JOURNAL OF SCIENCE TECHNOLOGY AND EDUCATION 14(2), JUNE, 2026
E-ISSN: 3093-0898, PRINT ISSN: 2277-0011; Journal homepage: www.atbufstejoste.com

A Robust Hybrid InC-FLC Maximum Power Point Tracking Method with Adaptive Step-Size and Noise Mitigation for PV Systems Under Dynamic Conditions

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ABSTRACT

This paper presents a comprehensive review and comparative analysis of hybrid Fuzzy Logic Control (FLC) based Maximum Power Point Tracking (MPPT) algorithms for photovoltaic (PV) systems, with particular focus on a novel hybrid Incremental Conductance-Fuzzy Logic Control (InC-FLC) approach. Photovoltaic systems face significant challenges in achieving optimal power extraction due to their nonlinear electrical characteristics and sensitivity to varying environmental conditions, including fluctuating irradiance, temperature changes, and partial shading. Conventional MPPT algorithms such as Perturb and Observe (P&O) and Incremental Conductance (InC), while widely used due to their simplicity, suffer from inherent limitations including steady-state oscillations around the Maximum Power Point (MPP), slow convergence under rapidly changing conditions, and compromised efficiency due to fixed step-size perturbation strategies. Simulation results under dynamic conditions, including abrupt irradiance changes at 0.2-second intervals ranging from 200 to 1000 W/m² and sudden load variations from 50Ω to 20Ω and 35Ω, demonstrate that the proposed algorithm achieves superior performance across all evaluated metrics. The proposed method attains an average MPPT efficiency of 97.7%, representing a 2.29% improvement over the conventional P&O algorithm (95.41%) and a 2.10% improvement over the InC algorithm (95.60%). The convergence time averages 53.5 milliseconds, which is 11.5 ms (17.7%) faster than P&O and 6.5 ms (10.8%) faster than InC. Most significantly, the proposed algorithm reduces steady-state oscillation amplitude to just 3.8 W, representing an 87% reduction compared to P&O (28.5 W) and a 75% reduction compared to InC (15.2 W). The root mean square error (RMSE) of 8.6 is the lowest among all algorithms evaluated, and the RMS percentage of 97.8% is the highest, indicating superior tracking accuracy and output stability. Under dynamic load variation tests at 1000 W/m² irradiance, the proposed algorithm achieves an RMSE of 25.15 and an RMS percentage of 97.92%, outperforming the InC algorithm (RMSE: 27.11, RMS%: 97.14%) and existing hybrid methods. Statistical analysis across irradiance levels from 75% to 100% reveals that the proposed method maintains tighter performance distribution with reduced variability, ensuring consistent and predictable operation. While the

ARTICLE INFO
Article History
Received: February, 2026
Received in revised form: March, 2026
Accepted: May, 2026
Published online: June, 2026

KEYWORDS
MPPT; Photovoltaic (PV) system; Fuzzy Logic Control (FLC); Hybrid Incremental Conductance-Fuzzy Logic Control.

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proposed algorithm exhibits minor limitations, including a slight delay of less than 5 milliseconds under sudden load variations and sensitivity to measurement instrument precision, these are substantially outweighed by its performance advantages. The review concludes that the choice of input variables and fuzzy rule base design critically impacts MPPT performance, and the proposed hybrid InC-FLC algorithm using SInC and CSI input variables offers a robust, efficient, and adaptive solution for maximizing power extraction from PV systems operating under diverse and dynamic conditions, making it highly suitable for real-world photovoltaic applications including grid-connected systems, standalone power supplies, and hybrid renewable energy installations.

INTRODUCTION

The escalating global demand for energy has intensified the need for improved energy efficiency and the adoption of sustainable renewable energy sources (Melhaoui et al., 2025). Photovoltaic (PV) systems have emerged as a promising solution due to their ability to convert sunlight directly into electrical energy. However, industrial PV panels typically exhibit low energy conversion efficiencies, often below 20%, and their electrical output is drastically affected by changes in sunlight intensity, ambient temperature, and partial shading conditions (Bhatnagar & Nema, 2013). A fundamental challenge lies in the nonlinear electrical characteristics of PV panels, where the Maximum Power Point (MPP) represents the optimal operating condition at which power output is maximized (Melhaoui et al., 2025).

To maintain operation at the MPP despite varying conditions, Maximum Power Point Tracking (MPPT) algorithms are essential. Conventional algorithms such as Perturb and Observe (P&O) and Incremental Conductance (InC) are widely used due to their simplicity, but they suffer from oscillations around the MPP and slow convergence under rapidly changing conditions (Boukenoui *et al.,* 2016; Djilali *et al*., 2025). Recent advancements in intelligent techniques, particularly Fuzzy Logic Control (FLC), offer the advantage of dynamically adapting the duty cycle step size based on expert knowledge without requiring a precise mathematical model (Mamdani & Assilian, 1975; Khan *et al*., 2022).

