UDC 621.3 https://doi.org/10.20998/2074-272X.2025.6.08

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# New adaptive modified perturb and observe algorithm for maximum power point tracking in photovoltaic systems with interleaved boost converter

***Introduction.*** *In recent years, maximum power point tracking (MPPT) has become a critical component in photovoltaic (PV) systems to ensure maximum energy harvesting under varying irradiance and temperature conditions. Among the most common algorithms, perturb and observe (P&O) and incremental conductance (IC) are widely adopted due to their simplicity and effectiveness.* ***Problem.*** *Conventional P&O suffers from steady-state oscillations and slow dynamic response, while IC requires higher computational complexity and loses accuracy under rapidly changing conditions. These drawbacks limit overall tracking efficiency and system reliability. The* ***goal*** *of this work is the development and evaluation of a novel adaptive modified perturb and observe (AM-P&O) algorithm for a PV system with an interleaved boost converter. The proposed method dynamically adjusts the perturbation step size to achieve faster convergence and lessen steady-state oscillations to enhance tracking efficiency. Its performance is assessed through simulation with varying irradiance. It is then compared to traditional methods (P&O and IC) using quantitative metrics such as convergence time, oscillation magnitude, tracking efficiency, and computational cost.* ***Methodology.*** *The AM-P&O algorithm introduces an adaptive step size adjustment strategy, in which the perturbation magnitude is dynamically tuned according to the slope of the PV power-voltage curve. A detailed PV system and converter model was developed in MATLAB/Simulink, and simulations were performed under varying irradiance conditions. Performance metrics include tracking efficiency, convergence time, steady-state oscillation amplitude, and computational complexity.* ***Results.*** *The proposed AM-P&O achieves a better tracking, reduces convergence time by approximately 35 %, and decreases steady-state oscillations by nearly 90 % compared to conventional P&O. Under fast irradiance variations, the AM-P&O also demonstrates superior dynamic performance with lower computational burden compared to IC.* ***Scientific novelty*** *of this work lies in the adaptive perturbation mechanism, which balances fast convergence and reduced oscillations without increasing algorithmic complexity.* ***Practical value.*** *The AM-P&O provides a practical MPPT solution for PV systems, ensuring higher energy yield and improved stability in real-world applications, thereby supporting more efficient renewable energy integration into power networks.* References 32, tables 8, figures 8.

*Key words:* **photovoltaic system, maximum power point tracking, adaptive step size, modified perturb and observe algorithm, interleaved DC- DC converter, tracking efficiency.**

***Вступ***. *В останні роки відстеження точки максимальної потужності (MPPT) стало критично важливим компонентом у фотоелектричних (PV) системах для забезпечення максимального збору енергії в умовах змінних освітленості і температури. Серед найбільш поширених алгоритмів, що широко застосовуються завдяки своїй простоті та ефективності, є алгоритми збурення і спостереження (P&O) і збільшення провідності (IC).* ***Проблема***. *Звичайний P&O схильний до коливань і повільного динамічного відгуку, в той час як IC вимагає більш високої обчислювальної складності і втрачає точність при швидко мінливих умовах. Ці недоліки обмежують загальну ефективність відстеження та надійність системи.* ***Метою*** *даної роботи є розробка та оцінка нового адаптивного модифікованого алгоритму збурення і спостереження (AM-P&O) для PV системи з підвищуючим перетворювачем з чергуванням. Запропонований метод динамічно регулює розмір кроку збурення для досягнення більш швидкої збіжності і зменшення усталених коливань для підвищення ефективності відстеження. Його продуктивність оцінюється шляхом моделювання зі змінною освітленістю. Також він порівнюється з традиційними методами (P&O та IC) з використанням кількісних метрик, таких як час збіжності, амплітуда коливань, ефективність відстеження та обчислювальні витрати.* ***Методологія***. *Алгоритм AM-P&O пропонує стратегію адаптивного регулювання розміру кроку, в якій амплітуда збурення динамічно налаштовується відповідно до нахилу кривої потужності-напруги PV системи. Детальна модель PV системи та перетворювача розроблена в MATLAB/Simulink, а моделювання виконано в умовах змінної освітленості. Метрики продуктивності включають ефективність відстеження, час збіжності, амплітуду коливань і обчислювальну складність.* ***Результати***. *Запропонований AM-P&O досягає кращого відстеження, скорочує час збіжності приблизно на 35 % і зменшує усталені коливання майже на 90 % у порівнянні з традиційним P&O. При швидких змінах освітленості AM-P&O також демонструє високі динамічні характеристики з меншим обчислювальним навантаженням у порівнянні з IC.* ***Наукова новизна*** *роботи полягає у механізмі адаптивного збурення, який забезпечує баланс між швидкою збіжністю та зниженням коливань без збільшення складності алгоритму.* ***Практична значимість***. *AM-P&O пропонує практичне рішення MPPT для PV систем, забезпечуючи більше вироблення енергії та покращену стабільність у реальних умовах експлуатації, сприяючи ефективнішій інтеграції відновлюваних джерел енергії в енергомережу.* Бібл. 32, табл. 8, рис. 8.

