



Performance evaluation of MPPT algorithms for PV system under real operating conditions

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ABSTRACT

The efficiency of photovoltaic systems is greatly dependent on operating conditions such as solar irradiance and temperature variations. To maximize power extraction, Maximum Power Point Tracking (MPPT) techniques ensure operation at the most efficient power output. This study compares three MPPT methods: the traditional Perturb and Observe (P&O), Incremental Conductance (INC), and a novel enhanced version proposed in this work, the Improved Incremental Conductance (ImprovedINC) algorithm. Unlike traditional approaches, ImprovedINC introduces moving average filtering, historical data buffers, and adaptive duty cycle adjustment with anti-windup protection to improve noise resilience, tracking precision, and convergence speed. Simulations are performed under varying irradiance profiles using controlled test scenarios and real meteorological data from the NASA POWER database. The analysis focuses on power output stability, tracking accuracy, and responsiveness to environmental fluctuations. Results show that while INC outperforms P&O in terms of stability and speed, the ImprovedINC algorithm demonstrates superior performance, maintaining a high average efficiency of 99.43%, minimal steady-state oscillations, and the fastest dynamic response. This contribution demonstrates the effectiveness of integrating intelligent control enhancements into conventional MPPT frameworks, offering a promising solution for maximizing photovoltaic system performance in real-world applications.

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1. INTRODUCTION

The growing global demand for clean and environmentally responsible energy sources has significantly driven innovation in the field of renewable energy. Solar energy, in particular, has gained recognition as a highly viable and promising renewable energy option to conventional fossil fuels due to its abundance, reliability, and minimal environmental impact (Çelikel & Gündoğdu, 2020). Photovoltaic (PV) technology are designed to generate electrical power directly from solar radiation, they have gained widespread adoption in residential, commercial, and industrial applications (Bensalmi et al., 2024). Nevertheless, the performance of PV energy conversion is affected by multiple factors, such as solar irradiance (SI) and temperature, and system configuration. To maximize energy harvesting, sophisticated control techniques are required in order to enhance the power output generated by PV panels under varying environmental conditions (Bollipo et al., 2020).

Among the various control strategies, MPPT stands out as essential for maximizing the efficiency of solar power systems by dynamically adjusting their operation to maintain maximum power extraction despite changing environmental conditions (Eltamaly, 2021). Since SI and temperature fluctuations affect the output characteristics of PV panels, MPPT continuously adjusts the operating current and voltage to maximize energy extraction. By implementing MPPT, PV systems can significantly improve their overall performance, reduce energy losses, and enhance reliability, making them a crucial component in modern solar energy applications. Without MPPT, PV systems would operate inefficiently, leading to suboptimal power generation and increased dependency on additional energy sources (Mao et al., 2020). As solar energy continues to expand as a key renewable resource, the development and refinement of MPPT techniques remain a priority for improving the sustainability and effectiveness of PV technology (Gonzalez-Castano et al., 2021; Mao et al., 2020).

Several studies have been conducted to enhance MPPT techniques, aiming to enhance the precision of tracking, response time, and stability under dynamic environmental conditions. Various approaches have been explored, ranging from modifications in DC-DC converters to advanced optimization algorithms. Belkaid et al. (2019) study the modeling and control of a Cuk converter utilizing direct duty cycle Incremental Conductance (INC) MPPT algorithm for photovoltaic (PV) battery systems. The proposed system enhances energy extraction efficiency by optimizing impedance matching between the PV module and a 12V lead-acid battery. Simulations conducted in MATLAB/Simulink Show that the system successfully follows the MPP in response to changing environmental conditions, achieving an average efficiency of 93.38% under SI changes and 94.74% under temperature variations. The study highlights the advantages of the Cuk converter in reducing switching losses, maintaining stable voltage regulation, and ensuring high tracking accuracy, making it a reliable choice for PV energy storage applications. Similarly, Ba et al. (2018) present a comparative analysis on various DC/DC power converters for optimizing photovoltaic systems using the MPPT (P&O) method. The study emphasizes the importance of selecting the appropriate converter type: Buck, Boost, or Buck-Boost, based on the direct coupling responses of the PV generator under varying weather conditions and load resistances. Simulations conducted in MATLAB/Simulink demonstrate that the choice of converter significantly impacts system efficiency and performance. Additionally, the study highlights the role of bypass diodes in mitigating partial shading effects and improving power extraction. The findings provide valuable insights for improving the stability and efficiency of standalone PV systems. Beyond converter-based improvements, recent research has focused on integrating intelligent control techniques to enhance MPPT performance. Mehazzem et al. (2022) propose an MPPT technique based on fuzzy logic combined with a spatio-temporal forecasting model to enhance PV power prediction in a tropical insular region. The study integrates a solar forecasting method using a spatio-temporal autoregressive model to predict short-term SI variations, which are then used to optimize MPPT performance. A fuzzy logic

controller is implemented to track the MPP efficiently, improving system stability under rapid SI fluctuations. Simulation results in MATLAB/Simulink demonstrate that the proposed method provides fast convergence, reduced steady-state oscillations, and accurate power prediction. In addition to fuzzy logic-based control, bio-inspired optimization techniques have been explored to further improve MPPT efficiency. In (Gonzalez-Castano et al., 2021), an MPPT method founded on the Artificial Bee Colony (ABC) is proposed for PV systems utilizing a DC-DC converter. This algorithm identifies the P-V characteristic of the solar module and searches for the optimal voltage reference, which is then used in a PI-controlled loop for power extraction. A hardware-in-the-loop framework was realized through an affordable digital signal processing platform, validates the proposed approach. In contrast to the traditional P&O technique, the obtained results demonstrate superior tracking accuracy, reduced steady-state oscillations, and faster convergence. Amara et al. (2018) propose an MPPT approach relying on the Adaptive Neuro-Fuzzy Inference System for the purpose of enhancing the performance of PV systems under varying environmental conditions. The method integrates a PI controller with ANFIS to enhance the precision of tracking, system stability, and convergence speed in comparison with traditional P&O MPPT techniques. The study, conducted using MATLAB/Simulink, demonstrates that ANFIS-MPPT significantly reduces power oscillations around the MPP and adapts more efficiently to rapid irradiance changes. The findings validate that the proposed method outperforms existing algorithms in terms of tracking speed and accuracy, making it well-suited for real-time PV applications. Further extending the exploration of metaheuristic approaches, Eltamaly et al. (2021) propose an innovative MPPT strategy for PV systems based on the Musical Chairs Algorithm (MCA). This algorithm dynamically adjusts the count of exploratory agents during the optimization process, enhancing exploration at the beginning and improving exploitation in the final stages. This approach significantly reduces the time required to reach convergence and lowers the probability of failure in comparing to traditional metaheuristic algorithms. Simulation and experimental results show that MCA outperforms five benchmark optimization techniques, achieving up to 50% faster convergence and reducing steady-state oscillations by 20–30%. These improvements make MCA a promising MPPT strategy, particularly under instances of irregular shading across the PV array.