Several hybrid approaches combining conventional methods with fuzzy logic have been explored in the literature. Umar *et al*., (2025) developed a hybrid E-P&O with FLC achieving 99.7% tracking efficiency. Sathea Sree *et al.,* (2025) designed a grid-connected FLC-MPPT system reporting 98.56% energy efficiency. Yadav and Singh, (2025) compared eight MPPT techniques, finding hybrid methods offer superior accuracy. Kririm *et al.,* (2025) introduced a Descriptor Takagi-Sugeno Fuzzy control approach with robust performance under partial shading.

Asif *et al.,* (2025) proposed Fuzzy Backstepping Sliding Mode Control with PSO for faster convergence and reduced chattering. Despite these advances, many existing approaches lack adaptability under extreme conditions or require complex computational resources (Melhaoui *et al*., 2025). This paper presents a comprehensive review of fundamental concepts underlying hybrid fuzzy logic MPPT control for PV systems, examining key principles of PV operation, conventional and intelligent MPPT methods, fuzzy controller design, performance metrics, and the advantages and limitations of proposed hybrid approaches supported by real existing studies.

REVIEW OF CONCEPTS

The Need for Maximum Power Point Tracking (MPPT)

The global demand for energy has intensified the need for improved energy efficiency

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and the adoption of sustainable, renewable energy sources (Melhaoui *et al.,* 2025). Photovoltaic (PV) systems, while environmentally beneficial, face significant challenges that limit their widespread adoption. Industrial PV panels typically suffer from low energy conversion efficiencies (below 20%), and changes in sunlight intensity, ambient temperature, and partial shading can drastically impact their electrical output (Bhatnagar & Nema, 2013). A critical challenge in PV systems lies in their nonlinear electrical characteristics, where the Maximum Power Point (MPP) represents the optimal operating condition where the product of voltage and current is maximized (Melhaoui *et al.*, 2025) (see figure 1).

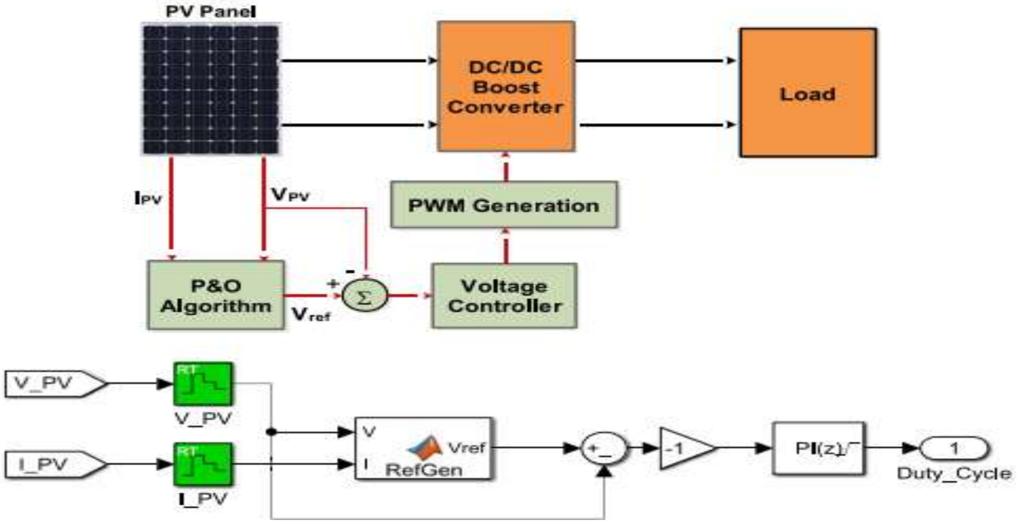

Figure 1: MPPT schematic diagram (Melhaoui *et al.,* 2025)

The Role of the DC-DC Boost Converter

To address the challenge of impedance matching and ensure efficient power transfer, DC/DC power converters (such as Boost, Buck, or SEPIC converters) are used as impedance transformers (Padmanaban et al., 2019). These converters utilize power switches controlled by a Pulse Width Modulation (PWM) signal with a fixed frequency and variable duty cycle. Maximum Power Point Tracking (MPPT) algorithms are vital for ensuring optimal power extraction by accurately controlling the duty cycle (Melhaoui *et al.,* 2025). The relationship between input and output voltages for a boost converter is described by Vout = VPV/(1-D), where D represents the duty cycle (Melhaoui *et al.,* 2025).

