



Research Article

A Hybrid Controller for Tolerating Climatic Variations Affecting PV Systems

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ABSTRACT

The article presents a hybrid controller based on the Incremental Conductance (Inc-Cond) and Interval Type-2 Fuzzy Logic (IT-2FL) algorithms as a Maximum Power Point Tracker (MPPT). The controller employs a three-phase Interleaved Boost Converter (IBC), which operates based on the pulses generated by the MPPT to ensure that the photovoltaic (PV) system operates at or near its Maximum Power Point (MPP). IT-2FL enhances the tracking process by applying rule fuzzification and managing uncertainties in response to significant fluctuations in climatic conditions. The proposed controller demonstrates precise and rapid convergence to the MPP, outperforming the individual application of both component methods, as well as traditional fuzzy logic, even when combined with Inc-Cond. The fault tolerance of the proposed tracker is validated through MATLAB simulations under various operational scenarios, evaluating response time, MPP tracking accuracy, efficiency, and other parameters.

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1. INTRODUCTION

Due to the rise in energy consumption, non-renewable energy sources are no longer considered sustainable. As a result, alternative energy sources have been developed, particularly photovoltaic energy, which involves converting sunlight into electrical energy using photovoltaic (PV) systems (Ishrat et al., 2024). Despite their numerous advantages, PV systems face challenges in achieving maximum power output when climatic variables like temperature and solar radiation fluctuate. To overcome this challenge, Maximum Power Point Tracking (MPPT) techniques are utilized (Esrām & Chapman, 2007), such as Perturb and Observe (P&O) (Abouobaida & EL Beid, 2017; Femia et al., 2005), Incremental Conductance (Inc-Cond) (Mei et al., 2011; Safari & Mekhilef, 2011), measurements of open-circuit voltage (FCO) and short-circuit current (FCC) (Mutoh et al., 2006), hill climbing (HC) (Abouobaida & EL Beid, 2017), and Fuzzy Logic Control (FLC) (Kececioglu et al., 2020; Kwan & Wu, 2016; Rajesh & Mabel, 2014) for its two types: Type-1 Fuzzy Logic Controller (T-1FLC) and Type-2 Fuzzy Logic Controller (T-2FLC) with its alternative approach, known as Interval Type-2 Fuzzy Logic Controller (IT-2FLC), Particle Swarm Optimization (PSO) (Letting et al., 2012), and others. MPPT methods optimize the PV system's production by regulating its operating point to keep it functioning at or near the Maximum Power Point (MPP), ensuring peak efficiency (Kececioglu et al., 2020; Magaji et al., 2022). However, under complex operating conditions such as partial shading, classical MPPT techniques struggle to track the Global Maximum Power Point (GMPP) (Basha et al., 2024). In such scenarios, the current-voltage (I-

V) and power-voltage (P-V) curves of the PV system exhibit multiple Local Maximum Power Points (LMPP) (Worku et al., 2023). As a result, the MPPT system may have difficulty distinguishing the true global MPP from these local points, leading to inefficiency if the MPPT stabilizes at a lower power point (Gupta et al., 2024). Therefore, there is a need for a system capable of dynamically determining the maximum power point and managing these uncertain conditions.

The tracking of the optimal power point in photovoltaic systems is a critical research area that has garnered significant attention in recent years. Various techniques have been compared, developed, and evaluated across different studies, highlighting their respective advantages and limitations. According to (Gupta et al., 2024; Kassmi et al., 2007), it was concluded that incorporating MPPT regulation in photovoltaic systems significantly enhances their efficiency. The findings demonstrated that, even with fluctuations in climate patterns and load variations, the system under MPPT control was able to rapidly adapt and reach favorable operating conditions within a short period. (Abouobaida & Abouelmahjoub, 2021) examined a photovoltaic system that utilizes a three-phase interleaved boost converter and tested two classical MPPT methods: Incremental Conductance (Inc-Cond) and Perturb & Observe (P&O). The results showed that while both methods exhibited similar detection times for the maximum power point (MPP), Inc-Cond outperformed P&O in reducing fluctuations. In a study by (Abbes et al., 2014), a thorough analysis was conducted comparing various MPPT methods including Inc-Cond, P&O, FCO, FCC, and FLC using the Simulink tool. The findings indicated that FLC demonstrated superior performance compared to the other methods, due to its