This paper presents a comprehensive analysis of MPPT algorithms, comparing the technical performance exhibited by the traditional P&O and INC methods alongside a newly proposed algorithm, ImprovedINC, under various SI levels. The study incorporates real meteorological data to examine the robustness and the effectiveness of these algorithms in practical operating conditions. Particular attention is given to the behavior of the duty cycle and its influence on power output stability, highlighting how algorithmic enhancements can significantly improve tracking accuracy and system efficiency. The following sections describe the theoretical background, system modeling, methodology, results, and key findings derived from the comparative analysis.

2. PV SYSTEM MODELING AND CHARACTERISTICS

PV technologies utilize semiconductor materials to directly convert sunlight into usable electrical energy. Precise modeling of PV systems is crucial for reliably forecasting their performance under various environmental conditions. The equivalent circuit configuration that simulates the electrical behavior of a PV cell, as illustrated in Fig 1, it comprises a diode (D) modeling the p-n junction, a current source that represents the generated photocurrent (I_{ph}), a resistance in parallel (R_{sh}) representing leakage currents, and a series resistance (R_s) accounting for internal losses. The output current (I_{pv}) and voltage (V_{pv}) are influenced by these components, affecting the overall efficiency of the PV module. This model provides a fundamental basis for analyzing PV system performance and implementing MPPT techniques to optimize energy extraction (Sarvi & Azadian, 2022).

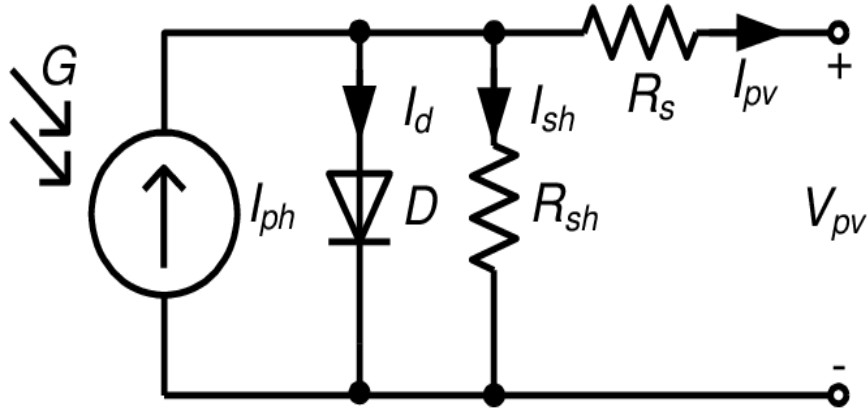


Fig 1. Equivalent circuit configuration of a PV cell.

The operational behavior of a PV cell is often modeled through an equivalent electrical circuit that captures the key characteristics influencing its performance. The single-diode model is often utilized for its balance between accuracy and simplicity. This model incorporates a photocurrent source, a diode representing the p-n junction, and resistive elements accounting for losses and leakage currents (Bipin et al., 2022; Jalil et al., 2022). The correlation between output voltage and current of a PV cell is governed by a fundamental equation, which considers the effects of the diode, shunt resistance, and series resistance, as expressed in the following equation (Bipin et al., 2022; Sarvi & Azadian, 2022):

$$I_{pv} = I_{ph} - I_s \left(e^{\frac{q(V_{pv} - R_s I_{pv})}{NkT}} - 1 \right) - \frac{V_{pv} - R_s I_{pv}}{R_{sh}} \quad (1)$$

Where:

- I_{ph} = Photogenerated current dependent on illumination (A)
- q = Electron charge (1.602×10^{-19} C)
- I_s = Reverse current (A)
- V_{pv} = Output voltage of the PV module (V)
- k = Boltzmann constant (1.381×10^{-23} J/K)
- N = Ideality coefficient of the diode
- T = PV cell temperature (K)
- R_s = Resistance in series (Ω)
- R_{sh} = Resistance in parallel (Ω)

To accurately assess the performance of the PV panel and compare its characteristics with the obtained results, it is essential to analyze its electrical behavior under different irradiation levels. Fig 2 presents the P-V and I-V characteristics of the PV module used in this study, illustrating how current and power output vary with voltage. This information is crucial for understanding the panel's operating points and evaluating the effectiveness for MPPT methods when applied in real-world environments.

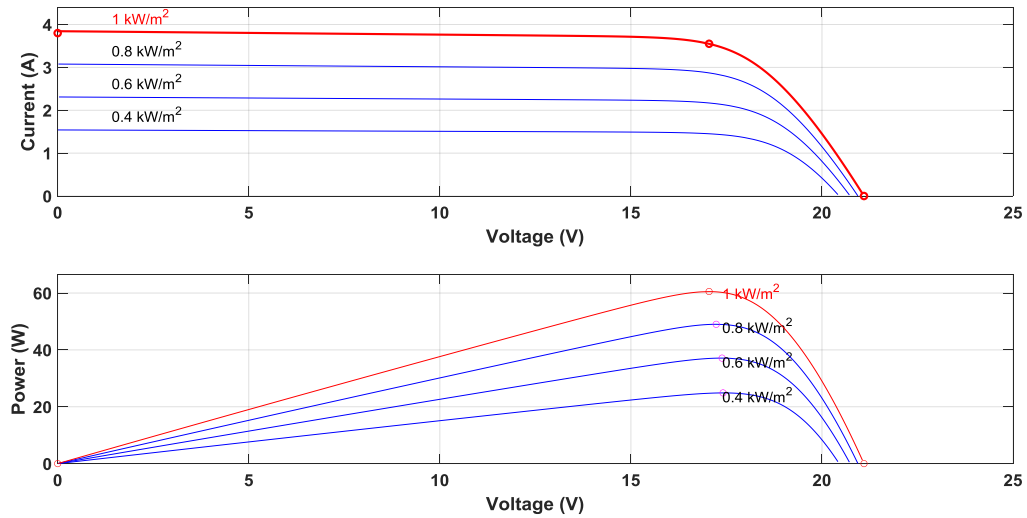


Fig 2. P-V and I-V characteristics of the PV module used in this study.