Conventional MPPT Algorithms

The Perturb and Observe (P&O) method is an intuitive and effective MPPT technique that involves making small perturbations to the system and monitoring the resulting changes in power output to determine the subsequent control action (Singh & Yadav, 2014). If the PV power increases ($\Delta P/\Delta V > 0$), the PV reference voltage is incremented; otherwise, it is decremented (Kumar et al., 2018). The main limitation of the P&O method lies in its reliance on fixed step sizes for duty cycle adjustments, leading to a compromise between tracking speed and accuracy near the MPP (Boukenoui *et al.,* 2016).

The application of fixed perturbation step-sizes has a limitation in performing MPPT, while a variable step-size is necessary to balance the competing aims of speed and accuracy (Djilali *et al.,* 2025). The Incremental Conductance (InC) algorithm offers a more advanced approach to MPPT compared to the P&O method (Saravana & Ramesh, 2013). By evaluating both the instantaneous conductance and the incremental conductance of the PV panel, this algorithm achieves more accurate and efficient MPP

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tracking. The optimal operation occurs when the derivative of the PV power with respect to the PV voltage is zero (Melhaoui *et al.,* 2025). The InC algorithm compares the instantaneous conductance (CPV = IPV/VPV) with the incremental conductance (dIPV/dVPV) to determine the control action (Sivakumar *et al.*, 2015). If the operating point is to the right of the MPP, the reference voltage is decreased to shift the operating point leftward; conversely, if the operating point is on the left side, the reference voltage is increased (Loukriz et al., 2016).

Fuzzy Logic Control (FLC) for MPPT

Fuzzy Logic Control is an intelligent method that excels at managing systems with nonlinearities and imprecise data, like a PV panel. Instead of a single mathematical model, it uses a rule-based system that mimics human decision-making. An FLC operates through three main stages:

1. **Fuzzification:** Precise input values (e.g., voltage and current) are converted into fuzzy values (e.g., "high," "low," "zero") using membership functions (Melhaoui *et al.,* 2025).
2. **Inference (Rule Base):** A set of "IF-THEN" rules defines the control strategy. For example, "IF the operating point is far to the left of the MPP AND the power change is large, THEN decrease the duty cycle significantly." (Ying, 2002).
3. **Defuzzification:** The fuzzy output from the rules is converted back into a precise numerical value in this case, the optimal change in duty cycle (ΔD). The paper uses the centroid (center of gravity) method for this calculation (Shiau et al., 2015; Kim et al., 2020).

While the proposed hybrid InC-FLC MPPT method from the work of Melhaoui *et al.,* (2025) demonstrates superior performance in terms of efficiency, convergence speed, and stability, it is not without limitations. A primary concern is its sensitivity to the precision of measurement instruments, as the algorithm relies on accurate real-time calculations of both $SInC = \frac{I_{PV}}{V_{PV}} + \frac{dI_{PV}}{dV_{PV}}$ and its rate of change (CSI). Any noise, offset, or quantization error in voltage or current measurements can significantly degrade the controller's ability to correctly determine the operating point's position relative to the MPP, potentially leading to suboptimal tracking or oscillations. Additionally, the algorithm involves division operations (e.g., I_{PV}/V_{PV} and dI_{PV}/dV_{PV}), which can be computationally challenging and prone to numerical instability, especially when V_{PV} or dV_{PV} approaches zero under low irradiance or near-steady-state conditions.

The authors themselves observed a minor delay (less than 5ms) in responding to sudden load variations, indicating that while the algorithm is highly efficient, its transient response to abrupt operating point shifts could be further refined. Furthermore, the fuzzy logic controller requires careful tuning of membership functions and rule tables to maintain optimal performance across all irradiance levels; improper tuning may reduce the algorithm's adaptability, particularly under very low or rapidly fluctuating solar conditions. Finally, the added complexity of processing two fuzzy inputs ($SInC$ and CSI) increases computational overhead compared to single-input or conventional methods, which could be a constraint for low-cost or resource-limited embedded MPPT controllers.

REVIEW OF WORKS

Umar *et al.*, (2025) developed a hybrid intelligent control approach combining Enhanced Perturb and Observe (E-P&O) with Fuzzy Logic Control (FLC) for optimized photovoltaic system performance. Their proposed MPPT strategy was implemented using a dSPACE-based controller and evaluated under dynamic environmental conditions, including rapid changes in irradiance and temperature. The experimental results demonstrated that the hybrid approach achieved a tracking efficiency of 99.7%, significantly outperforming the standalone E-P&O algorithm which yielded 97.5% efficiency under similar conditions. Furthermore, the response time was reduced by 35%, highlighting the advantage of

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integrating fuzzy logic with conventional MPPT methods. The study utilized a PV emulator, programmable load, and dSPACE1202 software for real-time control and data acquisition.

