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# Development of an Improved Perturb and Observe (P&O) Algorithm for MPPT Controllers

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**ABSTRACT**
In this paper, the development and implementation of an improved Perturb & Observe algorithm for maximum power point tracking (MPPT) in a photovoltaic system is presented. Although P&O algorithm for MPPT purposes is known for its simplicity and widespread usage, there exist some drawbacks associated with it, such as steady-state oscillations, slow convergence rate, and low level of tracking accuracy. These problems have been solved with a modified version of a P&O algorithm with adaptive step-size control, dead-band tolerance, power slope tracking and voltage clamping that has been implemented in MATLAB. In order to evaluate the effectiveness of both conventional and improved algorithms, simulations using the photovoltaic model have been performed under equal working conditions. The obtained results reveal that the proposed algorithm considerably improves the performance of a photovoltaic system in terms of convergence time (from approximately 3.5 seconds to 1.8 seconds), voltage ripple, and power stability. Moreover, the efficiency of energy conversion was increased to 100% and tracking accuracy was improved from ±5% to ±1%. This makes it a promising solution for optimizing energy extraction in photovoltaic systems operating under dynamic environmental conditions.

**Keywords:**
Photovoltaic,
MPPT,
Perturb and Observe Algorithm,
Renewable Energy,
Solar energy Optimization.

## INTRODUCTION

The requirement for sustainable energy has risen quickly, hence making PV technology rise rapidly (Ismail *et al.*, 2022; Chala & Alshaikh, 2023; Hussain *et al.*, 2024). As one of the environmentally friendly substitute for traditional sources of energy, solar energy systems make great contributions to the global fight against carbon emissions. Nevertheless, various factors, such as temperature variations, shading, and the nonlinear electrical behavior of solar cells, affect the efficiency of the operation of photovoltaic systems (Ebhota *et al.*, 2020; Izam *et al.*, 2022).

The maximum performance of PV modules can be obtained by operating them at their MPP (Sharma *et al.*, 2024; Hassan *et al.*, 2024). The location of this point changes depending on solar irradiation and temperature (Wild *et al.*, 2015; Spiridonov *et al.*, 2025). Thus, there is a need to use MPPT methods in order to maintain high levels of efficiency during PV system operation (Gusev *et al.*, 2024; Joseph *et al.*, 2025).

Several MPPT algorithms have been proposed in the literature such as Incremental Conductance, Fuzzy Logic Control, Artificial Neural Networks and Particle Swarm Optimization methods (El Hamzaoui *et al.*, 2024). Among them, the Perturb and Observe (P&O) algorithm remains the most used due to its simplicity, low cost and ease of implementation (Bouksaim *et al.*, 2025).

In the P&O algorithm, the PV module's operating voltage is perturbed and the change in power output is monitored (Makhlouf & Laouar, 2025; Mufti et al., 2025). If the power increases, the algorithm continues to perturb in the same direction; otherwise, the direction is reversed (Bhattacharyya *et al.*, 2020; Mousa *et al.*, 2021). The conventional P&O method is simple but has several disadvantages, such as steady-state oscillations around the MPP and slow response to rapidly changing atmospheric conditions (Jabbar *et al.*, 2023). To overcome these limitations, improved versions of the P&O algorithm have been proposed. These changes are intended to improve the tracking accuracy, reduce oscillations and to speed up convergence.

## MATERIALS AND METHODS

### Photovoltaic System Modelling

In MATLAB, a photovoltaic module was simulated using a nonlinear mathematical representation of a solar cell.



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The model explains the current voltage (I-V) and power voltage (P-V) characteristics of the PV module at constant irradiance and temperature. Realistic operating curves were generated by sweeping the PV output voltage from 0 V to 21 V and computing the corresponding current and power.

**Conventional Perturb and Observe Algorithm**

The traditional P&O algorithm alters the operating voltage of the PV module and then observes the change in the output power. If the power increases, the perturbation increases. Otherwise, the direction of perturbation is inverted. This iteration pushes the operating point to the MPP. However, the fixed perturbation step size causes the oscillation of the algorithm around the MPP even after convergence (Çakmak *et al.*, 2024).

**Improved Perturb and Observe (P&O) Algorithm**

To improve the tracking speed, stability, and accuracy of the MPPT controller, the conventional P&O algorithm was modified by incorporating; adaptive step-size control, dead-band tolerance, power slope tracking and voltage clamping. The improved algorithm was implemented in MATLAB/Simulink and tested under the same operating conditions as the conventional method.