*Ключові слова:* **фотоелектрична система, відстеження точки максимальної потужності, адаптивний розмір кроку, модифікований алгоритм збурення та спостереження, DC-DC перетворювач з чергуванням, ефективність відстеження.**

**Introduction.** Photovoltaic (PV) technology has seen rapid deployment worldwide as a cost effective, modular source of low carbon electricity. However, their output is nonlinear and strongly sensitive to environmental factors (irradiance, temperature, etc.) and operating conditions (partial shading, etc.) so the maximum power point tracking (MPPT) is vital but requires a robust, fast and low cost MPPT solution to improve MPPT energy yield [1–4].

Classical MPPT techniques such as perturb & observe (P&O) and incremental conductance (IC) remain widely used because of their simplicity and low implementation cost. Nonetheless they exhibit limitations, for example P&O tends to oscillate around the maximum power point (MPP) in steady state and can be misled by varying environmental conditions, while IC depends strongly on step size selection. These limitations introduced new concepts as variable/adaptive step-size schemes, hybrid methods, and occasional global search strategies to handle PV curves under partial shading [5–10].

Partial shading and module mismatch can cause the PV characteristics to have multiple local maxima which mislead the conventional MPPT techniques. To address this and the conventional techniques limitations, researchers proposed two broad directions. The first was to make them more adaptive (variable step-size, prediction/estimation, constrained search windows) so they remain lightweight yet dynamic, while the second was to incorporate occasional or hybrid global optimizers (particle swarm optimization

(PSO), grey wolf optimization (GWO), teaching learning based optimization etc.) that combine fast local search with less-frequent global exploration. Hybrid and metaheuristic approaches improve the global MPP (GMPP) at the cost of higher computational resources and complexity [3, 7].

Despite these efforts, a clear gap remains between simple low-cost controllers and advanced computationally intensive solutions. Many adaptive MPPT techniques either increase algorithmic complexity (difficult for low-cost microcontrollers) or still suffer from oscillations and delayed convergence under rapid irradiance fluctuations [6, 8, 11].

**Discussion in light of recent literature (2020–2025).** MPPT algorithms are evaluated primarily by their tracking efficiency and convergence time [12, 13]. Contemporary literature (2020–2025) shows that advanced AI-based methods typically achieve tracking efficiencies ~99 %, with very fast convergence, outperforming conventional methods [12, 13]. However, classical methods (like P&O and IC) remain popular for their simplicity and low implementation cost [12, 14]. In practice, the choice of MPPT involves trade-offs among efficiency, speed, complexity, and robustness to changing conditions (irradiance, shading, temperature) [12, 14].

P&O and IC are widely used «baseline» MPPT methods due to their simplicity and minimal sensor requirements [13, 14]. P&O works by perturbing the PV operating point and observing power changes. It is easy to implement but inherently oscillates around the MPP [13]. IC compares incremental and instantaneous conductance to decide the direction of tracking; it achieves smoother convergence and lower steady-state ripple than P&O which makes it a better choice [13, 15].

Empirical studies highlight these differences. For example, under varying irradiance (250–1000 W/m$^2$), authors [15] found that IC reached ~98.7 % tracking efficiency with a 0.15 s convergence, versus ~95.2 % for P&O. IC also yielded much smaller power ripple (~1.2 kW vs. 3.8 kW) [15]. In general, P&O tends to overshoot and oscillate around the MPP, resulting in longer settling times, while IC responds more smoothly [13, 15]. Under uniform insolation both work reasonably, but under partial shading their limitations become severe: they often lock onto a local maximum rather than the GMPP, causing large energy losses (up to ~70 %) [10, 13].