3. DC-DC BOOST CONVERTER DESIGN AND OPERATION

An MPPT control mechanism is integrated into PV systems to boost their energy conversion efficiency and maximize power extraction from the solar panel. Given that the panel's power output is nonlinear and influenced by environmental factors like temperature and SI, The MPPT technique persistently adjusts the system's operating parameters to ensure optimal power transfer (Li et al., 2021). This is typically achieved using a DC-DC converter, which regulates the current and voltage supplied to the load. Fig 3 illustrates a typical PV system incorporating an MPPT mechanism and a DC-DC energy conversion circuit. The photovoltaic panel generates a voltage (V_{pv}) and current (I_{pv}), which are monitored by the MPPT controller. This controller adjusts the D of the element S to regulate power flow through the inductor (L), diode (D), and capacitors (C1, C2). The load (R) receives the optimized power, ensuring improved efficiency and stability of the system (Manna et al., 2023).

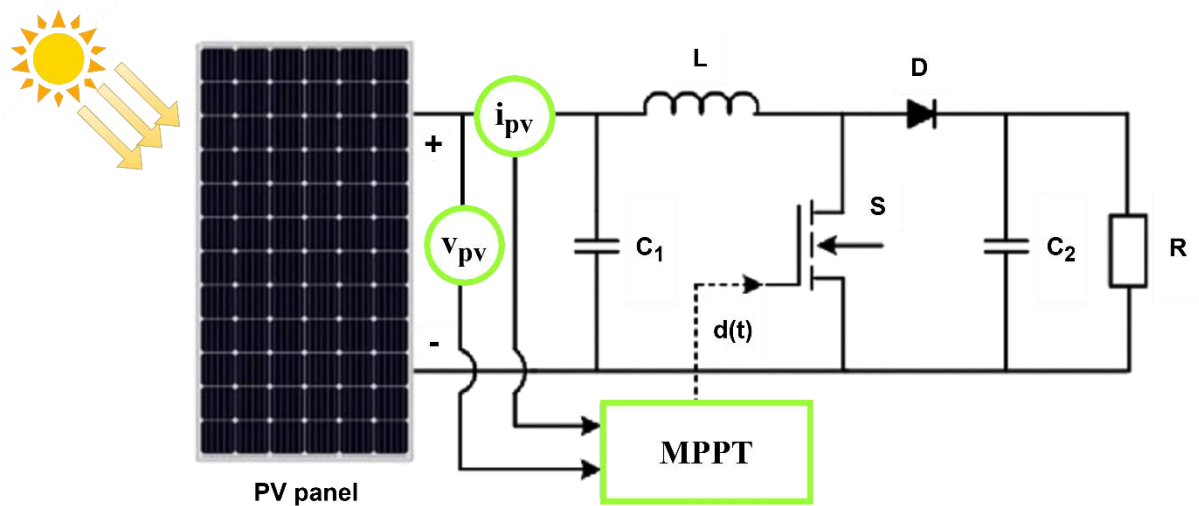


Fig 3. Schematic representation of a solar power system equipped with MPPT and dc-dc converter (Manna et al., 2023).

The voltage applied to an inductor varies directly with the rate of change of current flowing through it, as expressed by (ÇeliKel & Gündoğdu, 2021) :

$$V_s(t) = L \frac{dI_L}{dt} \quad (2)$$

This fundamental relationship governs the energy storage and transfer within the inductor. By approximating the change in inductor current over time, we obtain (ÇeliKel & Gündoğdu, 2021):

$$\frac{\Delta I_L}{\Delta t} = \frac{V_s}{L} \quad (3)$$

This equation indicates that the current increases with a slope determined by the input voltage V_s and the inductance L . During the switch-on period (DT_s), the energy stored in the inductor, leading to an increase in current described by (ÇeliKel & Gündoğdu, 2021):

$$\Delta I_L = \frac{V_s}{L} DT_s \quad (4)$$

Conversely, once the switch is turned off, the inductor begins to discharge its stored energy, resulting in a gradual decline in current as described in (ÇeliKel & Gündoğdu, 2021):

$$\Delta I_L = \frac{V_s - V_0}{L} (1 - D)T_s \quad (5)$$

This phase ensures continuous energy delivery to the load, with the rate of decrease influenced by the voltage difference between V_s and V_0 . The input-output voltage relationship is defined by (Mahmood et al., 2020):

$$V_0 = \frac{V_s}{1 - D} \quad (6)$$

This equation demonstrates the voltage step-up characteristic of the boost DC-DC converter. As the D increases, the output voltage rises, making this topology particularly suitable for photovoltaic applications where voltage regulation is necessary to maximize power extraction.

4. METHODOLOGY

This section presents the MPPT techniques utilized to enhance the performance of the photovoltaic system. The study focuses on three algorithms: the widely used P&O, the INC algorithm, and a newly developed version named ImprovedINC, which introduces advanced control features for enhanced performance under dynamic conditions. These methods are widely employed due to their effectiveness in tracking the MPP under varying environmental conditions. The following subsections describe their working principles and provide corresponding flowcharts for a clearer understanding.

4.2 Perturb and observe

The P&O algorithm is among the most commonly applied methods for MPPT due to its straightforward implementation. The method works through minor perturbations in the voltage applied and monitoring the corresponding power variation (Mahmood et al., 2020). When power output improves, the algorithm maintains the current direction of change; if it drops, the direction is reversed. This ongoing process

enables effective MPP tracking. The following flowchart in Fig 4 explains the iterative process followed by the P&O method (Mahmood et al., 2020).

