficiency, and electrical safety. He is pursuing Ph.D. degree at Electrical Engineering Department, King Fahd University of Petroleum and Minerals, Saudi Arabia. He can be contacted at email: fathurrahman@usk.ac.id.

Rika Sri Utami is a junior lecturer at the Department of Electrical and Computer Engineering, Faculty Engineering, Universitas Syiah Kuala. She completed her bachelor's degree in Chemistry Department at the Faculty of Mathematics and Natural Sciences, Universitas Syiah Kuala. She finished her master’s degree in Fuel Cell Institute at Universiti Kebangsaan Malaysia. Her current focus is on renewable energy. She can be contacted at email: rikasriutami@usk.ac.id.

Akhyar received a B.E. degree from the Department of Electrical Engineering, Syiah Kuala University, Indonesia, in 2010. In 2013, He obtained a master's degree program in information technology from the Department of Electrical Engineering and Information Technology, Gadjah Mada University, Indonesia. He joined Syiah Kuala University in March 2019. His research interests include information technology, computer vision, and IoT. He is a Ph.D. candidate at the Department of Eletrical, Electronic, and Systems Engineering, Faculty of Engineering and Built Environment, Universiti Kebangsaan Malaysia, Malaysia. He can be contacted at email: p126530@siswa.ukm.edu.my.



Khairun Saddami obtained bachelor’s degree in 2015 from Syiah Kuala University, Indonesia. He received his Ph.D. degree in electrical and computer engineering from Syiah Kuala University, Indonesia, in 2020, where he was awarded a scholarship from the Ministry of Research, Technology, and Higher Education, the Republic of Indonesia, under the Scheme of Pendidikan Magister Menuju Doktor Untuk Sarjana Unggul (PMDSU). He has been with Department of Electrical and Computer Engineering, Syiah Kuala University since 2020. He also acts as editor and reviewer in reputable journal such as Scientific Reports, Pattern Recognition, IEEE Access, and ACM Computer Survey. He is a member of IEEE and International Association for Pattern Recognition (IAPR). His research interests are in artificial intelligence, document image analysis, deep learning, biometric and biomedical image processing, and pattern recognition. He can be contacted at email: khairun.saddami@usk.ac.id.