To mitigate oscillations and improve speed, many adaptive or variable-step versions of P&O and IC have been proposed. These algorithms dynamically adjust the perturbation step based on PV conditions. For example, authors [5] introduced a variable-step P&O that uses multiple step sizes; simulations showed it reduced power ripple by ~80 % and cut response time by ~30 % compared to fixed-step P&O. Similarly, authors [3, 16] developed a 4-segment variable-step IC by dividing the $I$–$V$ curve into regions with optimized steps, it eliminated steady-state oscillation and greatly accelerated tracking under rapidly changing irradiance.

These adaptive schemes retain the basic simplicity of classical methods but add computational overhead for step-size logic. In practice, they offer faster convergence and lower ripple than their fixed-step counterparts while maintaining comparable steady-state efficiency. For instance, the improved IC was shown to achieve no oscillation and improved energy extraction under dynamic irradiance [3, 17].

AI-based (artificial neural network (ANN), fuzzy logic) and metaheuristic (PSO, GWO, whale optimization algorithm (WOA)) approaches use global-search or learning to overcome classical limits. These methods typically achieve very high tracking efficiency (often ≥97 %) and can handle multiple maxima, but they incur higher complexity and require more computation or training. Recent reviews report that AI and metaheuristic MPPTs routinely reach ~99 % of theoretical power [12, 18].

For example, a neural-network MPPT was shown to reach ~99.7 % efficiency on clear days (99.3 % on overcast), with much lower steady-state error and faster transient response than P&O or IC [18]. Fuzzy-logic controllers also perform strongly; a recent hybrid fuzzy-IC MPPT achieved ~97.7 % average efficiency and a convergence time of only 53.5 ms, outperforming conventional and other hybrid techniques [19]. Metaheuristics further push these metrics: WOA/GWO achieved ~98.9 % efficiency in simulation and measurement [20], and a chimp optimization algorithm reached ~99.63 % efficiency under shading [14].

However, these gains come at cost. AI and metaheuristic methods are computationally intensive: ANNs require off-line training and embedded hardware, fuzzy controllers need rule-tuning, and swarm algorithms iterate many function evaluations. Authors [12] note that classical methods have low computational cost while AI methods «demand more complex hardware/software». In terms of dynamic performance, metaheuristics may converge slower (~0.65 s for WOA in one study [21], versus <<0.1 s for some fast techniques) but they excel at finding the global optimum under variable conditions.

Hybrid methods combine the strengths of global optimization and local tracking. A common pattern is using a metaheuristic or AI for coarse tracking and a fast local method for fine adjustment. These techniques aim to achieve near-optimal efficiency with accelerated convergence. For instance, authors [19] proposed a P&O+PSO hybrid: it attained ~2 % higher efficiency than pure P&O (and a 0.2 ms faster convergence) under shading conditions. In [18] authors achieved by fuzzy-IC hybrid 97.7 % efficiency with only 53 ms settling time. Similarly, a modified hybrid predictive control and adaptive P&O (MPC+P&O) controller improved P&O's response by ~35 % and reduced overshoot by 28 % [13].

GWO/PSO hybrids exemplify this trade-off: authors' GWO–PSO method used GWO for exploration and PSO for exploitation. It required only two tuning parameters and converged quickly to the GMPP independently of initial conditions [15], outperforming standalone PSO or GWO. In general, global-local hybrids can achieve tracking efficiencies ≳98 % with fast convergence times, at the expense of doubled algorithmic complexity (and tuning of both components).

The recent literature (2020–2025) shows a clear hierarchy classical MPPTs are simple and low-cost but oscillatory and vulnerable to shading; adaptive classical methods improve dynamic behavior with modest complexity; intelligent/metaheuristic algorithms achieve very high efficiency and robust shading performance but are computationally demanding; and hybrid strategies combine global search with fast local refinement to optimize both convergence and accuracy. The choice depends on application priorities: if simplicity and low cost dominate, classical or adaptive methods suffice; if maximal energy yield under complex conditions is needed, modern AI or hybrid schemes are preferable [12, 15].

**Problem statement.** Although many MPPT approaches have been proposed, practical PV systems impose the following challenges that are not fully solved by conventional P&O or IC:

- Rapid irradiance changes shift the MPP quickly fixed-step algorithms either fail to converge fast enough or produce large steady-state oscillations [5, 11].
- Under partial shading multiple local maxima appear simple hill-climbing techniques can be trapped in local MPPs. Global or hybrid searches can find the GMPP but add complexity and runtime overhead [3, 7].
- There is no universal optimally methods. Methods that maximize speed often increase oscillation or computational effort [2, 9].

