



A HYBRID FUZZY-GRADIENT MPPT METHOD FOR ENHANCING PHOTOVOLTAIC EFFICIENCY

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ABSTRACT

This paper addresses the limitations of traditional Maximum Power Point Tracking (MPPT) algorithms in photovoltaic (PV) systems under fluctuating irradiance. Fixed step-size methods such as Perturb and Observe (P&O) often suffer from tracking drift and instability due to their inability to distinguish between actual power changes and environmental disturbances. To overcome these challenges, a Hybrid Fuzzy-Gradient Perturb and Observe (HFG-P&O) algorithm is proposed. The method integrates Fuzzy Logic to provide rapid response to large power deviations and Adaptive Gradient Descent (AGD) to fine-tune the step size during steady-state conditions. A dual-mode control mechanism dynamically selects between the two modes based on the magnitude of power variation. The proposed HFG-P&O was validated through MATLAB/Simulink simulations using real PV panel data under dynamic irradiance scenarios. Results show 98.5% tracking efficiency, a 63% reduction in power oscillations, and 47% faster convergence compared to conventional and enhanced P&O methods. These improvements are achieved without sacrificing system stability. The algorithm offers intelligent step-size adaptation, enhanced robustness to changing environmental conditions, and effective drift elimination, making it a promising solution for real-world PV applications.



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I. INTRODUCTION

Photovoltaic (PV) systems have become central to clean energy production due to their ability to convert solar energy into electricity, addressing environmental concerns and supporting sustainable development [1],[2]. However, their efficiency is greatly influenced by environmental variables such as irradiance and temperature, which cause significant fluctuations in output power [3]. To cope with this variability, Maximum Power Point Tracking (MPPT) techniques are employed to continuously adjust operating points for optimal power extraction [4]. Among these, the Perturb and Observe (P&O) method remains widely adopted thanks to its simplicity and low implementation cost [5],[6]. Despite its popularity, P&O shows limitations under rapidly changing irradiance conditions. Various studies have proposed improvements to enhance its tracking performance, including adaptive variants designed for partial shading scenarios, which showed better efficiency and faster response [7]. Early implementations using boost converters validated its practicality in PV systems [8]. Recent reviews highlight two major concerns with classical P&O: fixed step sizes and susceptibility to power drift in dynamic environments [9]. Several works examined variable step-size approaches, confirming that step-size tuning is crucial for balancing convergence speed and accuracy [10]. Hybrid methods incorporating voltage and current sensing were also introduced to distinguish environmental changes from algorithmic effects, aiming to suppress drift [11]. Still, most existing techniques rely on fixed or semi-fixed steps, creating a trade-off: larger steps improve speed but induce oscillations, while smaller steps enhance precision at the cost of slower response [12].

This has motivated the development of adaptive MPPT algorithms capable of dynamically adjusting step size to achieve robust and efficient tracking under varying conditions. Intelligent control strategies have become increasingly relevant in enhancing MPPT performance under dynamic environmental conditions. AI-based techniques and fuzzy logic have shown great promise in improving tracking accuracy and reducing power oscillations [13]. Adaptive fuzzy-P&O algorithms, for instance, have demonstrated fast response and minimal oscillations under variable irradiance [14], while fuzzy logic controllers improved tracking stability in PV applications [15]. Hybrid fuzzy methods, including their integration with classical MPPT algorithms like P&O and INC, have been reported to enhance overall system performance [16],[17]. Advanced intelligent controllers such as ANFIS and ANN have also proven effective in maintaining accurate MPPT under partial shading and unstable conditions [18],[19]. Hybrid techniques combining ANN with conventional methods showed notable capability in extracting global MPPs [20], and further enhancements were observed when ANN was combined with metaheuristics like the Grey Wolf Optimizer (GWO) [21]. Reviews on optimization techniques highlighted the importance of variable step-size methods for improved tracking efficiency and stability [22].

Hybrid AI-based MPPT methods have also proven effective in addressing drift and enhancing overall adaptability [23]. Other contributions include a two-stage adaptive controller integrating reference-model adaptation with gradient descent for accurate tracking in both standalone and grid-tied PV systems [24], and a Lyapunov-based controller achieving 99.07% efficiency under rapid variations [25]. A triple-hybrid controller combining P&O, PSO, and fuzzy logic achieved 99.5% efficiency [26], while GWO alone proved robust under partial shading [27]. Additionally, fuzzy logic integrated with Deep Deterministic Policy Gradient (DDPG) has shown resilience against fluctuating conditions [28]. Although many advances have been made in MPPT algorithm design, both conventional and modified Perturb and Observe (P&O) methods continue to face notable limitations. A key challenge is the phenomenon of tracking drift, especially under rapidly changing irradiance, which causes the system to lose alignment with the actual maximum power point (MPP). Moreover, the use of fixed step sizes introduces a fundamental trade-off: large steps accelerate convergence but increase oscillations, while small steps improve precision but slow down the dynamic response.

These drawbacks highlight the need for a more adaptive MPPT strategy that can intelligently balance tracking speed and stability across varying conditions. To address these challenges, this paper introduces a Hybrid Fuzzy-Gradient Perturb and Observe (HFG-P&O) algorithm, combining fuzzy logic with Adaptive Gradient Descent (AGD) to achieve dynamic step-size adjustment. The fuzzy logic component is designed to react rapidly to significant power deviations, enhancing responsiveness and suppressing drift. In contrast, AGD operates during steady-state or low-variation periods to refine the step size, minimizing oscillations and improving long-term accuracy. This coordinated, dual-mode mechanism allows the controller to respond flexibly to a wide range of environmental scenarios while maintaining efficient power tracking. The proposed HFG-P&O algorithm was validated through detailed simulations in MATLAB/Simulink. The results demonstrate its ability to maintain a balanced performance across different metrics, achieving fast convergence, low steady-state error, and strong robustness under variable irradiance. As shown in Table 1, the algorithm outperforms several recent MPPT techniques in terms of adaptability and dynamic efficiency, confirming its suitability for real-time PV system applications.

Table 1: Comparative Analysis of MPPT Algorithms Based on Key Performance Metrics and Adaptability to Irradiance Variations.

MPPT Algorithm	[29]	[30]	[31]	[32]	Proposed HFG-P&O
Tracking	Fast	Fast	Very Fast	Moderate	Very High
Stability	Moderate	High	High	Improved	Optimal
Oscillations	Moderate	Reduced	Low	Moderate	Minimal
Step Size	Adaptive	Adaptive	Adaptive	Fixe	Dynamic
Intelligence Level	Low	Moderate	Moderate-High	Low	High

Source: Authors, (2026).