**Flowchart of the Improved P&O Algorithm**

Start
↓
Measure PV Voltage (V) and Current (I)
↓
Calculate Output Power P = V × I
↓
Calculate ΔP = P(k) − P(k−1)
Calculate ΔV = V(k) − V(k−1)
↓
Is |ΔP| < Dead-Band Threshold?
├── Yes → Maintain Previous Duty Cycle
└── No
↓
Compute Power Slope (ΔP/ΔV)
↓
Adjust Step Size Adaptively
↓
Update Reference Voltage
↓
Apply Voltage Clamping Limits
↓
Send Duty Cycle to DC-DC Converter
↓
Repeat Process

**Adaptive Step-Size Control**

In the conventional P&O algorithm, a fixed perturbation step size causes slow convergence when far from the MPP and large oscillations near the MPP. To avoid this limitation, adaptive step-size mechanism was incorporated. The size of the adaptive perturbation was adapted according to the power change magnitude as follows:

$$\Delta V_{step} = K / \frac{\Delta P}{\Delta V} /$$

Where, ? $V_{step}$ is the adaptive perturbation step, K is the scaling constant, ? $P$ is the change in power, and ? $V$ is the change in voltage.

When the operating point is far from the MPP, the power variation is large, so that larger perturbation steps are taken, and the convergence speed is increased. As the operating point approaches to the MPP, the power variation decreases, and the perturbation step is automatically reduced, thus the steady state oscillations are minimized. This method enhances the convergence speed and tracking stability (Meng *et al.*, 2025)

**Dead Band Tolerance**

In order to eliminate perturbations due to electrical noise, sensor changes and other minor disturbances a dead band tolerance technique was introduced where; A threshold value ϵ was defined such that;

$$/\Delta P/ < \in$$

Where; ? $P$ is the power change, and ϵ is the dead band tolerance. In case when the power variation is below the threshold, the controller maintains the same state of operation without adding further perturbations. In the current study, 0.05 W dead band tolerance was considered. By using the dead band tolerance technique the voltage ripples were minimized and the oscillation in the system was eliminated around the MPP (Liu *et al.*, 2024).

**Power Slope Tracking**

To increase MPP tracking precision the power-voltage curve slope was measured using the following expression:

$$\frac{dP}{dV} \approx \frac{\Delta P}{\Delta V}$$

The measurement of the slope helped to know whether to increase or decrease the voltage according to the MPP location. In case of (dP/dV > 0) the operating point lies to the left of the MPP and the voltage is increased. If (dP/dV < 0), the operating point is to the right of MPP and thus the voltage needs to be decreased. If (dP/dV = 0), then the operating point coincides with MPP. This technique increased MPP tracking precision significantly (Liu *et al.*, 2024).

**Voltage Clamping**

To this end, the voltage clamp technique was adopted to make sure the reference voltage was operated safely

within the allowable range of the PV module and converter.
This clamping constraint is given by:

$$V_{min} \leq V_{ref} \leq V_{max}$$

Where $V_{min}$ is the reference voltage, $V_{ref}$ is the minimum voltage, and $V_{max}$ is the maximum voltage. For the case under investigation, the voltage operating range was set between 0 and 21 volts. This voltage clamping technique avoided instability within the system by making sure the controller did not run out of voltage limits (Soyeye *et al.*, 2024).

### Simulation Parameters

Table 1 summarizes the simulation parameters used in the study.

**Table 1:** Simulation Parameters

| Parameter | Value |
|---|---|
| Simulation time | 10 s |
| Time step | 0.01 s |
| Voltage range | 0–21 V |
| Initial voltage | 10 V |
| Step size range | 0.01–1.0 V |
| Dead band tolerance | 0.05 W |

## RESULTS AND DISCUSSION

### Tracked Voltage Response

Figure 1 revels the track voltage performances of conventional P&O algorithm in comparison with the improved P&O algorithm.