The **goal** of the work is the development and evaluation of a novel adaptive modified perturb and observe (AM-P&O) algorithm for a PV system with an interleaved boost converter (IBC).

The proposed method dynamically adjusts the perturbation step size to achieve faster convergence and lessen steady-state oscillations to enhance tracking efficiency. Its performance is assessed through simulation with varying irradiance. It is then compared to traditional methods (P&O and IC) using quantitative metrics such as convergence time, oscillation magnitude, tracking efficiency, and computational cost.

**Materials and methods.** The AM-P&O algorithm was implemented in MATLAB/Simulink. A standard PV module model was used under dynamic irradiance conditions to evaluate the algorithm's response to rapid changes in solar input. The performance of AM-P&O was compared to conventional P&O and IC using tracking efficiency, convergence time, and steady-state oscillation as quantitative metrics. Simulations were conducted using continuous, variable sampling.

**PV system modeling.** PV cell can be represented by an equivalent electrical circuit that models its non-linear *I-V* characteristics under different irradiance $G$ and temperature $T$ conditions. The most widely used representation is the single-diode model [21] (Fig. 1). It is adopted for its balance between accuracy and simplicity. While the double-diode model offers improved accuracy, it requires additional parameters that are rarely found in datasheet (diffusion and recombination diode reverse saturation current, diffusion and recombination diode ideality factor) and increases computational complexity.

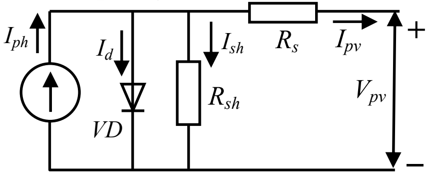

Fig. 1. PV cell single-diode equivalent model

The output current $I$ of a single-diode model is:

$$I = I_{ph} - I_0(\exp\left(\frac{q(V+IR_s)}{nkT}\right)-1), \qquad (1)$$

where $I_{ph}$ is the photocurrent; $I_0$ is the diode reverse saturation current; $R_s$, $R_{sh}$ are the series and shunt resistances; $n$ is the diode ideality factor; $q$ is the electron charge; $k$ is the Boltzmann constant; $T$ is the temperature.

The photocurrent $I_{ph}$ depends linearly on solar irradiance $G$ and is affected by temperature $T$:

$$I_{ph} = \left[I_{sc,ref} + \alpha(T - T_{ref})\right]\frac{G}{G_{ref}}, \qquad (2)$$

where $G$ is the incident irradiance; $G_{ref}$ is the reference irradiance (often 1000 W/m$^2$), $\alpha$ is the temperature coefficient of the current; $T_{ref}$ is the reference temperature; $I_{sc,ref}$ is the short-circuit current under reference conditions.

The diode reverse saturation current $I_0$ varies exponentially with temperature as:

$$I_0 = I_{0,ref}\left(\frac{T}{T_{ref}}\right)^3 \exp\left[\frac{qE_g}{nk}\left(\frac{1}{T_{ref}} - \frac{1}{T}\right)\right], \qquad (3)$$

where $I_{0,ref}$ is the reference current; $E_g$ is the semiconductor band-gap energy.

**Power converter modeling.** The converter used is an IBC due to its ability to handle high input currents, reduce current ripple, and improve overall efficiency. It consists of multiple boost converters in parallel interleaved in operation with a phase shift (180° for two-phase IBC) (Fig. 2). The interleaving reduces input current ripple thus minimizes stress on the PV module and lower electromagnetic interference.

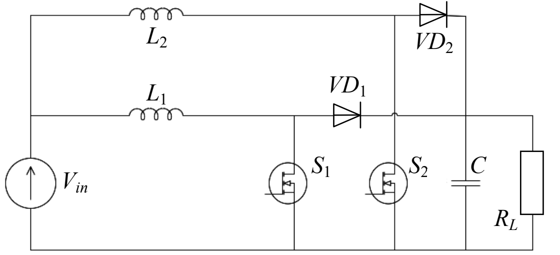

Fig. 2. Two-phase IBC circuit

The two-phase IBC [22] used in this work comprises: two inductors $L_1$, $L_2$ one per phase; two controlled switches $S_1$, $S_2$ (typically MOSFETs or IGBTs); two diodes VD$_1$, VD$_2$; an output capacitor $C$; a load resistance $R_L$. We can arrive to the following result after using state space representation and using the state space averaging technique:

$$\frac{\mathrm{d}X}{\mathrm{d}t} = \begin{bmatrix} 0 & 0 & \frac{D-1}{L_1} \\ 0 & 0 & \frac{D-1}{L_2} \\ \frac{1-D}{C} & \frac{1-D}{C} & -\frac{1}{RC} \end{bmatrix}\boldsymbol{X} + \begin{bmatrix} \frac{1}{L_1} \\ \frac{1}{L_2} \\ 0 \end{bmatrix} V_{in}; \qquad (4)$$

$$\boldsymbol{X} = \begin{bmatrix} i_{L1} \\ i_{L2} \\ V_0 \end{bmatrix} \quad (5) \quad \boldsymbol{Y} = \boldsymbol{C_{out}}\cdot V_{in}; \quad (6) \quad \boldsymbol{C_{out}} = [0\ \ 0\ \ 1], \quad (7)$$

where $X$ is the state vector; $Y$ is the output vector; $C_{out}$ is the output matrix; $i_{L1}$, $i_{L2}$ are the inductor currents; $V_0$ is the output voltage; $V_{in}$ is the input voltage; $R$ is the load resistance; $L_1$, $L_2$ are the inductance of both phases of the IBC; $D$ is the duty cycle; $C$ is the output capacitance.

The system consists of a PV panel connected to a two-phase IBC (Fig. 3). The PV voltage and current are measured and sent to the control block, which runs the MPPT algorithm. Based on these values, the control generates a duty ratio that drives the IBC to regulate the output and deliver maximum power to the load.

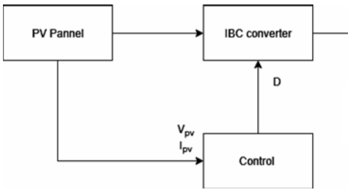

Fig. 3. System configuration schema

**MPPT algorithms.** For decades, researchers have focused on extracting the most power from PV systems, resulting in a wide range of MPPT techniques. These range from traditional methods (for example, P&O, IC and hill climbing) to more modern approaches like as fuzzy logic, neural networks, PSO and genetic algorithms. P&O is the most widely used MPPT technique due to its simplicity and low cost to implement. It perturbs the operating point of the PV and observes the power if power increases, perturbation continues in the same direction; if it decreases, the direction reverses.

It does however display oscillations around the MPP in steady state and can fail under rapidly changing irradiance. Furthermore, the fixed step size creates a trade-off , big step size allow for faster tracking but increased power loss due to oscillations while tiny step size reduce oscillations but hinder convergences.

**Principle of operation of P&O.** P&O is based on an iterative process that continuously adjusts the duty cycle of the DC-DC converter to extract the maximum amount of power possible from a PV [23].

The algorithm measures the new power and compares it to the last value. If power increases it continues perturbing in the same direction. If it decreases it perturbs in the opposite direction (see Table 1).

Table 1

Power voltage cases for P&O algorithm

| $\Delta P$ | $\Delta V$ | Action |
|---|---|---|
| $> 0$ | $> 0$ | Increase voltage |
| $> 0$ | $< 0$ | Decrease voltage |
| $< 0$ | $> 0$ | Decrease voltage |
| $< 0$ | $< 0$ | Increase voltage |

**Principle of operation of IC.** Its an algorithm that improves upon the conventional P&O by directly analyzing the slope of the power voltage curve of a PV panel. The core idea is that the derivative $dP/dV$ is 0 at MPP, positive to the left and negative to the right. Unlike P&O which only observes the power, IC attempts to mathematically determine whether the current operating point is to the left or right of the MPP using both instantaneous and IC [24] (Table 2). Let:

$$P = I \cdot V; \quad (8); \qquad dP/dV = I + V \cdot (dI/dV); \quad (9)$$

For:

$$dP/dV = 0; \quad (10) \qquad dI/dV = -I/V, \quad (11)$$

where $I$ is the PV current; $V$ is the PV voltage; $P$ is the PV power.