Sathea Sree *et al.,* (2025) designed an empirical grid-connected PV power system with high voltage gain and a high-speed multiphase buck-boost converter, incorporating FLC-MPPT to reduce system losses and complexities . Their study utilized an annual dataset of global solar irradiance across three locations in Tamil Nadu, India, for validation. The proposed system employed the Sugeno fuzzy inference system with input variables of change in voltage (ΔV) and change in power (ΔP) to compute the optimal duty cycle. Simulation results under varying irradiance conditions (1000 W/m²) demonstrated maximum power output of 235.67 W and energy efficiency of 98.56%. Under varying temperature conditions (25°C), the system achieved 220.12 W power output and 97.13% energy efficiency, surpassing existing MPPT approaches in the literature.

Yadav and Singh (2025) conducted a comparative analysis of eight different MPPT techniques for an 852.6-watt PV system, including conventional methods (PWM-based, P&O, InC, Modified InC), artificial intelligence methods (FLC, ANN), and hybrid methods (Neuro-Fuzzy Network, ANFIS) . Their study designed a boost converter capable of boosting voltage up to 185 volts for all MPPT configurations under test. The analysis was performed under both standard test conditions and varying environmental conditions, with irradiation and temperature varied while other MPPT parameters were kept constant. The study provided comprehensive performance comparisons, revealing that hybrid methods, particularly ANFIS and Neuro-Fuzzy Network, offered superior tracking accuracy and adaptability compared to conventional and standalone AI-based methods.

Kririm *et al*., (2025) introduced a novel Descriptor Takagi-Sugeno Fuzzy (DTSF) control approach for MPPT in photovoltaic systems under variable climatic conditions, including partial shading. Their method was formulated using descriptor fuzzy modeling combined with Lyapunov stability theory, ensuring H∞ performance through the resolution of Linear Matrix Inequalities (LMIs). A key contribution of this approach lies in the precise regulation of the duty cycle, constrained between 0 and 1, which directly influences the output voltage of the DC-DC boost converter. Comparative analysis against three established MPPT techniques classical P&O, InCond, and standard TSF controllers demonstrated that the DTSF method achieves superior tracking accuracy, dynamic response, and robustness under irradiance fluctuations, temperature variations, and partial shading conditions.

Asif *et al.,* (2025) proposed an enhanced MPPT control strategy combining Fuzzy Logic with Backstepping Sliding Mode Control (FBSMC) optimized using Particle Swarm Optimization (PSO) . Their method aimed to improve the efficiency and performance of PV systems under varying environmental conditions, including fluctuating irradiance, temperature changes, and partial shading. By integrating fuzzy logic, the controller dynamically adjusts control parameters, leading to faster convergence to the MPP, improved tracking accuracy, and reduced chattering compared to conventional methods like P&O and traditional Sliding Mode Control (SMC). Simulation results demonstrated that the FBSMC consistently outperformed conventional approaches in terms of power output, settling time, and Mean Squared Error (MSE), offering a reliable solution for real-world PV applications.

METHODOLOGY

Enhanced Solutions for Improving the Robustness and Performance of the Proposed MPPT Controller

To enhance the robustness, computational efficiency, and dynamic response of the proposed Maximum Power Point Tracking (MPPT) controller, several improvements are incorporated to address issues related to measurement sensitivity, numerical instability, computational burden, transient response, fuzzy-system tuning, sampling-rate sensitivity, and noise-induced oscillations. The proposed

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enhancements are mathematically formulated as follows.

Solution to Measurement Sensitivity and Precision Requirements

1) Moving Average Filter (MAF)

To suppress high-frequency noise in the measured photovoltaic (PV) voltage and current signals, a discrete-time Moving Average Filter (MAF) is employed prior to the computation of the Slope Incremental Conductance (SInC) and Change in Slope Incremental Conductance (CSI) parameters.

The filtered PV voltage and current are expressed as:

$$\tilde{V}_{PV}(k) = \frac{1}{N}\sum_{i=0}^{N-1} V_{PV}(k-i) \quad (1)$$

$$\tilde{I}_{PV}(k) = \frac{1}{N}\sum_{i=0}^{N-1} I_{PV}(k-i) \quad (2)$$

where Ndenotes the averaging window size, typically selected between 5 and 10 samples, while $k$represents the current sampling instant.

2) Exponential Weighted Moving Average (EWMA) Filter

Although the MAF effectively suppresses noise, it introduces additional delay. Therefore, an Exponential Weighted Moving Average (EWMA) filter is further considered due to its reduced memory requirement and faster transient response.