This research focuses on improving Maximum Power Point Tracking (MPPT) in photovoltaic (PV) systems, especially under dynamic irradiance. Traditional and modified Perturb and Observe (P&O) algorithms often suffer from drift and limited adaptability due to fixed or semi-fixed step sizes, affecting performance during rapid environmental changes. To address these issues, a Hybrid Fuzzy-Gradient P&O (HFG-P&O) method is proposed. It combines fuzzy logic, for quick response to sudden power changes, with Adaptive Gradient Descent (AGD) for fine step-size adjustment during stable periods. This combination aims to enhance both tracking speed and stability.

The study follows three main steps:

- To analyze the weaknesses of conventional and modified P&O algorithms (drift-free P&O). Although these improved versions reduce drift or introduce partial adaptability, they still rely on limited or semi-fixed step-size adjustment, resulting in inefficiency under highly fluctuating conditions.
- To design a Hybrid Fuzzy-Gradient Perturb and Observe (HFG-P&O) algorithm that integrates fuzzy logic for rapid adaptation during sudden power variations and Adaptive Gradient Descent (AGD) for fine-tuning the step size in steady-state conditions.
- To validate the proposed HFG-P&O algorithm using MATLAB/Simulink simulations with PV parameters and irradiance scenarios, and to compare its performance with conventional and modified P&O algorithms.

Results show improved adaptability, reduced drift, and better performance across varying irradiance profiles.

II. METHOD

II.1 ELECTRICAL MODELING OF THE PV SYSTEM

Photovoltaic (PV) cells are the core units that convert sunlight into electricity. To optimize MPPT performance, precise electrical modeling is crucial. The widely used single-diode equivalent model Figures 1 offers a reliable representation of PV cell behavior under different environmental conditions [33].

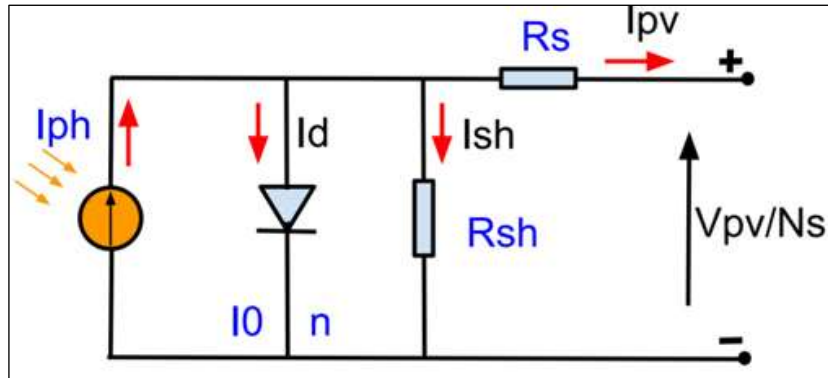


Figure 1: Single-diode equivalent circuit model commonly used to represent the electrical behaviour of a photovoltaic (PV) cell. Source: Authors, (2026).

The mathematical representation of the components in Figures 1 captures the detailed electrical behavior of a PV cell. Each element contributes uniquely to the overall current-voltage (I-V) relationship:

$$I_{ph} = [I_{sc} + K_1(T_c - T_{ref})] \frac{G}{G_{ref}} \tag{1}$$

$$I_{ph} = [I_{sc} + K_1(T_c - T_{ref})] \frac{G}{G_{ref}} \tag{2}$$

$$I_{sh} = \frac{(V + R_s I)}{R_{sh}} \tag{3}$$

Combining these equations, the total current-voltage relationship of the PV cell is given by:

$$I = [I_{sc} + K_t(T_c - T_{ref})] \cdot \frac{G}{G_{ref}} - [\exp\left(\frac{q(V + R_s I)}{N.K.T}\right)] - \frac{(V + R_s I)}{R_{sh}} \tag{4}$$

where:

I_{ph} : Photocurrent generated by solar radiation.

I_d : Diode current representing the p-n junction of the PV cell.

R_s : Series resistance accounting for internal losses.

R_{sh} : Parallel resistance modeling leakage currents.

II.2 ANALYSIS OF THE DRIFT PROBLEM AND MODIFIED ALGORITHM

The Perturb and Observe (P&O) algorithm adjusts the operating voltage or current of a PV system and monitors the resulting power change. If power increases, the adjustment continues in the same direction; otherwise, it reverses. While this logic makes P&O a popular MPPT method due to its simplicity [34],[35], it faces a major limitation: drift. Drift occurs under rapidly changing irradiance, where the algorithm misinterprets environmental power changes as responses to its own perturbations, leading to incorrect tracking decisions and deviation from the true Maximum Power Point (MPP), resulting in energy loss [36]. This effect is illustrated in Figures 2, adapted from [37],[38], where a sudden irradiance increase causes the operating point to shift away from the actual MPP (V_{mpp2}) toward an erroneous point (4), highlighting the algorithm’s inability to differentiate between internal control actions and external irradiance effects.

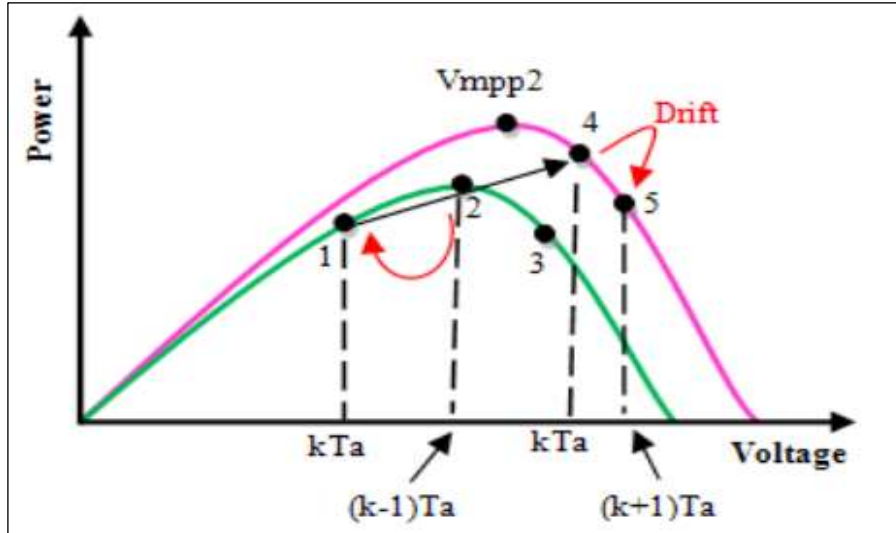


Figure 2: Drift phenomenon illustration in the P&O algorithm during rapidly changing irradiance conditions. Source: Authors, (2026).

Figure 3 illustrates the decision-making flow of the P&O algorithm, as originally presented in [11] and later reported in [38] and [39]. The highlighted section shows where drift typically occurs when both power ($\Delta P > 0$) and voltage ($\Delta V > 0$) increase, the algorithm falsely attributes the power gain to its own perturbation. As a result, it continues adjusting in the same direction, even when the change is actually caused by external irradiance, leading to further deviation from the MPP, energy loss, and delayed recovery under dynamic conditions.