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adaptability in dealing with nonlinearities and complex relationships between the input and output data. This made FLC especially suitable for enhancing energy conversion in a PV system under various conditions. To determine the best structure for optimal MPP tracking under varying irradiance, (Rajavel & Rathina Prabha, 2021) introduced T-1FLC combined with various converters such as buck-boost, boost, and buck converters. Their approach resulted in maximum power extraction from the system. In (Abdellatif et al., 2021; Bouchafaa et al., 2011), researchers focused on comparing traditional control techniques (Inc-Cond and P&O) with T-1FLC. Their experimental and simulation results demonstrated the shortcomings of the classical methods in MPP tracking, while T-1FLC achieved excellent performance with short response times, minimal fluctuations, and greater flexibility under changing conditions. The findings that were published in (Bogaraj et al., 2014; Derbeli et al., 2023) further validated the efficacy of this approach. In (Bataineh, 2019), author discussed two hybrid methods for optimizing MPP tracking in PV systems, combining the strengths of P&O and Inc-Cond with T-1FLC. These hybrid methods proved effective and accurate in locating the global maximum power point, even under varying climatic conditions. This was further confirmed by performance indicators in (Arulmurugan, 2020). (El Khateb et al., 2013) introduced a method using a single-ended primary inductor converter and T-2FLC to achieve MPPT in standalone PV systems. This method outperformed traditional techniques by effectively handling noisy and rapidly changing irradiation levels. (Magaji et al., 2022) also proposed this controller to monitor the energy output of a PV array and compared it with Inc-Cond, P&O, and PSO. Their work showed that the T-2FLC strategy was superior in tracking and quickly converging to the MPP, though the comparison was limited to classical algorithms without testing against other intelligent ones. (Meryem et al., 2019) evaluated the performance of three MPPT methods, including Inc-Cond, T-1FLC, and T-2FLC, for PV systems. Their results demonstrated that T-2FLC provided the best efficiency, whereas Inc-Cond showed limitations in stability and response time. (Kececioğlu et al., 2020) introduced a hybrid MPPT, AIC-IT2-TSK FLC, combined with a basic DC-DC converter structure. Their tests showed that this approach outperformed traditional MPPT methods in robustness, tracking speed, and minimizing generation costs. (Basha et al., 2024; Kumar & Balakrishna, 2024; Pamuk, 2023; Worku et al., 2023) focused on MPPT under partial shading conditions in PV systems, presenting various techniques for tracking the global maximum power point (GMPP). While each technique demonstrated both strengths and weaknesses, the developed hybrid approaches consistently outperformed the simpler methods.

Upon reviewing the literature on fuzzy logic controller-based MPPT approaches, it was observed that while these methods have shown notable benefits, the combination of the Incremental Conductance (Inc-Cond) algorithm and the Interval Type-2 Fuzzy Logic Controller (IT-2FLC) has not yet been explored. This study introduces a novel hybrid approach that integrates the IT-2FLC with the Inc-Cond algorithm (referred to as Inc-Cond-based IT-2FLC) and employs an Interleaved Boost Converter (IBC) to enhance MPPT tracking performance. The hybrid method is evaluated against several MPPT algorithms, including Inc-Cond, Type-1 Fuzzy Logic Controller (T-1FLC), IT-2FLC, and Inc-Cond-based T-1FLC, under both uniform and partial shading conditions.

The primary contributions of this study are summarized as follows:

- **Proposing an Adaptive Hybrid Controller:** A new MPPT strategy combining the Inc-Cond algorithm with IT-2FLC is introduced to optimize performance.
- **Integration of IT-2FLC and Inc-Cond:** IT-2FLC generates an instantaneous reference voltage, which is utilized by the Inc-Cond block for precise and efficient tracking of the MPP.
- **Adjustment of Duty Cycle:** The hybrid controller effectively adjusts the specific duty cycle of the IBC converter to achieve optimal results.
- **Enhanced Performance in Complex Conditions:** The hybrid approach demonstrates significant improvements in MPPT tracking, particularly under challenging scenarios such as partial shading.
- **Robustness and Efficiency:** The proposed system exhibits exceptional flexibility in handling abnormal situations, achieving higher efficiency and precision while minimizing fluctuations compared to other methods.