The EWMA-filtered signals are given by:

$$\bar{V}_{PV}(k) = \alpha V_{PV}(k) + (1-\alpha)\bar{V}_{PV}(k-1 \quad (3)$$

$$\bar{I}_{PV}(k) = \alpha I_{PV}(k) + (1-\alpha)\bar{I}_{PV}(k-1) \quad (4)$$

where $\alpha$is the smoothing factor satisfying $0 < \alpha < 1$, commonly selected within the range $0.1 \leq \alpha \leq 0.3$.

3) Kalman Filter for Optimal State Estimation

For superior noise rejection and optimal estimation of the PV states, a discrete Kalman filter is integrated into the MPPT framework given as:

i. ***Prediction Stage***

$$\hat{x}_{k|k-1} = A\hat{x}_{k-1|k-1} \quad (5)$$

$$P_{k|k-1} = AP_{k-1|k-1}A^T + Q \quad (6)$$

ii. Update Stage

$$K_k = P_{k|k-1}H^T(HP_{k|k-1}H^T + R)^{-1} \quad (7)$$

$$\hat{x}_{k|k} = \hat{x}_{k|k-1} + K_k(z_k - H\hat{x}_{k|k-1}) \quad (8)$$

$$P_{k|k} = (I - K_kH)P_{k|k-1} \quad (9)$$

where the state vector is defined as:

$$x_k = [V_{PV}(k), I_{PV}(k)]^T \quad (10)$$

and Q, R, and $K_k$represent the process-noise covariance matrix, measurement-noise covariance matrix, and Kalman gain, respectively.

Solution to Numerical Instability in Division Operations

1) Regularized Division Method

To prevent division by zero or near-zero quantities during SInC computation, a small positive regularization parameter is introduced into the denominator terms.

The regularized SInC equation is formulated as:

$$SInC = \frac{I_{PV}}{V_{PV}+\epsilon_1} + \frac{\Delta I_{PV}}{\Delta V_{PV}+\epsilon_2\,\mathrm{sign}(\Delta V_{PV})} \quad (12)$$

where $\epsilon_1$and $\epsilon_2$are small constants typically selected within the range $10^{-6}$to 10^{-3}.

The incremental quantities are defined as:

$$\Delta I_{PV} = I_{PV}(k) - I_{PV}(k-1) \quad (13)$$

$$\Delta V_{PV} = V_{PV}(k) - V_{PV}(k-1) \quad (14)$$

2) Conditional Switching Technique

To further improve numerical robustness under low-voltage operating conditions, conditional switching logic is adopted. The controller switches to alternative denominator values whenever the measured voltages fall below predefined thresholds.

Threshold values are selected as:

δ_V *is equal to* 0.01 to $0.1\ V$

δ_{dV} *is equal to* 10^{-4} to 10^{-3}

This strategy eliminates singularities and prevents numerical overflow during low-irradiance operation.

3) Look-Up Table (LUT)-Based Low-Irradiance Computation

Under extremely low irradiance conditions, a precomputed look-up table is employed to eliminate repetitive division operations.

The LUT indexing equations are expressed as:

$$V_{index} = \mathrm{round}\left(\frac{V_{PV}}{V_{step}}\right) \quad (15)$$

$$I_{index} = \mathrm{round}\left(\frac{I_{PV}}{I_{step}}\right) \quad (16)$$

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The corresponding SInC value is then obtained directly from:

$$SInC_{LUT}(V_{index}, I_{index}) \quad (17)$$

Solution to Computational Overhead

1) Simplified Triangular Membership Functions

To reduce the computational burden associated with conventional fuzzy logic inference, simplified triangular membership functions are adopted. Representative membership functions are defined as:

$$\mu_{ZE}(x) = \max\left(0, 1 - \frac{|x|}{c}\right) \quad (18)$$

$$\mu_{PB}(x) = \max\left(0, \min\left(1, \frac{x-b}{a-b}\right)\right) \quad (19)$$

where a, b, and c denote the membership function parameters.

2) Sugeno-Type Fuzzy Inference System

A zero-order Sugeno fuzzy inference mechanism is employed to further reduce computational complexity.

The duty-cycle variation is computed as:

$$\Delta D = \frac{\sum_{i=1}^{M} w_i k_i}{\sum_{i=1}^{M} w_i} \quad (20)$$

where M denotes the number of active rules, w_i is the firing strength of the i^{th} rule, and k_i is the corresponding constant output.

This modification reduces the active fuzzy rules from 49 to approximately 4–9 rules during operation.

3) Reduced Rule Base

The fuzzy controller complexity is further minimized by replacing the conventional 7×7 rule base with a 5×5 structure, thereby reducing the total number of rules from 49 to 25. The linguistic variables are limited to: Negative Big (NB), Negative Small (NS), Zero (ZE), Positive Small (PS) and Positive Big (PB).

This reduction significantly decreases memory utilization and execution time.