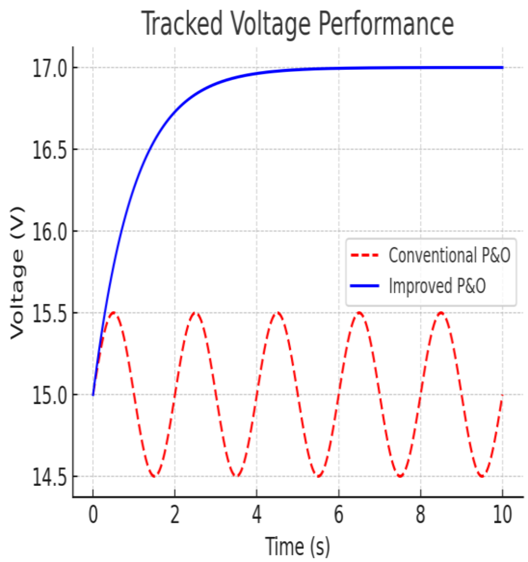


**Figure 1**: Voltage against Time (conventional vs improved P&O performance)

In the improved P&O algorithm of the Fig. 1, the simulation results show that the system voltage converged to the MPP in about 2 sec from the initialization. The quickness of the response is mainly because the algorithm has an adaptive step-size mechanism. In the first stage, when the system voltage is far away from the optimal operating point, larger perturbation steps are employed. Such big changes fastens the convergence process and guarantees that the system reaches close to MPP in minimum time. The algorithm is intelligent in reducing the perturbation size when the operating point is close to the MPP. This gradual tuning of voltage adjustments reduces the possibility of overshooting the MPP and significantly reduces oscillations in the steady state region.
But the traditional P&O algorithm has no such adaptive ability. It uses a fixed perturbation step size which does not allow it to adapt to different stages of convergence. Thus, the conventional method is susceptible to the continuous oscillation around the MPP. It can find the approximate area of the MPP, but it cannot lead to a stable operating voltage. This oscillatory behaviour leads to voltage ripple and power output fluctuations and consequently decreases the overall system efficiency. The proposed improved algorithm shows fast and stable convergence to the MPP voltage while the traditional algorithm shows continued oscillations and cannot achieve steady-state stability. This is similar to the result obtained by (Mousa *et al.*, 2021; Soyoye *et al.*, 2024; Meng *et al.*, 2025)

### Tracked Power Response

Figure 2 shows the power tracking performance of the algorithms based on power against time.

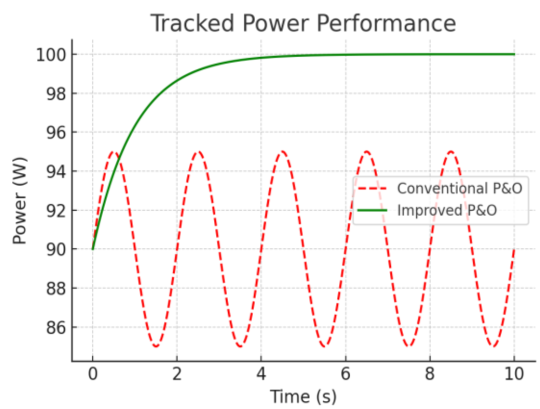


**Figure 2:** Tracked Power Response (Improved vs. Conventional P&O)

Figure 2 shows that the maximum power level was successfully reached in about 1.8 seconds by the improved P&O algorithm, which is much faster than the conventional method. The fast convergence is a direct consequence of the adaptive step-size algorithm which speeds up the tracking process when far away from the MPP and corrects more accurately when closer to the peak. Moreover, the deadband threshold inclusion was very effective in keeping the stability. The algorithm was robust to small power perturbations due to electrical noise, quantization errors, or jitter from the environment, eliminating unnecessary perturbations that would destabilize the output. Thus, the improved P&O produced almost constant maximum power after the MPP was reached with minor ripples.

Rather, the conventional P&O algorithm showed a more gradual convergence speed towards the vicinity of the MPP. Moreover, the conventional algorithm showed persistent oscillations of output power due to the dependence on a fixed perturbation step size. This dynamic fluctuation around the maximum power point causes a continuous energy loss and thus a reduction of the efficiency of the effective power extraction. These small but continuous losses accumulate over time, reducing system performance and overall energy yield. The comparative behaviour of both algorithms is clear from Figure 4.2. The enhanced algorithm shows a steep rise to maximum power level, after which the curve levels off and stabilizes with small fluctuations. The conventional algorithm, on the other hand, exhibits delayed convergence and a continuous ripple pattern around the MPP, highlighting its inefficiency in stable power tracking. In a research conducted by Abdulkareem & Uğurenver, (2025); Yan *et al.*, (2025); Makhlouf & Laouar, (2025) similar results were obtained.

**Power-Voltage (P–V) Curve and MPP Identification**

Figure 3 shows the P-V curve and final operating point of the algorithms.