Table 2

IC principle

| Condition | Action |
|---|---|
| $\Delta V \neq 0$ and $\Delta I / \Delta V = -I / V$ | Stay at MPP |
| $\Delta V \neq 0$ and $\Delta I / \Delta V > -I / V$ | Increase voltage |
| $\Delta V \neq 0$ and $\Delta I / \Delta V < -I / V$ | Decrease voltage |
| $\Delta V = 0$ | If $\Delta I$=0: stay at MPP;<br>if $\Delta I \neq 0$: perturb |

**Proposed modified P&O algorithm.** To overcome the trade-off due to the step size seen in traditional P&O and IC, an adaptive step-size strategy is introduced, in which it dynamically adjusts based on the $P$-$V$ curve and rate of change of power. Algorithm description is next (Table 3). Let:

$$\Delta_1 = P(k) - P(k-1); \quad (12) \qquad \Delta_2 = V(k) - V(k-1). \quad (13)$$

Adaptive step size:

$$\alpha(k) = \alpha_{\max}\left[1 - \exp\left(-\mu\left|\frac{\Delta_1}{\Delta_2}\right|\right)\right], \qquad (14)$$

where $P$ is the PV power; $V$ is the PV voltage; $\alpha_{\max}$ is the maximum perturbation step, $\mu$ is the sensitivity coefficient (in this article we took $\mu$=0.01); $\Delta_1$, $\Delta_2$ are the difference of power and voltage.

Table 3

Power voltage cases for novel modified P&O algorithm

| $\Delta P$ | $\Delta V$ | Duty cycle $D$ |
|---|---|---|
| $> 0$ | $> 0$ | Increase by $\alpha(k)$ |
| $> 0$ | $< 0$ | Decrease by $\alpha(k)$ |
| $< 0$ | $> 0$ | Decrease by $\alpha(k)$ |
| $< 0$ | $< 0$ | Increase by $\alpha(k)$ |

**Simulation setup. PV module parameters.** The PV system model is developed using a commercially available PV module, with all key parameters carefully extracted directly from the manufacturer's datasheet. These parameters include characteristics such as rated power, open-circuit voltage, short-circuit current, temperature coefficients, and other essential electrical specifications. Table 4 summarizes the simulation model parameters used in this study of the different control methods for the PV panel.

Table 4

PV module parameters

| Parameter | Value |
|---|---|
| Module | Zytech Solar ZT280P |
| Maximum power $P_{\max}$, W | 280.33 |
| Cells per module | 72 |
| Open circuit voltage $V_{oc}$, V | 45.25 |
| Short-circuit current $I_{sc}$, A | 8.4 |
| Voltage at MPP $V_{mpp}$, V | 35.62 |
| Current at MPP $I_{mpp}$, A | 7.87 |
| Temperature coefficient of $V_{oc}$, %/°C | –0.3199 |
| Temperature coefficient of $I_{sc}$, %/°C | 0.0483 |
| Model parameters | |
| Light-generated current $I_L$, A | 8.475 |
| Diode saturation current $I_0$, A | $6.39 \cdot 10^{-11}$ |
| Diode ideality factor | 0.9562 |
| Shunt resistance $R_{sh}$, Ω | 194.59 |
| Series resistance $R_s$, Ω | 0.564 |

**Converter parameters.** The IBC used in the simulation is designed according to the power rating of the PV module and the desired DC bus voltage (Table 5).

Table 5

IBC converter parameters

| Parameter | Value |
|---|---|
| Inductor per phase $L$, mH | 4 |
| Output capacitor $C$, μF | 1000 |
| Switching frequency $f_s$, kHz | 10 |
| Number of phases | 2 |
| Duty ratio range $D$ | [0.1 – 0.9] |

**Load parameters.** The load considered in this study consists of a 900 W electrical device connected in parallel with a rechargeable energy storage system (Table 6). The energy storage system is a Li-Ion battery, which is chosen for its high energy density, long cycle life, and efficient charge/discharge characteristics. This configuration allows the system to supply the load continuously while accommodating fluctuations in generation and consumption. The parallel configuration also allows for the analysis of transient responses and the impact of load variations on both the PV system and the battery performance.

Table 6

Load parameters

| Component | Parameter | Value |
|---|---|---|
| Battery | Type | Li-Ion |
| | Nominal voltage, V | 96 |
| | Rated capacity, Ah | 50 |
| | Initial state of charge, % | 20 |
| | Battery response time, s | 30 |
| Load | Rated power, W | 900 |
| | Connection | In parallel with the battery |

**Test scenarios.** To evaluate the performance of the system, several test scenarios are considered, focusing on variations in environmental and operating conditions. The primary scenario involves changes in solar irradiance levels, simulating real-world fluctuations in sunlight intensity.

**Performance evaluation metrics.** System performance is evaluated by tracking efficiency, convergence time, steady-state oscillations, and computational cost, which together measure power extraction, speed, stability, and algorithm efficiency.