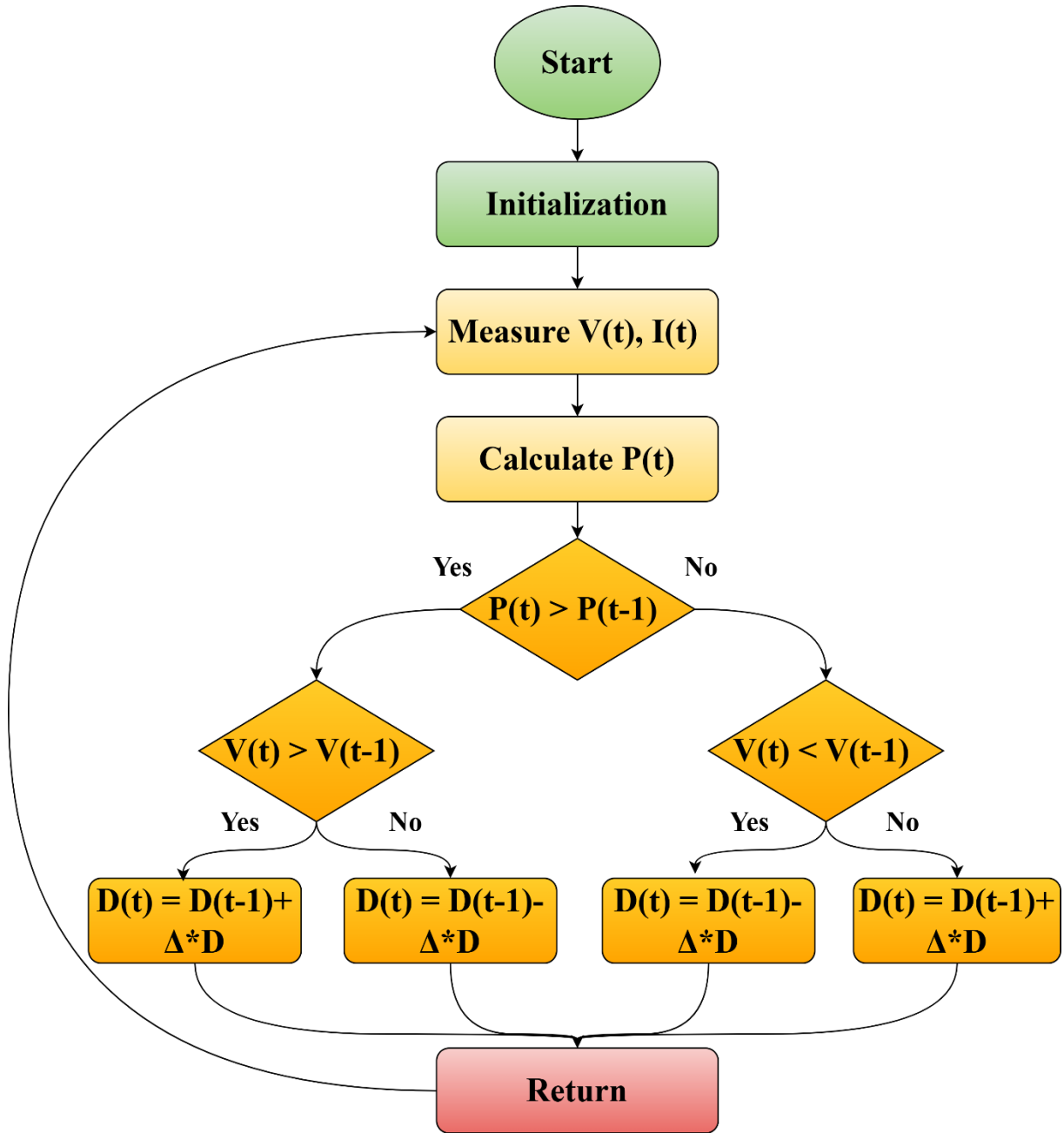


Fig 4. Perturb and observe MPPT algorithm flowchart.

4.2 Incremental conductance

The INC method is an advanced MPPT algorithm that overcomes the limitations of the P&O method, particularly in rapidly changing environmental conditions. The MPP is identified by evaluating the ratio of current change to voltage change ($\Delta I/\Delta V$) against the real-time conductance (I/V). Using this comparison, the algorithm modifies the duty cycle to track the MPP more accurately (Abd Alhussain & Yasin, 2020) (Bouksaim et al., 2021). The following flowchart in Fig 5 illustrates the step-by-step operation of the INC algorithm (Abd Alhussain & Yasin, 2020; Bouksaim et al., 2021).