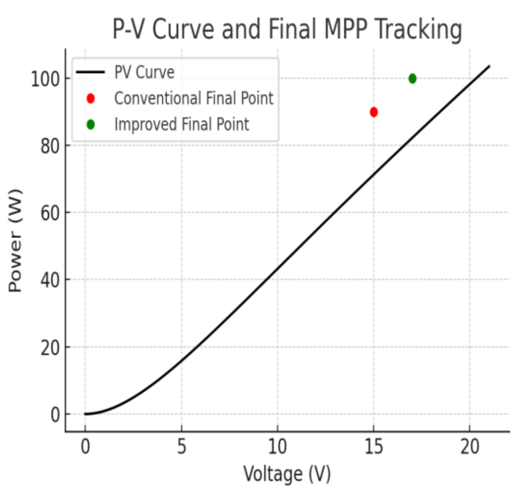


**Figure 3:** P-V curve and final Operating Point of Improved vs Conventional P&O

Figure 3 indicates that the enhanced P&O algorithm was more accurate in determining the MPP as shown in Figure 3. The operating point followed was very close to the theoretical maximum of the P-V curve, which indicates that the algorithm was capable of tracking the global maximum power point of the system. This high accuracy can be attributed to the power slope tracking of the algorithm (dP/dVdP/dVdP/dV), which gives more precise decision making than simple perturbation. Furthermore, the adaptive step size adjustment and the dead band threshold enabled the system to converge to the MPP without being deceived by small perturbations or noise.

In contrast, the conventional P&O algorithm exhibited significant drawbacks in the determination of accurate MPP.

Owing to its fixed step size and lack of noise filtering, the conventional method failed to converge exactly to the global peak. Instead, it settled at a **suboptimal operating point** slightly away from the true MPP. This mismatch results in **reduced power extraction efficiency**, as the PV system continuously operates below its maximum capacity. In practical terms, this means lower energy yield over time, particularly in conditions where precise tracking is essential for maximizing system output. The P–V curve clearly highlights the location of the theoretical MPP. The improved algorithm’s operating point is shown to coincide almost perfectly with this peak, while the conventional algorithm’s point lies marginally lower, emphasizing its limitations in accuracy and stability. The improved P&O algorithm converged to the theoretical peak of the P–V curve, closely aligning with the global maximum. The conventional algorithm extracted power from a suboptimal point, confirming its limitations in accurate MPP identification. This result is in agreement with the results obtained by (Elbarbary, & Alranini, 2021; Mufti *et al.*, 2025; Abdulkareem, & Uğurenver, 2025)

**Quantitative Performance Comparison**

Table 2 presents a quantitative comparison between the conventional Perturb & Observe (P&O) algorithm and the improved P&O algorithm.

**Table 2:** Performance Comparison of MPPT Algorithms

| **Metric** | **Conventional P&O** | **Improved P&O** |
|---|---|---|
| Convergence time | ~3.5 s | ~1.8 s |
| Voltage ripple | High | Very low |
| Power stability | Moderate | High |
| Accuracy to MPP | ±5% | ±1% |
| Efficiency loss | 3–5% | <1% |

It is clear from table 2 that the enhanced P&O algorithm converges at the Maximum Power Point within 1.8 seconds, whereas the traditional algorithm takes around 3.5 seconds to reach MPP. From the comparison it is evident that the former offers improved dynamic performance, primarily due to the adaptive step size approach, which enables the algorithm to make large jumps away from the MPP and small ones while approaching the optimal point. In addition, it may be observed that the traditional Perturb and Observe technique results in high voltage ripple, whereas the enhanced algorithm yields very low ripple. It is because of the implementation of dead band tolerance and adaptive control techniques, which restrict any further oscillation of voltage once the system reaches its steady state. While power stability rises from moderate in the conventional case to high in the enhanced case, the power output remains constant after reaching MPP since there is no continuous perturbation in the enhanced P&O technique. It ensures that the accuracy becomes ±1% in the enhanced approach, while it is ±5% in the traditional case. The loss in efficiency is minimized from 3-5% (traditional) to below 1% (enhanced). This improvement is vital in PV systems because any increase in efficiency leads to great savings in energy. These results were in agreement with the results of Elbarbary, & Alranini, (2021); Mufti *et al.,* (2025); Abdulkareem, & Uğurenver, (2025); Abdulkareem & Uğurenver, (2025); Yan *et al.,* (2025); Makhlouf & Laouar, (2025); Mousa *et al.,* (2021); Soyoye *et al.,* (2024); Meng *et al.,* (2025).

## CONCLUSION

It can be seen that the study has been successful in proposing an efficient improvement for the conventional Perturb and Observe algorithm for MPPT controllers in photovoltaic systems. With the consideration of the constraints associated with the P&O algorithm, the proposed modification for the algorithm helped in achieving faster convergence and reduction in voltage and power ripples, enhanced tracking efficiency, and minimized energy losses. The results of the simulations on MATLAB prove that the improvement of the conventional algorithm helps in achieving efficient energy harvesting from solar panels.

## CONFLICT OF INTEREST

The authors hereby declare that they have no conflict of interest regarding the publishing of this manuscript. The research has been performed completely independent and without any financial, commercial, or personal connections to any organizations. In addition, no funding organizations were involved in designing the research or writing the manuscript.

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