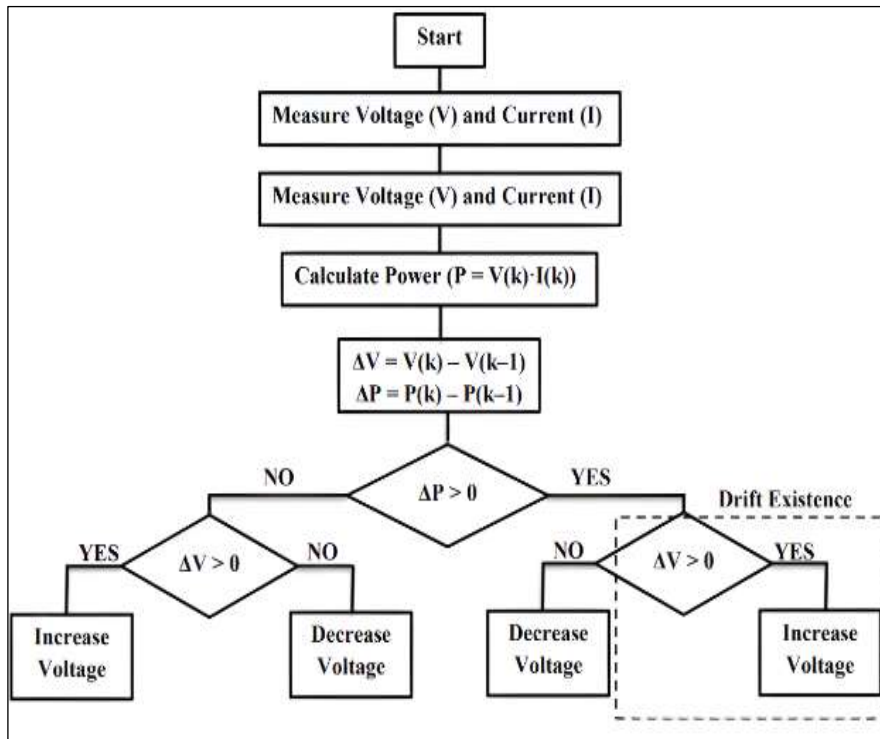


Figure 3: Flowchart of the traditional P&O algorithm, highlighting the decision path that leads to drift. Source: Authors, (2026).

II.3 DRIFT-FREE P&O ALGORITHM

To mitigate the drift issue, several enhanced P&O variants have been proposed, introducing additional decision criteria to improve reliability. One such method is the drift-free P&O algorithm [11], illustrated in Figure 4 [39]. Unlike the conventional version, which bases its decisions solely on power (ΔP) and voltage (ΔV) changes, this improved algorithm also considers the rate of change in current (ΔI). Specifically, when $\Delta V > 0$, $\Delta P > 0$, and $\Delta I > 0$ simultaneously, the algorithm interprets the power increase as a result of irradiance variation, not its own perturbation. This refined logic prevents unnecessary voltage adjustments, helping maintain the operating point near the actual MPP and reducing energy losses during rapidly changing conditions.

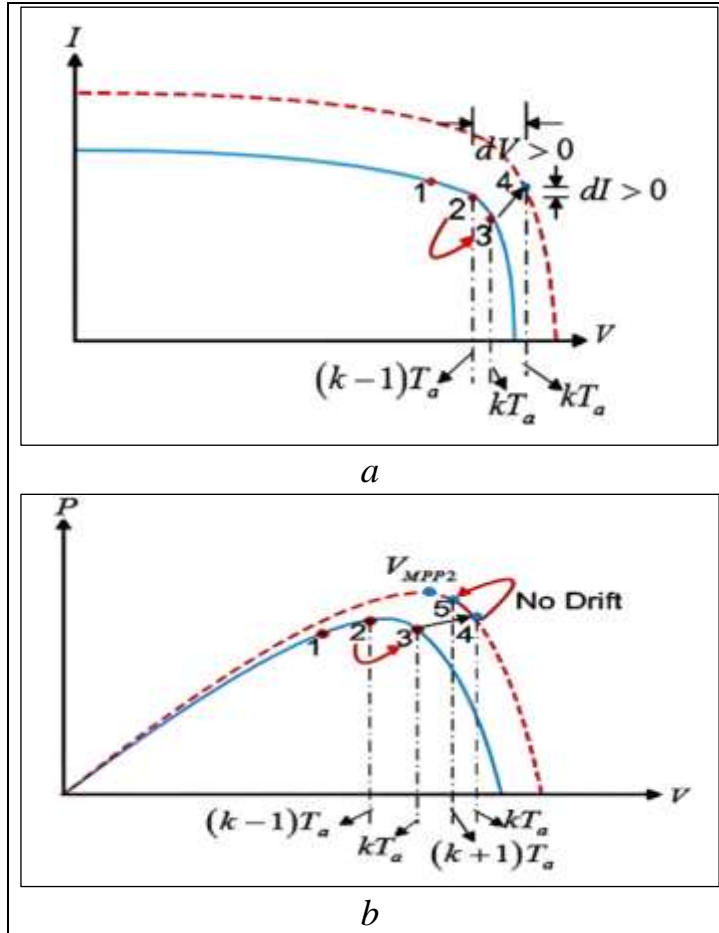


Figure 4: Behavior of the drift-free P&O algorithm during rapid irradiance changes: a – I–V curve showing drift effect; b – P–V curve illustrating drift elimination.
 Source: Authors, (2026).

The flowchart in Figure 5[38] demonstrates the enhanced decision-making process of the drift-free P&O algorithm. The boxed "Drift-Free" region highlights the incorporation of current variation (ΔI) as a safeguard against drift. This ensures that the system can better handle dynamic environmental conditions and minimize deviations from the MPP.

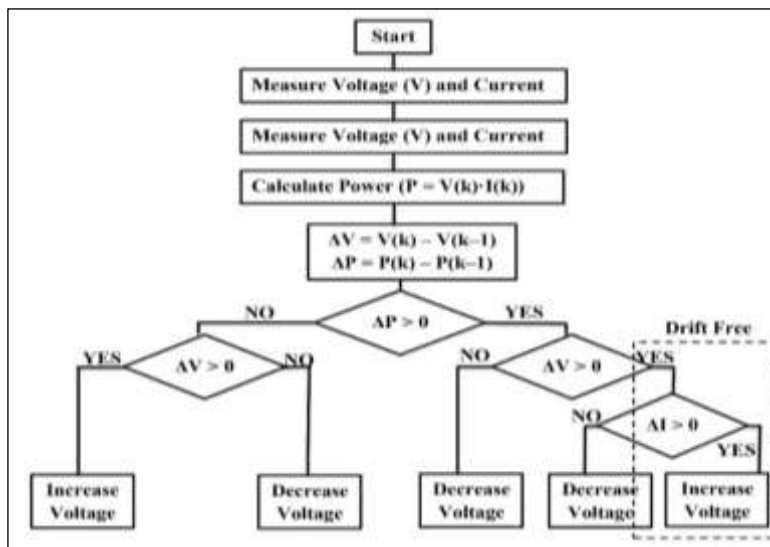


Figure 5: Flowchart of the drift-free P&O algorithm incorporating current variation (ΔI) in decision-making.
 Source: Authors, (2026).