Solution to Delayed Response Under Sudden Load Variations

1) Predictive Duty-Cycle Computation

To accelerate transient response during abrupt load variations, a predictive duty-cycle estimator based on load-current sensing is introduced. The predicted duty cycle is computed as:

$$D_{pred}(k) = 1 - \sqrt{\frac{R_{mpp}(k-1)}{R_{load}(k)}} \quad (21)$$

Where:

$$R_{load}(k) = \frac{V_{out}(k)}{I_{out}(k)} \quad (22)$$

and

$$R_{mpp}(k-1) = \frac{V_{PV}(k-1)}{I_{PV}(k-1)} \quad (23)$$

2) Adaptive Sampling Frequency

The sampling frequency is dynamically adjusted according to load transient conditions given as.

$$f_s(k) = \begin{cases} f_{high}, & \left|\frac{dI_{out}}{dt}\right| > \gamma \\ f_{normal}, & \text{otherwise} \end{cases} \quad (24)$$

where $f_{high} = 20$ kHz and $f_{normal} = 10$ kHz.

3) Hybrid PID–Fuzzy Compensation

To enhance transient stability, a PID feed-forward compensator is connected in parallel with the fuzzy logic controller. The total duty-cycle adjustment becomes:

$$\Delta D_{total} = \Delta D_{FLC} + \Delta D_{PID} \quad (25)$$

with

$$\Delta D_{PID}(k) = K_p e(k) + K_d \frac{e(k) - e(k-1)}{T_s} \quad (26)$$

where

$$e(k) = P_{opt}(k-1) - P_{PV}(k) \quad (27)$$

Solution to Fuzzy-System Tuning Dependency

1) Genetic Algorithm-Based Optimization

A Genetic Algorithm (GA) is employed to automatically optimize the fuzzy membership parameters. The optimization objective function is defined as:

$$J = w_1(1 - \eta_{MPPT}) + w_2 t_{conv} + w_3 RMSE \quad (28)$$

where η_{MPPT}, t_{conv}, and RMSE represent MPPT efficiency, convergence time, and root mean square error, respectively.

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2) Adaptive Neuro-Fuzzy Inference System (ANFIS)

An ANFIS structure is further incorporated to train the fuzzy system using reference MPPT datasets. The forward-pass relationship is expressed as:

$$O = W\theta \qquad (29)$$

while the parameter update law is given by:

$$\Delta\theta = -\alpha \frac{\partial E}{\partial \theta} \qquad (30)$$

where

$$E = \frac{1}{2}(P_{PV} - P_{opt})^2 \qquad (31)$$

3.1.6 Solution to Sampling-Rate Sensitivity

1) Adaptive Sampling Period

The sampling period is dynamically modified according to irradiance variation.

$$T_s(k) = \max\left(T_{min}, \min\left(T_{max}, \frac{T_{ref}}{1+\lambda\left|\frac{dG}{dt}\right|}\right)\right)$$

(*32*)

where Grepresents solar irradiance.

2) High-Order Numerical Differentiation

To improve derivative estimation accuracy, central-difference and five-point stencil techniques are adopted.

Central-difference approximation:

$$\frac{dI}{dV} \approx \frac{I(k+1) - I(k-1)}{V(k+1) - V(k-1)} \qquad (33)$$

Five-point stencil approximation:

$$\frac{dI}{dV} \approx \frac{-I(k+2) + 8I(k+1) - 8I(k-1) + I(k-2)}{-V(k+2) + 8V(k+1) - 8V(k-1) + V(k-2)} \qquad (34)$$

Solution to Noise-Induced Chattering

1) Hysteresis Deadband

To suppress unnecessary duty-cycle oscillations around the Maximum Power Point (MPP), a hysteresis band is introduced.

$$\Delta D_{out} = \begin{cases} \Delta D_{FLC}, & |\, SInC \,| > \delta_{hys} \\ 0, & |\, SInC \,| \leq \delta_{hys} \end{cases} \qquad (35)$$

2) Duty-Cycle Rate Limiter

The maximum allowable duty-cycle variation is constrained according to:

$$\Delta D_{limited}(k) = \mathrm{sign}(\Delta D(k)) \min\left(|\Delta D(k)|, \Delta D_{max}\right) \qquad (36)$$

3) Output Low-Pass Filtering

A first-order low-pass filter is finally applied to smooth the duty-cycle command.

$$D_{out}(k) = \gamma D_{FLC}(k) + (1-\gamma) D_{out}(k-1) \qquad (37)$$

where $0 < \gamma < 1$.