The performance assessment focuses on key factors such as response time, ripple occurrence near the MPP, efficiency, and accuracy. The structure of this study is organized as follows:

1. **Section 2:** Provides an overview of the selected photovoltaic (PV) system.
2. **Section 3:** Explains the utilized methods and presents detailed descriptions of each MPPT approach.
3. **Section 4:** Displays simulation results conducted in the Simulink environment and provides a comprehensive analysis.
4. **Section 5:** Concludes the study with key findings and insights.

2. OVERVIEW OF PV SYSTEM

The photovoltaic power system components are illustrated in Figure 1. The system consists of several elements, including a PV panel serving as an energy source, a DC-DC boost converter intended to increase panel's voltage output so that it can produce the highest amount of power feasible, and a resistive load (Abbes et al., 2014; Benyoucef et al., 2022; Bogaraj et al., 2014).

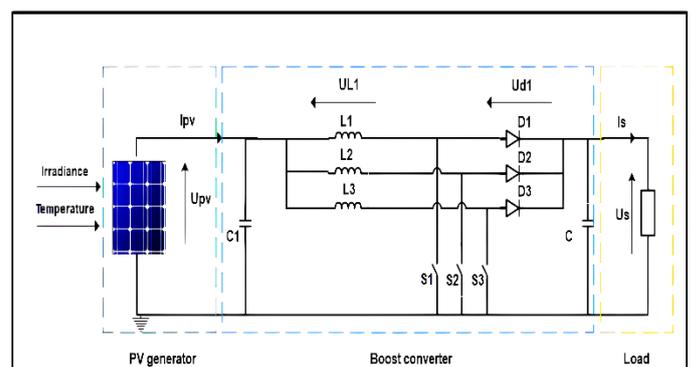


Figure 1. Photovoltaic system

2.1. Photovoltaic generator

Table 1 presents the PV panel parameters at 25°C and 1000 W/m²

Table 1. Photovoltaic panel properties.

Properties	Values
Parallel strings N _p	40
String's linked series N _s	10
Module cells (N _{cell})	60
Maximal power P _{max} (W)	85000
MPP current I _{mp} (A)	293.15
MPP voltage V _{mp} (V)	290

The electrical properties of photovoltaic (PV) panels are highly sensitive to changes in temperature (T) and irradiance (G), as highlighted by (Bouchafaa et al., 2011). Figure 2 depicts the influence of fluctuating irradiance levels (from 800 to 1000 W/m²) on current-voltage (I-V) and power-voltage (P-V) characteristics while maintaining a constant temperature of 25°C. It is evident that power output increases with higher irradiance levels, primarily due to a rise in current, while the voltage remains stable around 290V. Conversely, Figure 3 illustrates the effect of temperature variations (ranging from 10°C to 45°C at a constant irradiance of 1000 W/m²), showing significant changes in voltage while the current remains nearly constant.

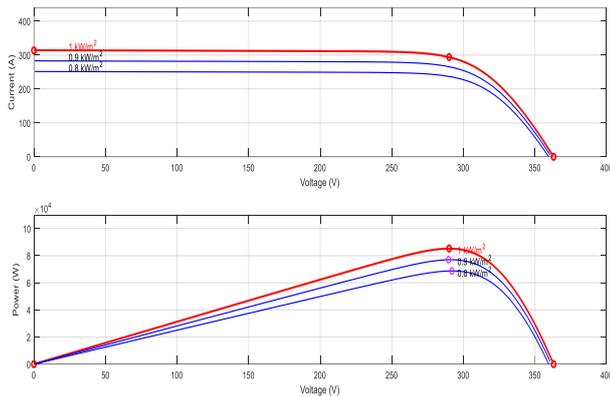


Figure 2. Current-Voltage (I-V) and Power-Voltage (P-V) during constant temperature and varying radiation