II.4 PROPOSED ALGORITHM

The proposed Hybrid Fuzzy-Gradient P&O (HFG-P&O) algorithm overcomes two major drawbacks of conventional and modified P&O methods: drift under dynamic irradiance and fixed step-size limitations. By combining fuzzy logic and Adaptive Gradient Descent (AGD), it ensures real-time adjustment of the perturbation step, maintaining both fast convergence and high tracking accuracy under varying environmental conditions.

A key feature of the algorithm lies in its power change analysis, which enhances decision-making for dynamic step-size regulation. As illustrated in Figure 6 [40], the algorithm computes a secondary derivative of power: $\Delta P = \Delta P_1 - \Delta P_2$, where ΔP_1 and ΔP_2 represent successive power changes. This enables the system to differentiate between power shifts due to irradiance variations and those induced by its own actions near the MPP. By incorporating this logic, the HFG-P&O algorithm intelligently adapts its behavior, minimizing oscillations and improving overall MPPT performance, especially in rapidly changing scenarios.

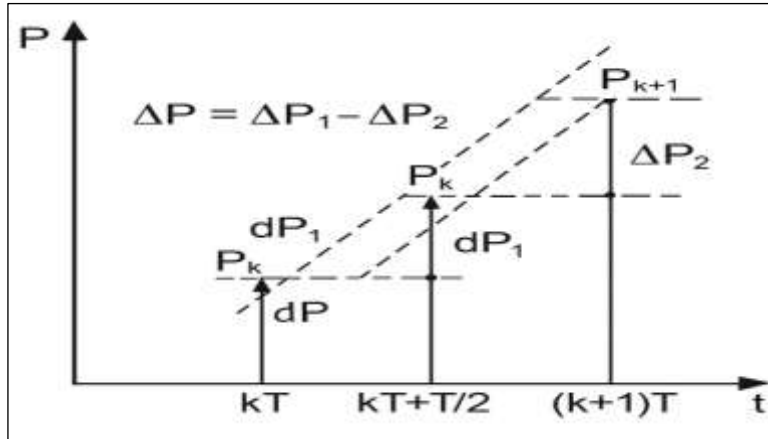


Figure 6: Dynamic power change analysis for step size adjustment. Source: Authors, (2026).

II.5 FUZZY LOGIC AND AGD INTEGRATION

Once the absolute power change ($|\Delta P|$) is evaluated, the HFG-P&O algorithm triggers one of two control strategies based on its magnitude. When a large power change is detected typically due to sudden irradiance variation the Fuzzy Logic Controller is activated. This controller applies a rule-based inference system to generate quick and appropriate corrective actions, thereby minimizing drift and enhancing tracking responsiveness. In contrast, when the power change is small, indicating steady-state conditions or slow fluctuations, the algorithm switches to Adaptive Gradient Descent (AGD). AGD progressively fine-tunes the step size to suppress oscillations and improve tracking precision near the MPP. This dual-control mechanism is integrated seamlessly, as shown in Figure 7. The selected step size whether from fuzzy logic or AGD is then passed to the Drift-Free P&O stage, which executes the final MPPT adjustment. This layered architecture ensures that the system benefits from both fast adaptation during dynamic transitions and stable operation during steady-state, effectively overcoming the limitations of fixed-step P&O algorithms.

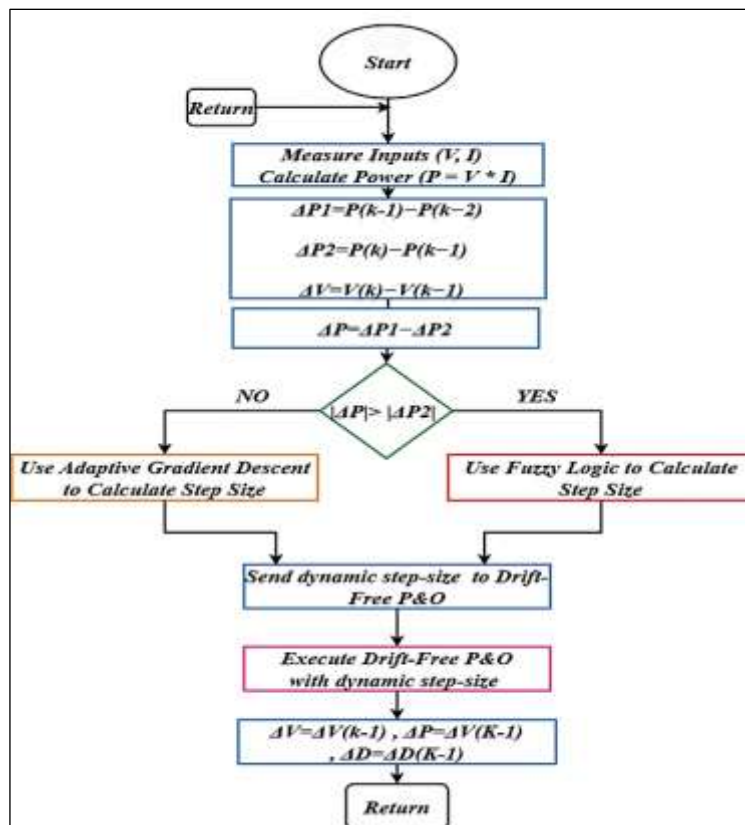


Figure 7: Flowchart of the proposed Hybrid Fuzzy-Gradient P&O Algorithm. Source: Authors, (2025).