**Results and discussion.** In this simulation, the initial duty cycle variation ($\Delta D$) was fixed at 0.01 across all methods, ensuring a consistent and fair basis for comparison. Figure 4 shows the irradiance profile applied during the simulation. The irradiance begins at 1000 W/m$^2$, at 0.6 s drops to 700 W/m$^2$, and then rises to 800 W/m$^2$ from 1.2 s to 1.8 s.

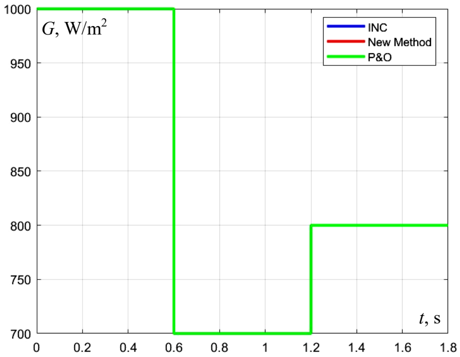

Fig. 4. Time profile of irradiance applied during the simulation

These irradiance variations are applied to assess the dynamic performance of the PV system, focusing on its voltage, current, and power response under rapidly changing solar conditions. Such an analysis offers valuable insight into the system's stability and efficiency when operating under realistic, time-varying irradiance profiles. Figure 5 illustrates the duty cycle performance comparison of 3 MPPT algorithms: IC, P&O, and the proposed method over a period of 1.8 s. The most notable characteristic is the dramatically different behavior patterns between the methods.

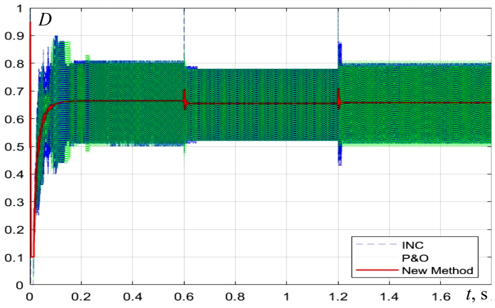

Fig. 5. Duty cycle variation obtained using IC, P&O and the proposed AM-P&O method

IC and P&O algorithms exhibit pronounced oscillations, with duty cycles fluctuating between 0.5 and 0.8 due to the fixed perturbation step ($\Delta D$). In contrast, the proposed method demonstrates much greater stability, with only brief disturbances around 0.6 s and 1.2 s, after which it quickly returns to the steady operating point. This stable behavior highlights the effectiveness of the adaptive mechanism in minimizing oscillations, enabling more accurate MPPT, improved energy harvesting efficiency, and reduced power loss compared to traditional methods.

Figure 6 shows the PV power output of the 3 MPPT algorithms over a simulation period of 1.8 s. The results illustrate how effectively each method tracks the MPP under changing irradiance conditions. The output stabilizes around 1400 W initially, then drops to approximately 1000 W, and finally settles near 1132 W.

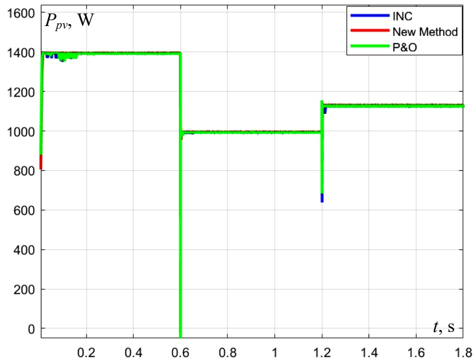

Fig. 6. Instantaneous PV power response under different MPPT algorithms IC, P&O and the proposed method

While all algorithms are able to follow the MPP transitions, the proposed method exhibits faster stabilization and smoother tracking compared to IC and P&O. Figure 7 presents the PV power output of the 3 MPPT algorithms over a 0.04-second window to provide a clearer view of their dynamic behavior.

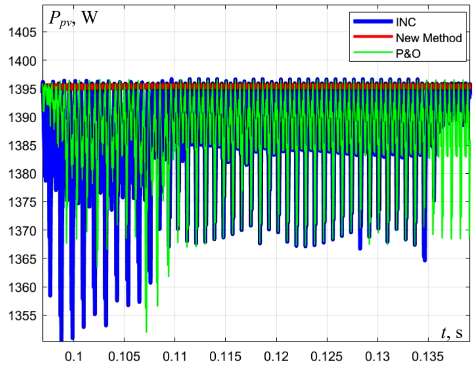

Fig. 7. Zoomed-in view of PV power variations under IC, P&O, and the proposed method

While all methods eventually reach the MPP, their responses differ noticeably in terms of oscillations. The proposed method delivers the most stable performance, keeping the output within just 1–2 W of the optimum. By comparison, the P&O algorithm shows moderate oscillations of about 15–20 W above and below the MPP due to its continuous P&O operation.