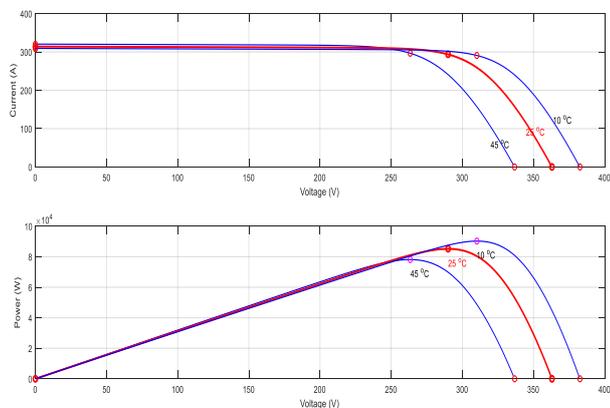


Figure 3. Current-Voltage (I-V) and Power-Voltage (P-V) during constant radiation and varying temperatures.

By examining photovoltaic (PV) curves, the Maximum Power Point (MPP) can be identified as the peak energy output of the system. However, the MPP is highly sensitive to fluctuating weather conditions. To ensure that the PV system

operates at or near the MPP despite dynamic environmental changes, Maximum Power Point Tracking (MPPT) control methods are employed (Abouobaida & Abouelmahjoub, 2021). These methods work by adjusting the duty cycle to an optimal level and transmitting it to the converter, thereby enhancing the energy output of the system (Hamed & El-Moghany, 2012; Kassmi et al., 2007).

Nevertheless, MPPT methods face challenges under complex conditions, such as partial shading or rapidly fluctuating irradiance levels (Pamuk, 2023). During partial shading conditions (PSC), multiple local maxima appear on the power-voltage (P-V) curve of the PV generator (Worku et al., 2023). This phenomenon occurs because shaded sections generate less current than unshaded ones, altering the generator's current-voltage (I-V) characteristics. Conventional tracking algorithms, such as Incremental Conductance (Inc-Cond), may fail to locate the Global Maximum Power Point (GMPP), instead converging to a local maximum, which results in reduced system efficiency (Gupta et al., 2024). To address this, more sophisticated algorithms must be developed to overcome the limitations of basic methods and accurately track the GMPP under shading conditions.

Figure 4 demonstrates the impact of partial shading conditions (PSC) on the P-V curve in comparison to Standard Test Conditions (STC), where the temperature is maintained at 25°C and irradiance at 1000 W/m².

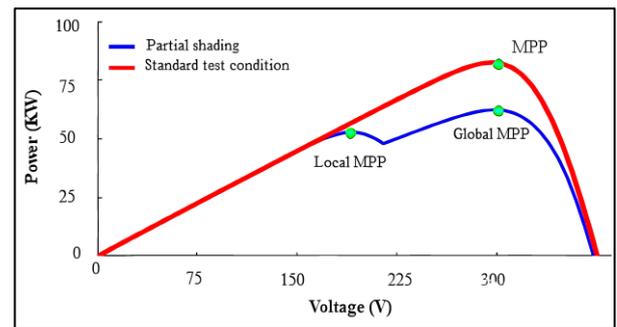


Figure 4. Impact of partial shading condition on the power-voltage curve.

2.2. Interleaved Boost Converter

The Interleaved Boost Converter (IBC) plays a key role in enabling the photovoltaic (PV) system to adapt to varying load conditions, thereby maximizing energy extraction (Rajavel & Rathina Prabha, 2021). Moreover, the interleaving technique integrated within the IBC minimizes current ripples, ensuring smoother operation. The IBC is designed with three identical phases, each comprising switches (S1 to S3), implemented as Insulated Gate Bipolar Transistors (IGBTs), and antiparallel diodes (D1 to D3), as illustrated in Figure 1. The specific operational parameters of the IBC are detailed in Table 2 (Abbes et al., 2014; Abouobaida & Abouelmahjoub, 2021).