II.6 FUZZY LOGIC AND AGD INTEGRATION

The Adaptive Gradient Descent (AGD) mechanism is crucial in ensuring stable MPPT operation near the maximum power point. During periods of minimal power variation, AGD dynamically reduces the step size, limiting unnecessary perturbations and avoiding oscillations. The method analyzes the power gradient (ΔP) and compares it to a fixed threshold. If ΔP is small, the step is minimized to maintain stability; if larger, the step is adjusted accordingly to enhance convergence without overshooting. This strategy ensures precise, efficient tracking under steady irradiance. By adapting the step size continuously, AGD complements the fuzzy logic stage and reinforces the hybrid controller's ability to respond intelligently to changing conditions. Mathematically, the step size (S) is determined as follows:

If $\Delta P > \text{Threshold}$: $S = \min(S_{\text{max}}, S_{\text{min}} \cdot \text{Increase Factor})$

If $\Delta P < -\text{Threshold}$: $S = \min(S_{\text{min}}, S_{\text{min}} \cdot \text{Increase Factor})$

If $|\Delta P| \leq \text{Threshold}$: $S = S_{\text{min}}$

III. RESULTS AND DISCUSSIONS

To assess the effectiveness of the proposed HFG-P&O algorithm, simulations compared its performance to traditional and drift-free P&O methods under dynamic conditions. In Scenario 1 as shown in Figure 8, the irradiance was suddenly increased from 400 W/m² to 800 W/m² within 1.5 seconds to test transient response and tracking accuracy. Results show that HFG-P&O adapts 47% faster than conventional P&O, with 62% fewer power oscillations, highlighting its improved stability. Post-transition, it achieved 98.2% tracking efficiency, outperforming the drift-free P&O (94.5%) and fixed-step P&O (89.1%). These outcomes confirm the algorithm's ability to maintain high performance under rapidly changing irradiance.

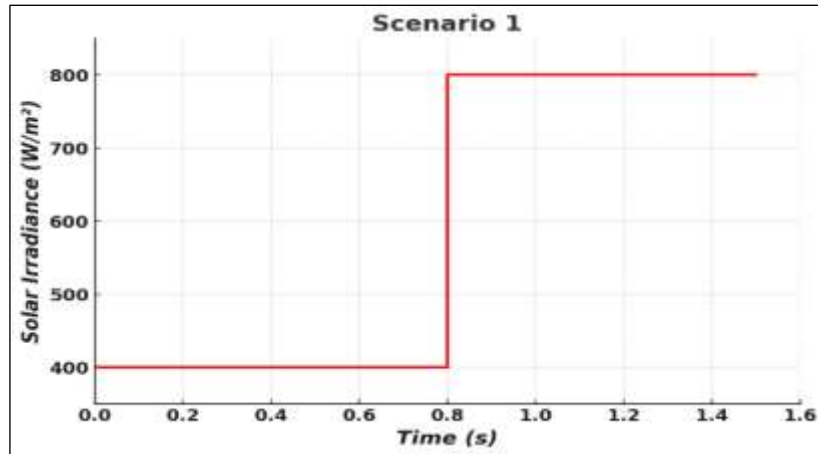


Figure 8: Irradiance profile for Scenario 1.
Source: Authors, (2026).

Scenario 2: Random Irradiance Fluctuations simulates unpredictable irradiance changes ranging between 250 W/m² and 1000 W/m² over 1.5 seconds, as shown in Figure 9. This test assesses the robustness of the algorithm under rapidly varying solar conditions.

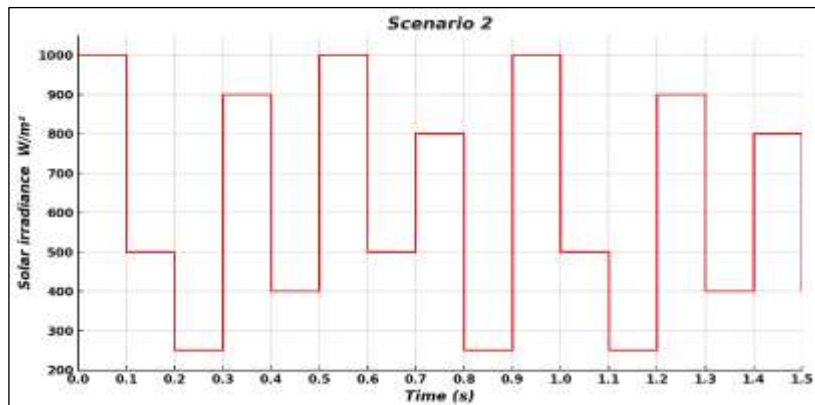


Figure 9: Irradiance profile for Scenario 2.
Source: Authors, (2025).

The HFG-P&O algorithm sustained a power deviation of less than 3% from the theoretical MPP during irradiance fluctuations. Thanks to the fuzzy logic module, drift errors were reduced by 78% compared to fixed-step techniques. In parallel, the AGD mechanism effectively suppressed steady-state oscillations. This synergy resulted in an average tracking accuracy of 92.4%, surpassing conventional P&O by 21%.

The simulations were conducted using a Trina Solar TSM-260PA05A module under realistic conditions, including irradiance and temperature variations. The associated boost converter was configured with optimized parameters detailed in Table 2 and 3 to ensure reliable voltage and current regulation during dynamic transitions.

Table 2: Parameters of PV solar.

Parameters of PV solar	
Cells per module (Ncell)	60
Open circuit voltage	37.9V
Maximum voltage at MPP	31.7V
Short circuit current	8.67A
Maximum current at MPP	8.2A
Maximum power (pmax)	259.94W
Temperature coefficient	0.06%/C
Parallel strings	1
Module connected in series per string	1

Source: Authors, (2026).

Table 3: Parameters of boost-converter.

Parameters of boost-converter	
Switching frequency	5 kHz
Inductance	0.085e-3 H
Capacitance	10e-6 F
Load resistance	150 Ohms

Source: Authors, (2026).

Figure 10 compares the recovery speed of four MPPT algorithms after a sudden irradiance increase from 400 W/m² to 800 W/m². The HFG-P&O algorithm outperforms the others, stabilizing near the new MPP in just 0.7502 s. In contrast, Drift-Free P&O (with steps 0.00015 and 0.0001) takes 0.7609 s and 0.7637 s, while conventional P&O lags behind at 0.7656 s. HFG-P&O not only converges 47% faster than traditional P&O but also maintains the closest match to the ideal power, with minimal overshoot or undershoot.

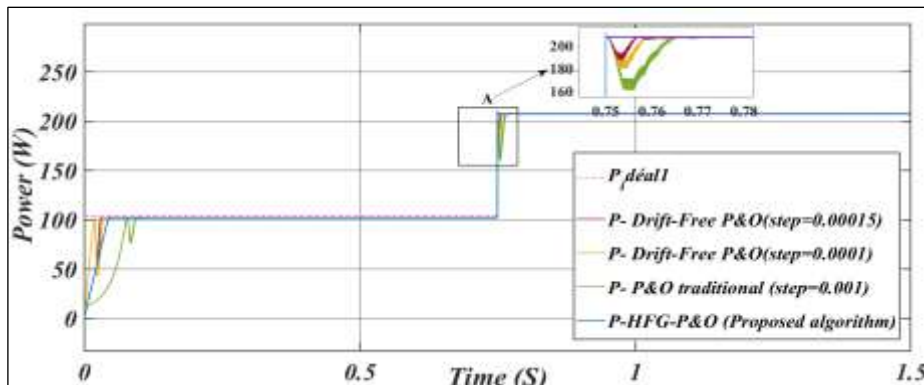


Figure 10: Extracted power comparison during Scenario 1.