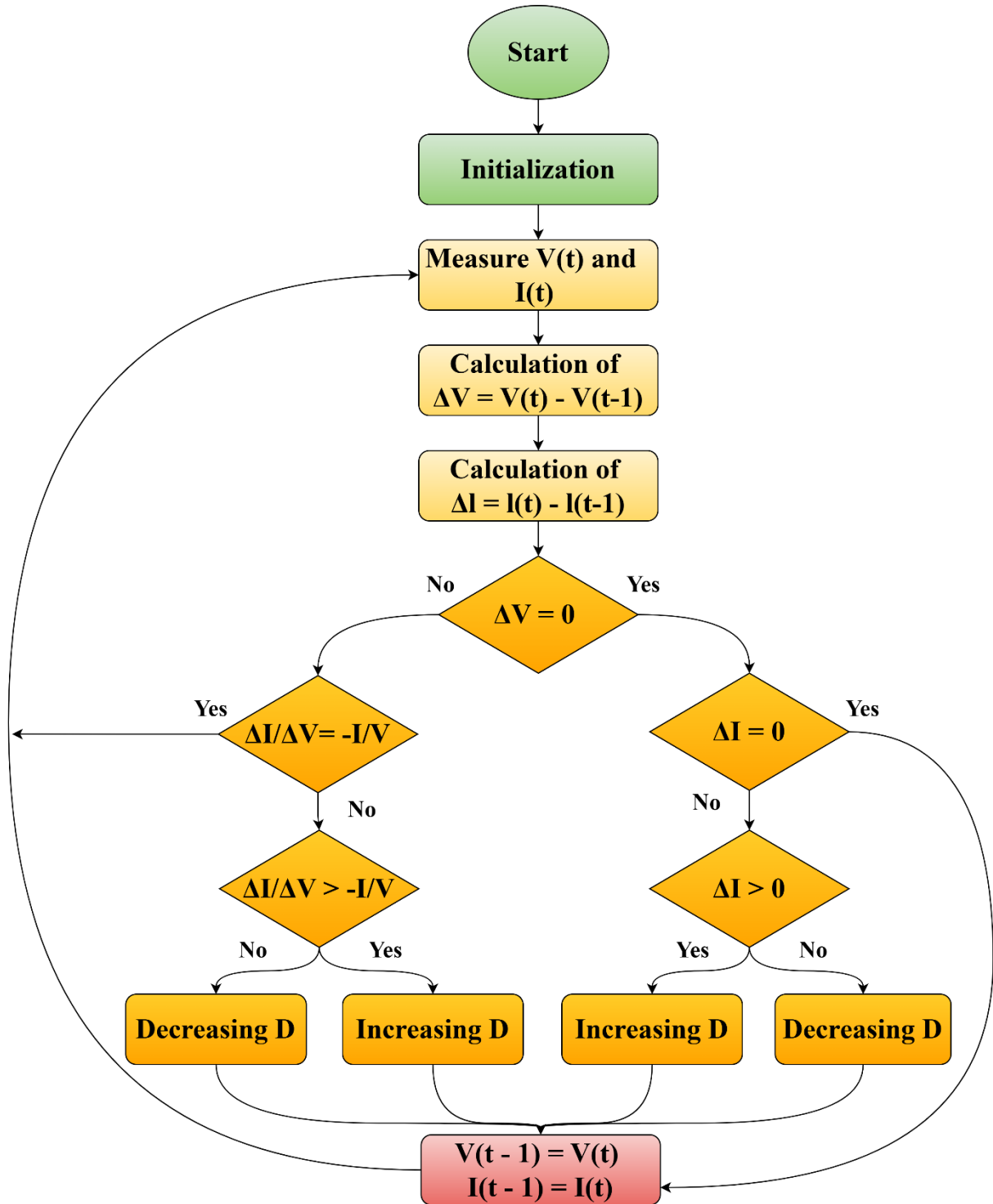


Fig 5. Incremental conductance MPPT algorithm flowchart.

4.3 Improved incremental conductance (improvedinc)

The ImprovedINC algorithm is a refined version of the traditional INC method developed to optimize the performance of MPPT in PV systems under real-world operating conditions. Unlike the conventional approach that relies solely on instantaneous voltage and current measurements, the ImprovedINC algorithm introduces a stability-oriented strategy based on moving averages and historical data buffers. By continuously updating the historical values of voltage, current, power, and duty cycle over a fixed observation window, it calculates averaged signals to suppress transient noise and short-term

fluctuations. This enhancement significantly improves tracking accuracy and ensures smoother convergence to the MPP, particularly in situations involving rapidly changing solar irradiance and temperature. The algorithm computes the deviation of current and voltage from their respective moving averages and uses these differences to assess the system's dynamic behavior rather than relying on raw values alone. If the changes in both voltage and current are negligible, the system is considered to be operating stably and the duty cycle remains unchanged. Otherwise, the algorithm evaluates how incremental conductance compares to instantaneous conductance to determine the appropriate direction of duty cycle adjustment.