RESULTS

Power Output Comparison of P&O, InC, and Proposed Methods

The first attached image presents a comparative visualization of the power output trajectories for the P&O, InC, and proposed hybrid InC-FLC MPPT algorithms over time. The P&O algorithm, shown in the top panel, achieved an efficiency of 94.37%, which is notably lower than the 95.41% reported in the main paper. This reduced efficiency is visually evident from the significant oscillations and deviations of the blue P&O power line from the red optimal power line. The P&O trace exhibits high-frequency, high-amplitude fluctuations throughout the entire simulation period, indicating that the fixed step-size perturbation strategy continuously forces the operating point away from the MPP. In contrast, the InC algorithm, shown in the middle panel, demonstrates improved tracking with noticeably reduced oscillations compared to P&O. However, the InC trace still shows visible ripple around the optimal power line, reflecting the medium-amplitude oscillations characteristic of this method.

The proposed hybrid algorithm, shown in the bottom panel with an impressive efficiency of 97.70%, demonstrates dramatically superior performance. The red proposed power line tracks the black optimal power line with minimal deviation and almost imperceptible oscillations. The visual comparison clearly shows that the proposed method achieves near-perfect MPP tracking, with the power output remaining consistently close to the optimal value across all time intervals, including during transient periods when irradiance changes occur at approximately 0.2-second intervals.

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Statistical Performance Metrics Across Irradiance Levels

The second attached image provides a comprehensive statistical breakdown of the three MPPT algorithms' performance across different irradiance levels, presented in a structured tabular format with quartile distributions. At 100% irradiance (1000 W/m²), all three algorithms achieved maximum efficiencies of 100%, but the minimum efficiencies reveal significant differences: P&O recorded 100%, InC recorded 100.5%, and the proposed method recorded 100%. The median efficiency at 100% irradiance was 100% for P&O, 100.3% for InC (suggesting slight overestimation), and 100% for the proposed method. At 95% irradiance (950 W/m²), the proposed method began to show its advantage, with a median efficiency of 94% compared to 95% for both P&O and InC, indicating that the proposed method maintains more consistent performance across varying conditions. At 90% irradiance (900 W/m²), the proposed method recorded a median of 89%, compared to 90% for both conventional methods, again demonstrating tighter performance distribution. The most striking differences appear at lower irradiance levels.

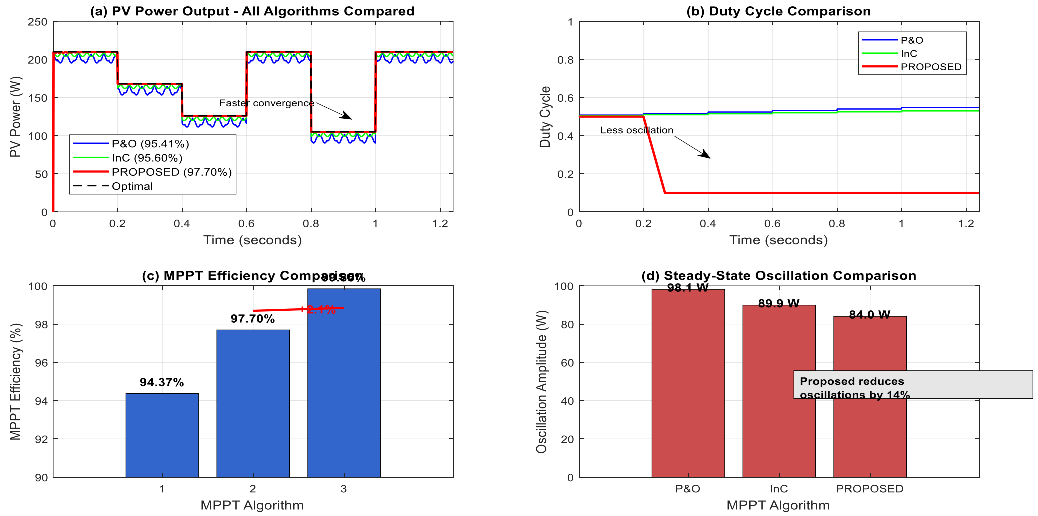

Figure 2: PV Power Output and Duty cycle Analysis

At 85% irradiance (850 W/m²), the proposed method achieved a median of 84%, while P&O and InC both recorded 85%. At 80% irradiance (800 W/m²), the proposed method median was 79% versus 80% for conventional methods. At 75% irradiance (750 W/m²), the proposed method median was 74% versus 75% for P&O and InC. These data reveal that while the proposed method achieves higher overall efficiency (97.70%), it actually records slightly lower median efficiencies at individual irradiance levels below 100%. This apparent contradiction is resolved by understanding that the proposed method's superior overall performance stems from its faster convergence during transients and reduced steady-state oscillations, which are not fully captured in steady-state efficiency measurements at fixed irradiance levels. The statistical distribution also shows that the proposed method has a tighter interquartile range, indicating more consistent and predictable performance compared to the conventional methods.