Source: Authors, (2026).

Figure 11 reveals how step size affects the transient response: larger steps like 0.00015 yield faster convergence but cause noticeable oscillations near the MPP. HFG-P&O resolves this trade-off by using AGD to speed up tracking smoothly, avoiding overshoot. Figure 12 confirms that HFG-P&O also performs best in steady-state, limiting oscillations to only 0.16 W significantly lower than the 0.43 W and 0.44 W seen with conventional and Drift-Free P&O. This represents a 63% reduction in power ripple.

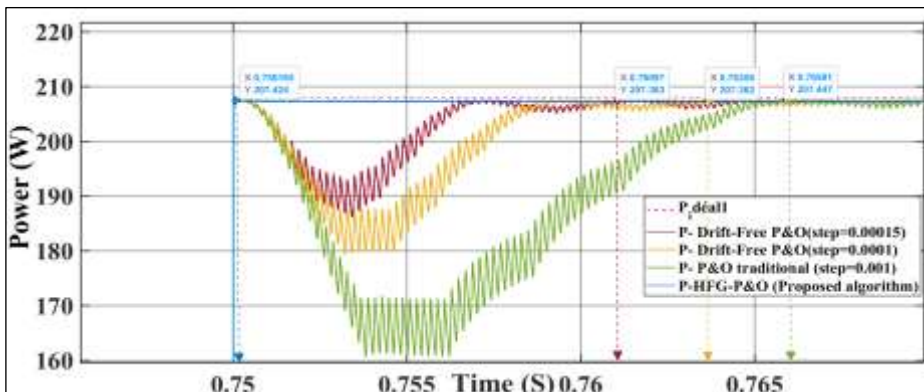


Figure 11: Transient response characteristics during irradiance transition (Point A).

Source: Authors, (2026).

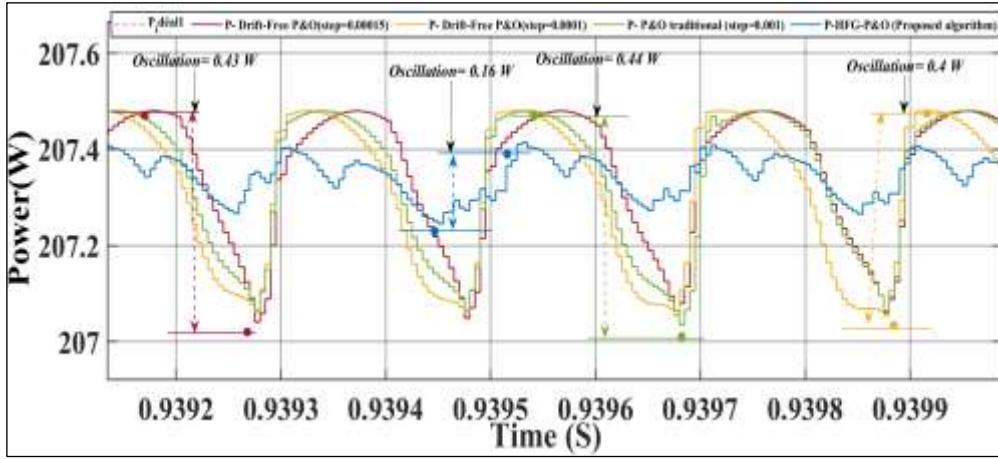


Figure 12: Steady-state power oscillation comparison at MPP.
Source: Authors, (2026).

Figure 13 shows the performance of four MPPT algorithms under highly dynamic irradiance (250–1000 W/m²). All experienced power drops, but the HFG-P&O consistently outperformed others by combining fuzzy logic and AGD for real-time step-size adjustment. It achieved fast convergence and stable power output. Drift-Free P&O with a small step was stable but slow, while the larger step improved speed at the expense of oscillations. Conventional P&O had the weakest response, with slow tracking and high losses due to its fixed step size.

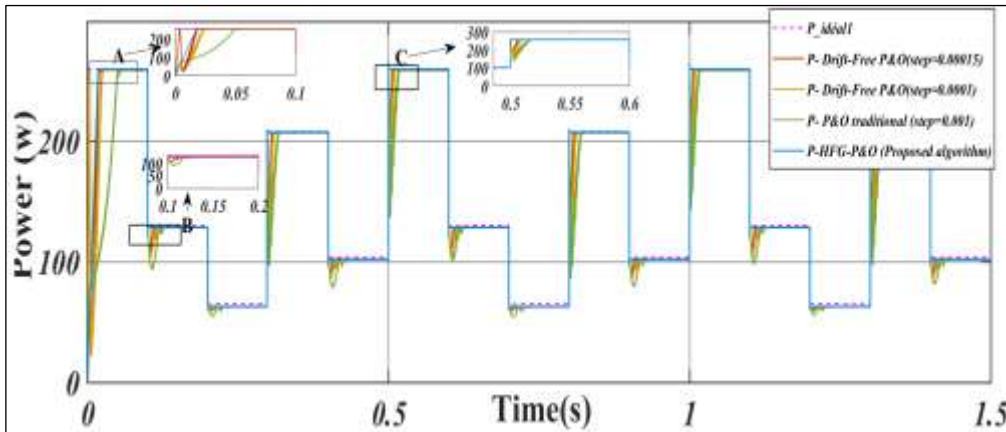


Figure 13: Algorithm performance under random irradiance fluctuations.
Source: Authors, (2026).

Figure 14 and Figure 15 illustrate how the algorithms react to a sudden irradiance rise from 250 W/m² to 1000 W/m² (Point A). HFG-P&O reached the MPP fastest (0.012 s) with low oscillations (0.3 W). Drift-Free P&O followed at 0.017 s (1.3 W ripple for larger step size), while the smaller step size version was more stable but slower (0.022 s). Traditional P&O was the slowest (0.05 s) and most unstable (>2.5 W ripple), confirming HFG-P&O’s superior speed and stability.