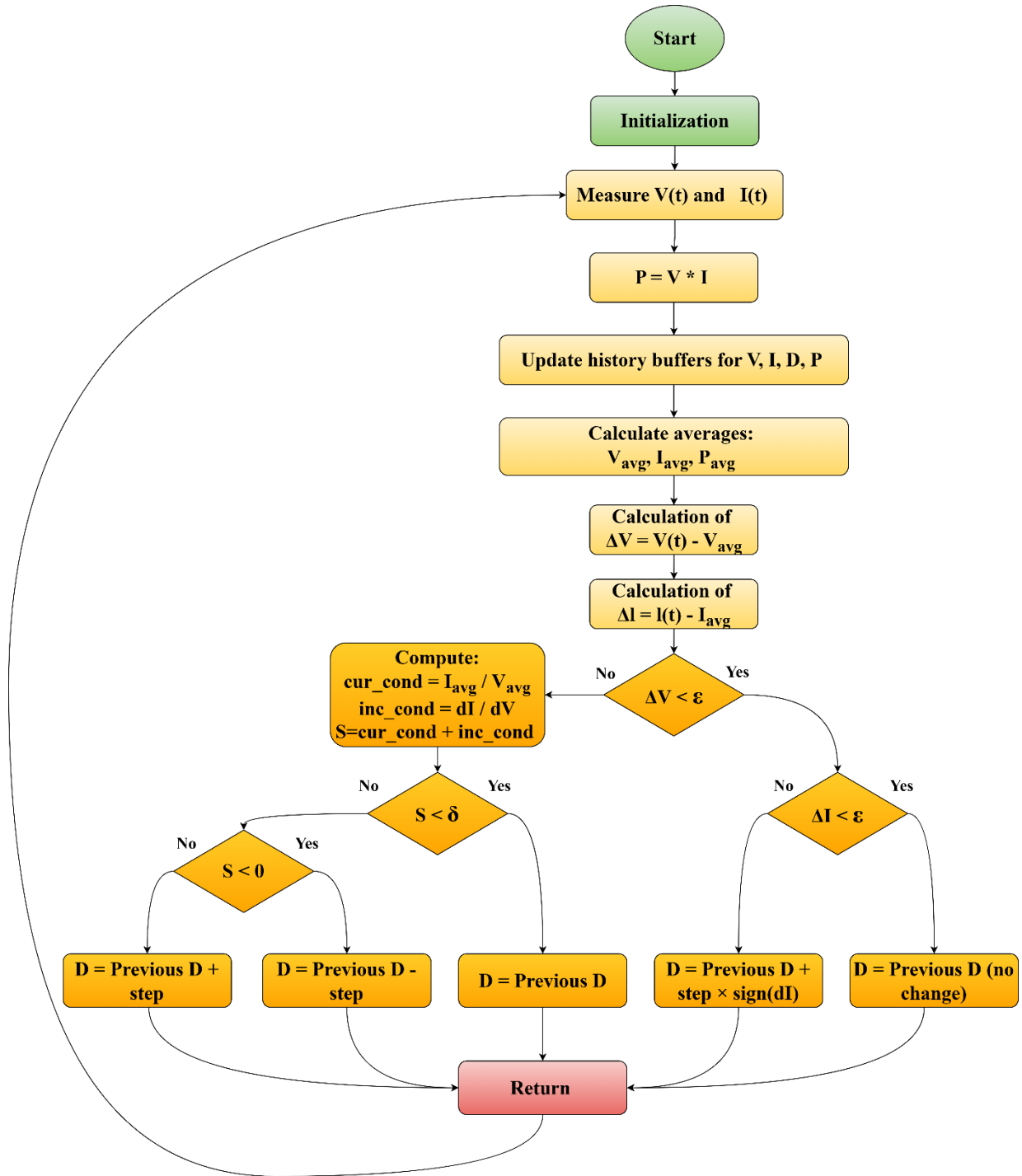


Fig 6. Improved Incremental Conductance MPPT algorithm flowchart.

As shown in Fig 6, the flowchart outlines the sequential process of the proposed ImprovedINC algorithm. A key innovation of this method lies in its decision-making condition which checks whether the absolute value of the sum of incremental and average conductance is within a small threshold. If the condition is satisfied, the system is deemed to be at or very close to the MPP and no modification is applied to the duty cycle. If not, the controller modifies the duty cycle by increasing or decreasing it based on the system's position relative to the MPP on the power-voltage curve. This logic avoids unnecessary oscillations around the MPP and improves the stability of power output. Additionally, the algorithm includes anti-windup protection by limiting the duty cycle between predefined minimum and maximum values. This prevents control saturation and further enhances system robustness. The use of a fixed step size also simplifies the implementation while ensuring predictable and consistent control behavior.

5. RESULTS AND DISCUSSIONS

In order to analyze the performance of the MPPT approaches, simulation studies were conducted under different environmental scenarios. The analysis focuses on comparing the effectiveness of the P&O, conventional INC, and the newly developed ImprovedINC methods in tracking the MPP under different solar irradiance (SI) levels. The results provide insights into power output behavior, duty cycle variation, and system stability, highlighting the strengths and limitations of each algorithm. The following analysis examines the dynamic response of the three algorithms to changes in SI and temperature, offering a comprehensive assessment of their tracking accuracy, adaptability, and robustness under real-world operating conditions.

The simulation is conducted under a fixed temperature of 25°C while varying the SI levels as $G = [0, 400, 600, 800, 1000, 900, 700]$ W/m². The results, illustrated in Fig 7, compare the tracking capability of P&O, INC, and ImprovedINC MPPT methods in terms of output power and duty cycle variation. The first plot shows the output power response over time, highlighting the ability of all three methods to track the MPP under changing SI conditions. Initially, as SI increases, all algorithms effectively track the MPP, with INC and ImprovedINC demonstrating smoother responses and faster convergence compared to P&O. However, during rapid SI changes (e.g., at $t = 1$ s and $t = 6$ s), P&O exhibits more oscillations around the MPP, while INC performs better and ImprovedINC shows the most stable and consistent response. The second plot presents the duty cycle variation, showing the control response of each MPPT method. The P&O method exhibits more fluctuations, particularly during transient conditions, whereas INC provides a more stable adjustment, and ImprovedINC further enhances this stability with smoother duty cycle transitions. This behavior indicates that ImprovedINC is the most effective in handling dynamic SI changes, leading to superior overall performance in real-world PV applications.

To achieve a more practical evaluation of MPPT techniques, real meteorological data has been utilized in this study. Fig 8 illustrates the variations in solar irradiation and temperature over a full day in the city of Constantine during July. The data was obtained from the NASA POWER database, which provides accurate information on solar resources and atmospheric conditions. The upper graph represents solar irradiation, starting from zero before sunrise, peaking at noon, and gradually decreasing to zero after sunset. Meanwhile, the lower graph depicts temperature variation, following a similar pattern, rising during the day as solar irradiation increases and dropping in the evening as irradiation decreases. These environmental variations in irradiation and temperature will be used to assess the effectiveness of the P&O, INC, and ImprovedINC MPPT techniques under real operating conditions, allowing for a comprehensive evaluation of how each method responds to dynamic changes and its effectiveness in tracking the maximum power point.

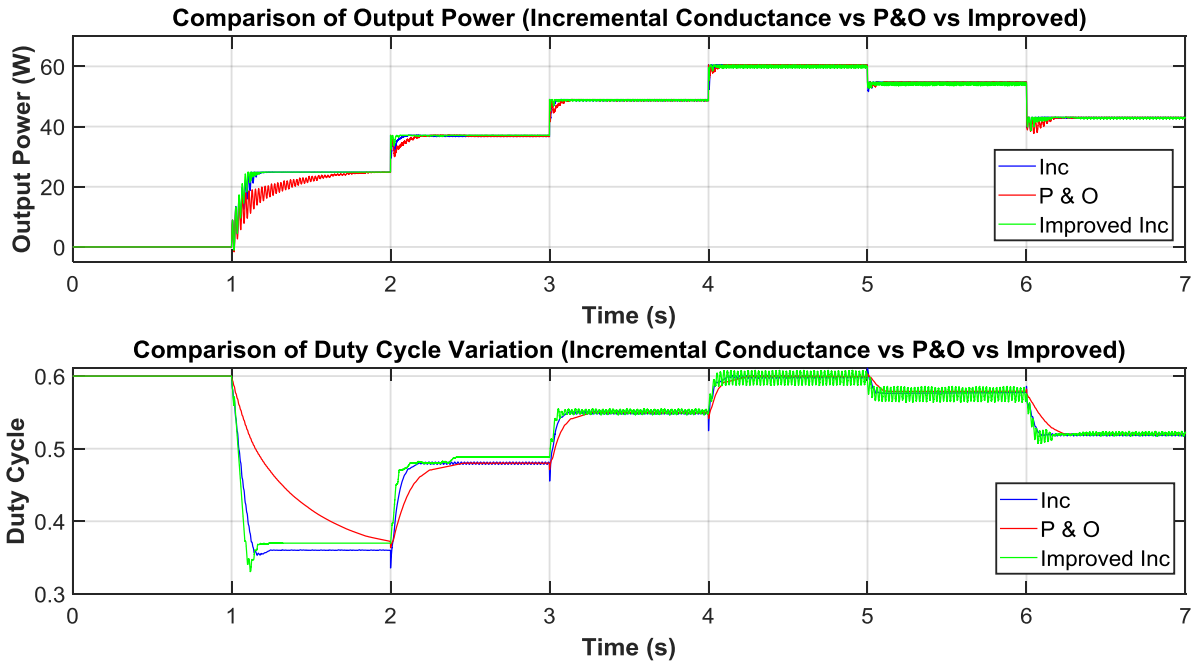


Fig 7. Comparison of output power and duty cycle Inc and P & O MPPT methods.