The IC algorithm exhibits the most significant oscillations, with power swings of 20–25 W around the MPP, particularly pronounced during the initial portion of the measurement period before somewhat stabilizing.

Overall, these results underline the superior stability and efficiency of the proposed method compared with conventional approaches.

Figure 8 compares the mean output power of the three MPPT algorithms. The proposed method delivers the highest performance at 955 W, followed by P&O at 949.5 W and IC at 946.5 W. Although the numerical differences may seem modest about 0.6 % higher than P&O and 0.9 % higher than IC this improvement translates into more efficient energy harvesting over extended operation. These results confirm the proposed method's superior capability to track the MPP while minimizing power losses.

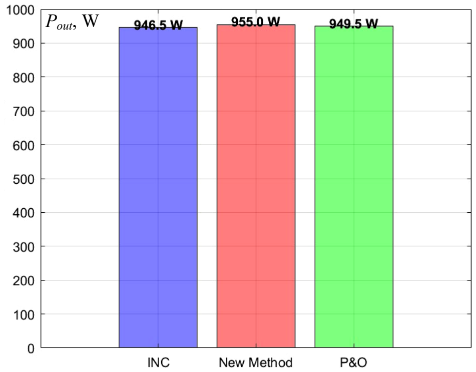

Fig. 8. Mean output power comparison of IC, P&O, and the proposed method

**Analysis of trade-offs between speed, accuracy, and complexity.** The comparison of the 3 MPPT methods (Tables 7, 8) highlights key trade-offs. P&O and IC respond quickly but exhibit higher oscillations (±15–25 W), leading to slightly lower mean power (949.5 W and 946.5 W) and reduced tracking accuracy. The proposed method achieves high accuracy and minimal oscillations (±1–2 W) with a higher mean power of 955 W, but at the cost of increased computational complexity. These results demonstrate that improved stability and energy harvesting efficiency can be obtained with more complex algorithms, while simpler methods offer faster but less precise tracking.

Table 7

Comparative table of the methods

| MPPT method | Duty cycle behavior | Computational cost |
|---|---|---|
| P&O | High oscillations, fluctuates between 0.5 and 0.8 | low |
| IC | High oscillations, fluctuates between 0.5 and 0.8 | low |
| Proposed method | Stable, minor disturbances at ~0.6 s and 1.2 s | high |

Table 8

Power comparative table of the methods

| MPPT method | Power oscillations around MPP | Mean output power, W |
|---|---|---|
| P&O | moderate, ±15–20 W | 949.5 |
| IC | significant, ±20–25 W | 946.5 |
| Proposed method | minimal, ±1–2 W | 955.0 |

**Conclusions.** The proposed method achieved the highest mean output power at 955 W, outperforming both P&O (949.5 W) and IC (946.5 W) algorithms. More importantly, it demonstrated exceptional stability with minimal oscillations around the MPP, maintaining steady-state operation without the continuous perturbation's characteristic of conventional methods.

The duty cycle analysis revealed that traditional IC and P&O algorithms exhibit significant oscillatory behavior as they continuously search for the optimal operating point. In contrast, the proposed method quickly converges to a stable duty cycle and maintains it throughout the test period, indicating superior tracking precision and reduced power losses.

Under dynamic conditions with varying irradiance levels, the proposed method consistently followed the desired MPP while maintaining stable power output. The reduced oscillations and improved tracking stability translate to enhanced energy harvesting efficiency, making it particularly valuable for practical PV applications where consistent power generation is crucial.

Future work can focus on implementing the AM P&O algorithm on embedded hardware to validate its real-time performance and computational efficiency. Its structure also allows for integration with hybrid or predictive schemes to further enhance convergence under extreme irradiance fluctuations or partial shading conditions. Moreover, combining the proposed method with real-time irradiance estimation or forecasting techniques could further optimize energy extraction in grid-connected PV system.

**Conflict of interest**. The authors declare that they have no conflicts of interest.

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*Received 11.05.2025*
*Accepted 09.07.2025*
*Published 02.11.2025*

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*How to cite this article:*
Makhlouf M., Laouar O. New adaptive modified perturb and observe algorithm for maximum power point tracking in photovoltaic systems with interleaved boost converter. *Electrical Engineering & Electromechanics*, 2025, no. 6, pp. 57-63. doi: https://doi.org/10.20998/2074-272X.2025.6.08