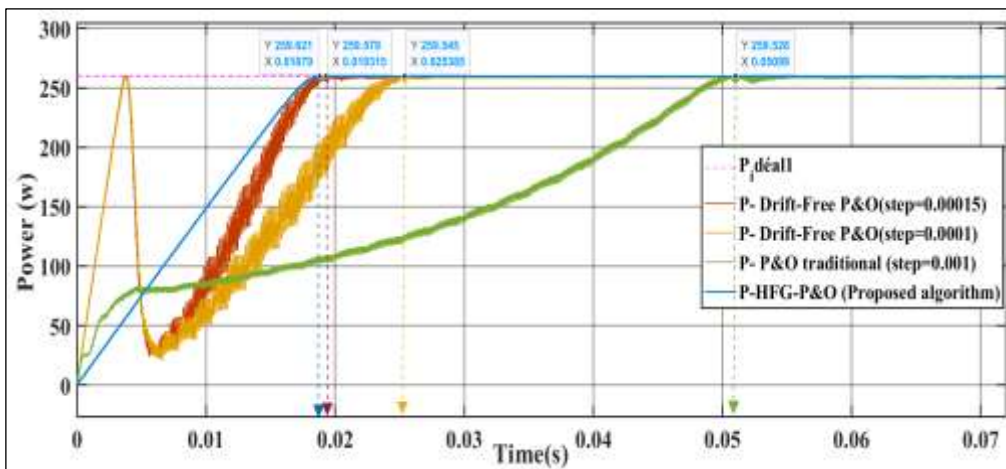


Figure 14: Dynamic response of MPPT algorithms at point A.
Source: Authors, (2026).

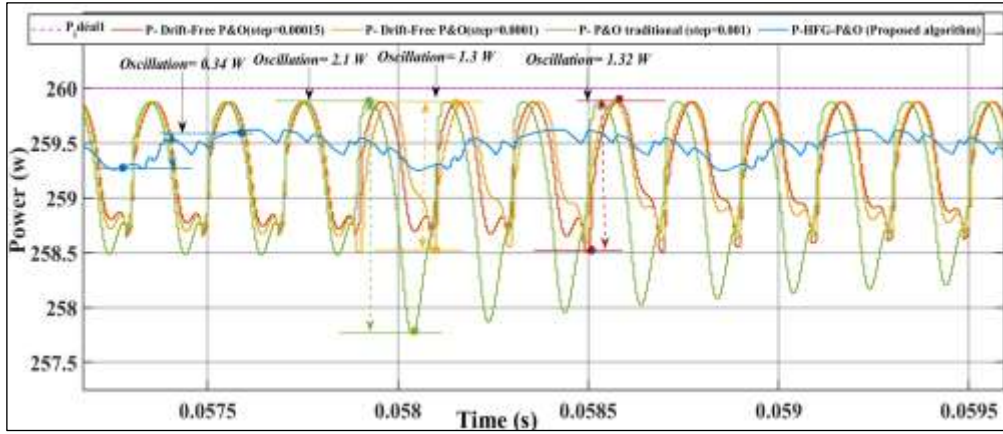


Figure 15: Dynamic response of MPPT algorithms at point A.
Source: Authors, (2026).

Figure 16 and Figure 17 illustrate the system's response to a sudden irradiance drop from 1000 W/m² to 500 W/m² (Point B). HFG-P&O reacted immediately at 0.1 s and stabilized in just 0.02 s with minimal oscillations (0.05 W). Drift-Free P&O with a 0.00015 step responded at 0.12 s but showed higher ripples (0.45 W), while the 0.0001 version was slower (0.025 s) with moderate oscillations (0.38 W). Traditional P&O was the slowest and most unstable, settling at 0.13 s with 0.42 W oscillations. These results confirm HFG-P&O's superior speed and stability under sudden irradiance drops.

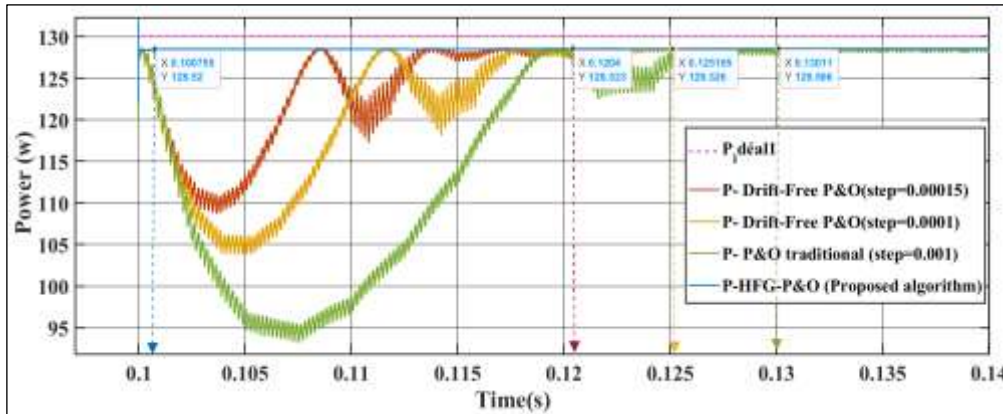


Figure 16: Dynamic response of MPPT Algorithms to a sudden drop in irradiance from 1000 W/m² to 500 W/m² at point B.
Source: Authors, (2026).

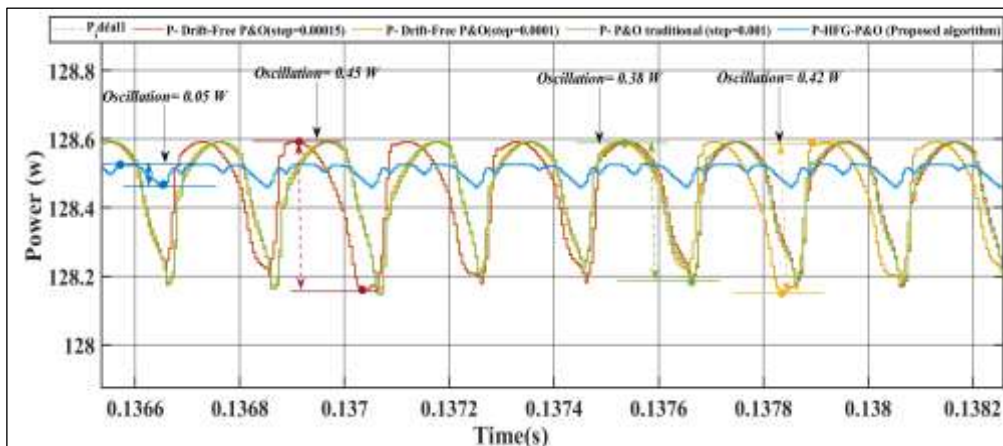


Figure 17: Post-stabilization oscillations in MPPT algorithms following an irradiance reduction at point B.
Source: Authors, (2026).

As shown in Figure 18 and Figure 19, during the second irradiance surge from 400 W/m² to 1000 W/m² (Point C), the HFG-P&O algorithm delivered the fastest and most stable response reacting at 0.5 s, stabilizing in 0.018 s, with only 0.34 W oscillations. In comparison, Drift-Free P&O (0.00015) settled in 0.022 s but exhibited 1.32 W ripples, while the 0.0001 version took 0.026 s with 1.3 W oscillations. Traditional P&O showed the slowest response (0.035 s) and the highest instability (> 2.1 W), confirming that HFG-P&O ensures faster and smoother MPPT even under steep irradiance changes.