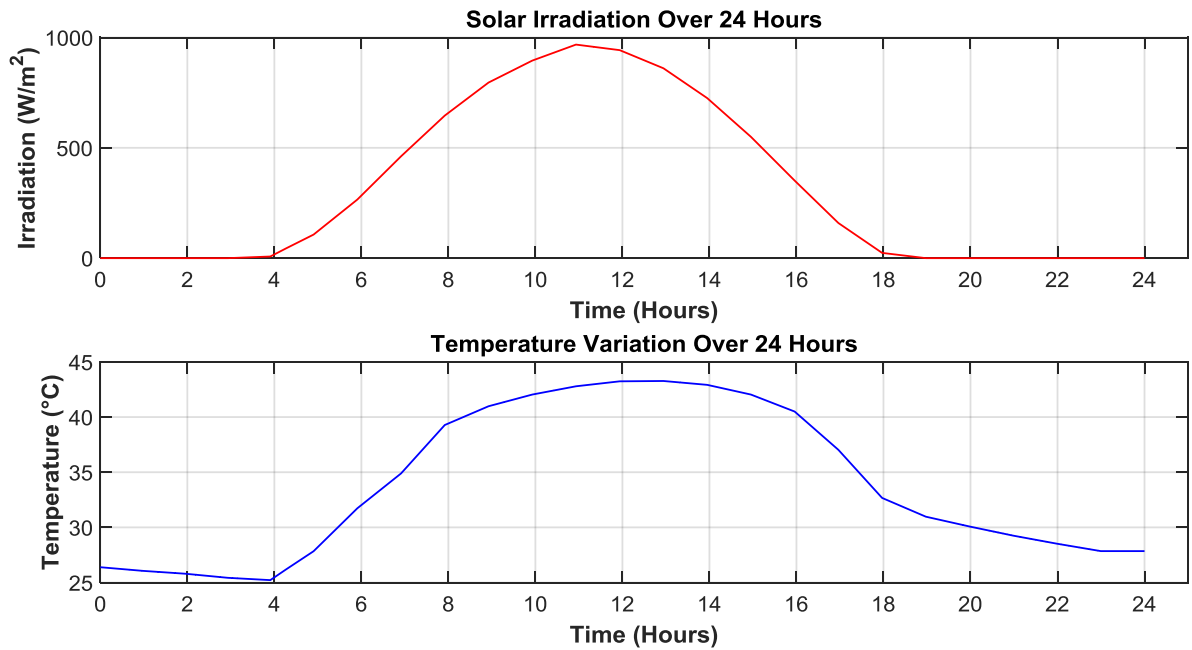


Fig 8. Solar irradiation and temperature variation over 24 hours.

To gain deeper insights into the practical performance of MPPT algorithms, a comparative analysis was conducted using real-world environmental conditions. This evaluation aims to assess how each method responds to dynamic changes in solar irradiation and temperature throughout the day. Fig 9 presents an evaluation study of the effectiveness of three MPPT algorithms (P&O, INC, and ImprovedINC) over a full 24-hour cycle using real data. The upper graph illustrates the output power variations, showing that all algorithms successfully track changes in solar irradiation throughout the day. The power output increases as irradiation rises, stabilizes at peak values during midday, and decreases toward the evening. The lower graph represents the duty cycle variations, reflecting how each algorithm adjusts its operation in response to environmental changes. The results confirm the observations made in the previous

analysis, where power output closely follows irradiation variations, and the duty cycle dynamically adapts to ensure maximum power extraction. However, differences in the behavior of the algorithms become evident, particularly during periods of rapid irradiation changes. The P&O method exhibits more oscillations, especially in the morning and late afternoon, whereas the INC technique provides smoother and more stable tracking. ImprovedINC outperforms both, showing minimal oscillations and maintaining consistent power output and duty cycle regulation even during sudden changes in irradiation. This indicates that while all three algorithms effectively track the maximum power point, ImprovedINC offers superior stability and adaptability under fluctuating conditions. During peak irradiation hours, all methods perform efficiently with minimal deviation, demonstrating their reliability in steady-state conditions. This analysis highlights the influence of real-world environmental fluctuations on MPPT performance and reinforces the importance of selecting an advanced and adaptive algorithm for maximizing PV energy system efficiency.