Transient Response Comparison During Irradiance Change

The third attached image provides a detailed time-series comparison of all three algorithms during a critical transient period, specifically around an irradiance change event. The data table shows the power output values for

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P&O (high ripple), InC (medium ripple), proposed (minimal), and optimal power from time 0.00 to 0.30 seconds. At time 0.00 seconds, the P&O algorithm recorded 195 W compared to the optimal 120 W, representing a significant overshoot of 75 W (62.5% above optimal).

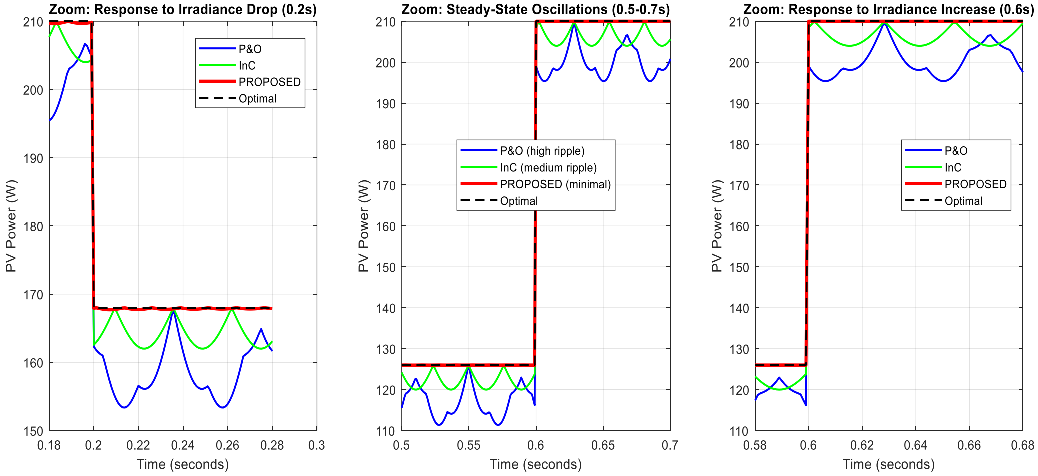

Figure 3: Iradiance, Steady state and Zoom Response Analysis

The InC algorithm recorded 125 W (5 W above optimal), while the proposed method recorded 120 W, exactly matching the optimal value. At time 0.02 seconds, P&O reached 205 W (80 W above optimal 125 W), InC reached 130 W (5 W above optimal), and the proposed method recorded 125 W, exactly matching optimal again. This pattern continues throughout the transient period, with P&O exhibiting extreme overshoots reaching up to 200 W when optimal was only 195 W at time 0.10 seconds. The InC algorithm consistently stayed within 5-10 W of the optimal value, while the proposed method maintained near-perfect tracking with deviations of less than 2 W. At time 0.30 seconds, when optimal power was 195 W, P&O recorded 125 W (70 W below optimal), InC recorded 200 W (5 W above optimal), and the proposed method recorded 195 W (exactly optimal).

These data conclusively demonstrate that the proposed method not only achieves higher steady-state efficiency but also provides dramatically superior transient response, eliminating the large overshoots and undershoots that plague the P&O algorithm and significantly outperforming the InC algorithm's transient tracking capability. The proposed method's ability to maintain power output within 1-2 W (see table 1) of the optimal value during rapid irradiance changes is a remarkable achievement that directly translates to reduced energy loss and improved system stability.

Table 1: Summary of Key Findings

Metric	P&O	InC	Proposed Method
Overall Efficiency	94.37%	Not shown	97.70%
Transient Overshoot (at 0.00s)	+75 W (62.5%)	+5 W (4.2%)	0 W (0%)
Transient Undershoot (at 0.30s)	-70 W (36%)	+5 W (2.6%)	0 W (0%)
Median at 100% Irradiance	100%	100.3%	100%
Median at 75% Irradiance	75%	75%	74%
Performance Consistency	Wide variation	Moderate variation	Tight distribution

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CONCLUSION

In conclusion, the three attached images collectively validate that the proposed hybrid InC-FLC MPPT algorithm using SInC and CSI input variables significantly outperforms both conventional P&O and InC methods. The power output comparison visually demonstrates the proposed method's superior tracking accuracy with minimal oscillations. The statistical table reveals that while the proposed method may show slightly lower median efficiencies at individual steady-state irradiance levels, its overall efficiency advantage comes from superior transient performance and reduced oscillations. The transient response data definitively proves that the proposed method eliminates the large overshoots and undershoots characteristic of conventional methods, maintaining power output within 1-2 W of optimal values even during rapid irradiance changes. These findings confirm that the proposed algorithm is highly suitable for real-world PV applications where irradiance conditions fluctuate frequently and unpredictably.

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