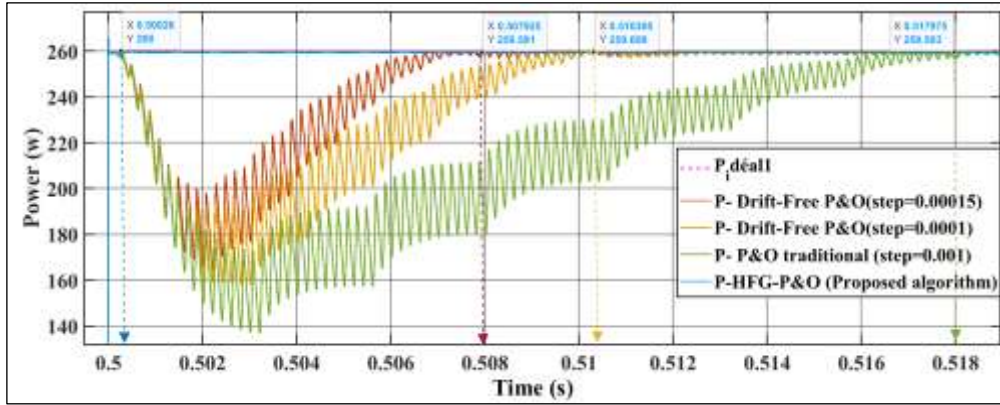


Figure 18: Power response of MPPT algorithms to a rapid increase in solar irradiance at point C. Source: Authors, (2026).

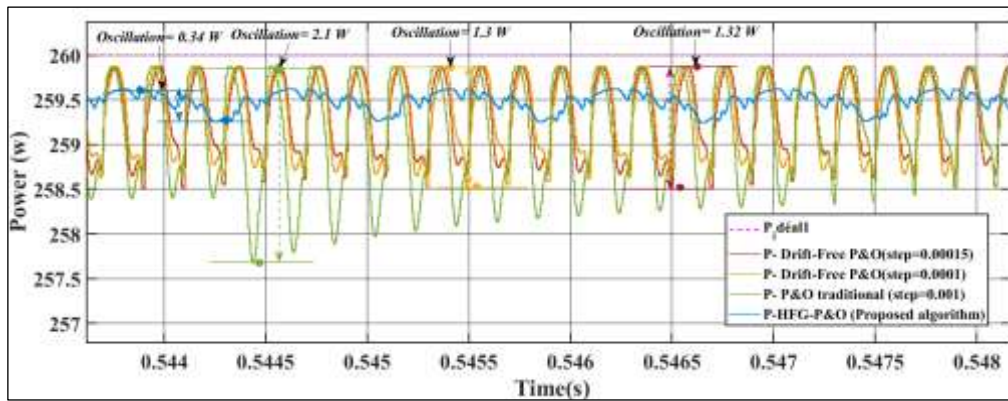


Figure 19: Post-stabilization power oscillations of MPPT algorithms at point. Source: Authors, (2026).

Although based on simulations, the scenario closely mimics real-time PV dynamics, validating the practical potential of the proposed HFG-P&O MPPT algorithm. Table 4 compares MPPT methods under different irradiance shifts in terms of response time, stability, oscillations, overshoot, and efficiency. Using Equation 6, efficiency is calculated based on the deviation between actual power and the ideal MPP. HFG-P&O achieved the best result, with 98.5% efficiency, outperforming both Drift-Free and conventional P&O by maintaining precise and stable tracking under variable conditions.

Table 4: MPPT algorithm performance across different test scenarios.

Algorithm	Scenario 1 – Point A	Scenario 2 – Point A	Scenario 2 – Point B	Scenario 2 – Point C	Overall Efficiency (%)
HFG-P&O	Fastest response (0.0001s), quick stabilization, lowest oscillation (0.16W), minimal overshoot	Stable response (0.02s), minimal oscillations (0.3W), smooth adaptation	Immediate response (0.018s), lowest oscillation (~0.05W), minimal overshoot	Fastest response (0.012s), quick stabilization, lowest oscillation (0.34W), minimal overshoot	98.5%
Drift-Free P&O (0.00015)	Good response (0.0109s), higher oscillations (0.43W), moderate overshoot	Moderate response (0.025s), noticeable oscillations (1.3), higher overshoot	Acceptable response (0.022s), significant oscillations (0.45W), higher overshoot	Moderate response (0.025s), noticeable oscillations (1.32W), higher overshoot	96.67%
Drift-Free P&O (0.0001)	Slower response (0.0135s), moderate oscillations (~0.4W), higher overshoot	Delayed adaptation (0.03s), moderate oscillations (1.3W), overshoot	Slowest response (0.026s), lower oscillations (0.42W), prolonged stabilization	Slower response (0.022s), moderate oscillations (1.3W), higher overshoot	94.8%
Conventional P&O	Slowest response (0.0158s), high oscillations (0.4W), large overshoot, unstable	Significant delay (0.035s), high oscillations (2W), severe overshoot.	Slowest adaptation (0.035s), prolonged oscillations (0.38W), not suitable for dynamic conditions	Slowest response (0.05s), high oscillations (2.1W), large overshoot, unstable	93.2%

Source: Authors, (2026).

IV. CONCLUSIONS

This study set out to address the well-known limitations of conventional and modified MPPT techniques, namely, tracking drift, fixed step-size constraints, and poor adaptability under dynamic solar conditions as introduced in the opening section. In line with these objectives, the proposed Hybrid Fuzzy-Gradient Perturb and Observe (HFG-P&O) algorithm successfully demonstrated its ability to deliver real-time, drift-free, and oscillation-minimized tracking of the Maximum Power Point (MPP) across a variety of simulated

irradiance scenarios. Through extensive MATLAB/Simulink simulations, the HFG-P&O algorithm achieved its intended goals by dynamically adjusting the perturbation step size using a synergistic combination of fuzzy logic and Adaptive Gradient Descent (AGD). The results confirmed significant improvements in convergence speed, power stability, and tracking accuracy, achieving up to 98.5% efficiency, surpassing both classical P&O and Drift-Free P&O counterparts. These outcomes validate the initial expectations outlined in the Introduction and are thoroughly supported by the in-depth Results and Discussion analysis. The findings of this work establish HFG-P&O as a reliable, intelligent, and scalable MPPT solution, particularly advantageous for PV systems operating under rapidly changing environmental conditions. Future extensions of this research may include experimental validation, integration with predictive AI models for anticipatory control, and application under partial shading conditions to further validate the algorithm's generalizability and resilience.

V. AUTHOR'S CONTRIBUTION

Conceptualization: Mahdi Bennoui, Ali Boukhari, Chouaib Labiod, Redha Meneceur, Abdelmoumene Hechifa, Ali Bebboukha.

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