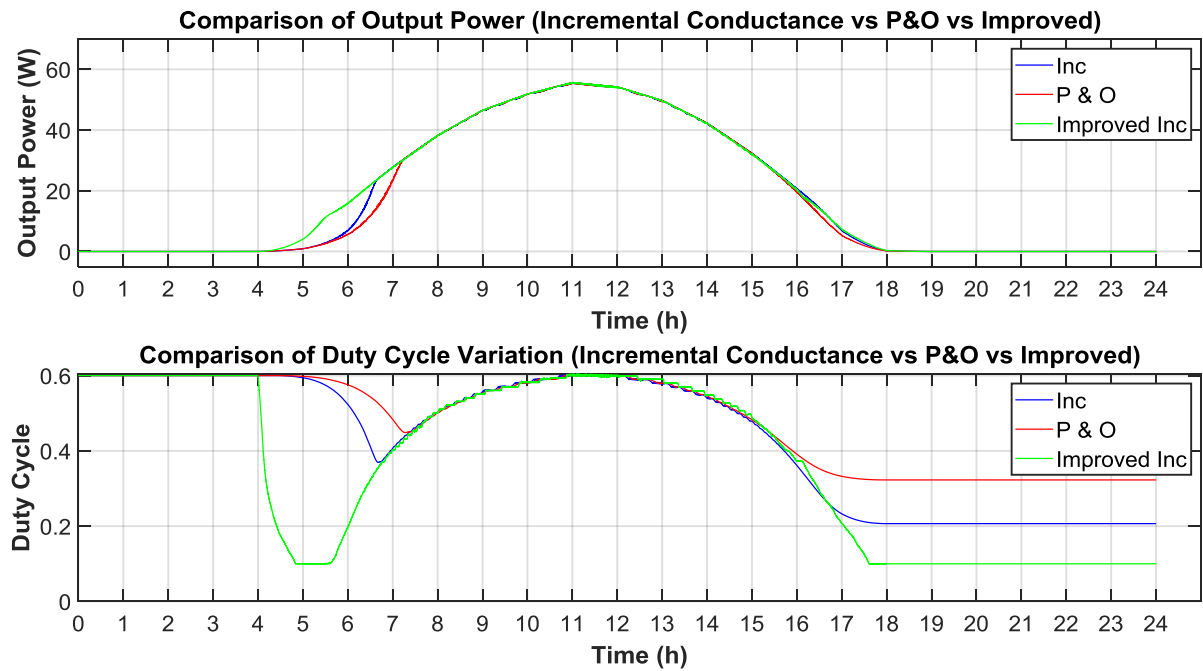


Fig 9. Comparison of MPPT performance over 24 hours.

Based on the obtained results and performance evaluation, Table 1 summarizes the key characteristics of the MPPT methods used in this study, namely P&O, INC, and the proposed ImprovedINC. This extended comparison highlights the differences among the three approaches based on tracking accuracy, response time, computational complexity, and system stability under varying environmental conditions. The inclusion of ImprovedINC offers a clearer perspective on the potential of enhanced algorithms to outperform traditional methods. The table serves as a comprehensive reference for selecting the most suitable MPPT strategy for photovoltaic systems operating in dynamic and real-world environments.

The insights drawn from the comparative results suggest several key observations regarding the behavior of the evaluated MPPT algorithms. First, it is evident that while the P&O method remains attractive Because of its simplicity and low computational demand, it suffers from notable limitations in dynamic scenarios, particularly under rapidly changing irradiance levels. The classical INC algorithm offers a tangible improvement in stability and response time, yet it remains sensitive to noise and lacks mechanisms to effectively suppress steady-state oscillations. In contrast, the ImprovedINC algorithm bridges these gaps by integrating averaged feedback, noise filtering, and bounded duty cycle adjustments, which collectively enhance its adaptability and reliability. Furthermore, the analysis

reveals that even minor architectural refinements in the control logic (such as the introduction of historical data buffers and tolerance thresholds) can lead to significant gains in overall MPPT performance. These enhancements allow the ImprovedINC method to maintain system efficiency and output consistency under a wider variety of practical operating scenarios. The systematic comparison presented in this study underscores the importance of not only algorithm selection but also algorithm design, especially when considering deployment in PV systems operating under non-uniform or highly variable environmental inputs. These observations reinforce the practical need for robust, adaptive MPPT strategies and open the door for further exploration into hybrid methods or AI-assisted control models that can build upon the strengths demonstrated by the ImprovedINC algorithm.

Table 1. Comparative Performance Analysis of MPPT Algorithms: P&O, INC, and ImprovedINC.

Criteria	P&O Algorithm	INC Algorithm	ImprovedINC Algorithm
Tracking Accuracy	Moderate (oscillations around MPP with efficiency of 97.89%)	High (accurate tracking of MPP with efficiency of 99.07%)	Very High (enhanced stability with efficiency of 99.43%)
Response Time	Slower during rapid changes (200–300 ms)	Faster adaptation to changes (100–150 ms)	Fastest convergence (50–100 ms)
Computational Complexity	Low (simple implementation)	Moderate (requires additional calculations)	Moderate (requires averaging and logic control with buffers)
Stability	Less stable under varying conditions	More stable under dynamic conditions	Very stable with minimal oscillations under all tested conditions
Performance in Rapid Irradiance Changes	Poor (delayed response)	Better adaptation to fluctuations	Excellent (real-time adaptation with predictive smoothing)
Steady-State Oscillations	High (power variation +1–4%)	Low (power variation +0.05–1.5%)	Very Low (power variation < 0.9%)
Noise Immunity	Low (sensitive to measurement noise)	Moderate (limited filtering mechanisms)	High (uses historical averaging to suppress noise)
Duty Cycle Control	Direct perturbation, prone to instability	Smoothed but still sensitive to rapid input shifts	Bounded and adaptive with anti-windup protection

6. CONCLUSION

This study investigated the performance of MPPT techniques in PV systems, with a specific focus on the P&O, INC, and the newly developed ImprovedINC algorithms. Through simulations and real-world data analysis, the results demonstrated that while P&O and INC can effectively track the MPP under varying solar irradiance and temperature conditions, the ImprovedINC algorithm consistently outperformed both in terms of tracking accuracy, stability, and response speed. Its integration of historical data, moving average filtering, and bounded duty cycle adjustment allowed it to adapt more efficiently to dynamic environmental fluctuations while minimizing steady-state oscillations.

The findings emphasize the critical role of algorithm design in maximizing energy extraction from PV systems, especially under rapidly changing conditions. The enhanced stability and robustness of ImprovedINC make it a strong candidate for real-time PV control applications. Furthermore, the use of a DC-DC boost converter in conjunction with MPPT algorithms was shown to be essential for maintaining optimal voltage regulation and improving overall system efficiency.

Future work could explore the integration of predictive control models or intelligent systems such as machine learning and fuzzy logic to further enhance the adaptability of MPPT algorithms. In addition, hybrid techniques which comprise the advantages of traditional and advanced methods could be developed to balance simplicity, performance, and computational cost. Finally, experimental validation using full-scale PV systems in different climatic conditions would provide deeper insights into the practical applicability of the ImprovedINC algorithm and support its potential deployment in commercial solar energy solutions.

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