Table 2. IBC parameter

Properties	Values
f (Hz)	20000
C (F)	0.00047
C ₁ (F)	0.0033
L ₁ =L ₂ =L ₃ (H)	0.002

The IBC model was described thoroughly by (Abouobaida & Abouelmahjoub, 2021) and is presented as follows:

$$\dot{U}_{PV} = \frac{I_{PV}}{C_1} - \frac{1}{C_1} [M]^T [I_L] \quad (1)$$

$$[i_L] = \frac{U_{PV} - U_S}{L} [M] + \frac{U_S}{L} [\alpha] \quad (2)$$

$$[i_L] = \begin{bmatrix} I_{L1} \\ I_{L2} \\ I_{L3} \end{bmatrix}; [\alpha] = \begin{bmatrix} \alpha_1 \\ \alpha_2 \\ \alpha_3 \end{bmatrix}; [M] = \begin{bmatrix} 1 \\ 1 \\ 1 \end{bmatrix} \quad (3)$$

where:

- U_S and U_{PV} : output and input voltages.
- I_S and I_{PV} : output and input currents
- I_{L1} to I_{L3} : inductor currents.
- α_1 to α_3 : control inputs duty cycles.

3. SUGGESTED STRATEGY

Zadeh introduced a novel concept known as Type-2 Fuzzy Sets (T-2FS) in 1974, representing a significant generalization of traditional Type-1 Fuzzy Sets (T-1FS) (Zadeh, 1974). Unlike T-1FS, which is limited in addressing uncertainties, T-2FS offers enhanced capability for managing imprecision. The T-1FS is defined by a two-dimensional membership function (MF), as represented in Equation (4), where each input x has a specific membership value $\mu_A(x)$ that lies within the range of 0 to 1 (Kececioglu et al., 2020; Mendel, 2007).

$$A = \{(x, \mu_A(x)) | \forall x \in X, \mu_A(x) \in [0,1]\} \quad (4)$$

In scenarios where the membership degree of a variable is uncertain, T-2FS is a more suitable choice (Kececioglu et al., 2020). Unlike T-1FS, T-2FS employs a three-dimensional MF, which makes it significantly more effective in handling cases with high levels of uncertainty in both input and output variables. This distinction provides T-2FS with superior performance in complex situations (Kececioglu et al., 2020; Liang & Mendel, 2000; Mendel, 2007). The formal representation of T-2FS is given in Equation (5):

$$\tilde{A} = \{(x, u, \mu_{\tilde{A}}(x, u)) | \forall x \in X, \forall u \in J_x \subseteq [0,1], \mu_{\tilde{A}}(x, u) \in [0,1]\} \quad (5)$$

Here, each element in the domain has a primary membership value x in the set X , a secondary membership value u in the range J_x , and a secondary grade $\mu_{\tilde{A}}(x, u)$. The visual distinction between T-1FS and T-2FS is demonstrated in Figure 5, highlighting the additional dimension of uncertainty captured by T-2FS.

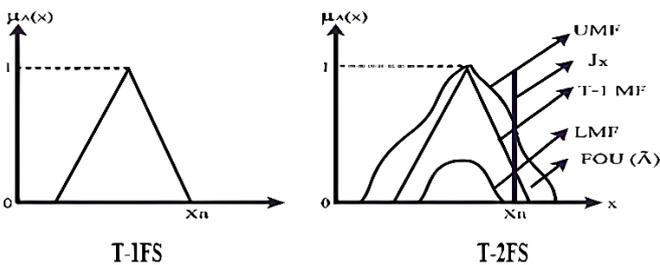


Figure 5. Triangular Type-1 and Type-2 fuzzy sets differences.

The membership functions (MFs) in Type-2 Fuzzy Logic Controllers (T-2FLC) include Upper (UMF) and Lower (LMF) Membership Functions, each represented by Type-1 fuzzy sets. The region between these two functions is referred to as the Footprint of Uncertainty (FOU), which accounts for the third dimension that enhances precision compared to traditional fuzzy logic. To simplify computations, Interval Type-2 Fuzzy Sets (IT-2FS) are introduced, where $\mu_{\tilde{A}}(x, u)$ is set to 1, reducing the computational burden without significantly compromising performance (Kececioglu et al., 2020; Meryem et al., 2019).

While fuzzy logic enhances the adaptability and accuracy of Maximum Power Point Tracking (MPPT), it can sometimes be computationally demanding and slower to converge (Basha et al., 2024). Conversely, traditional MPPT methods, such as the Incremental-Conductance (Inc-Cond) algorithm, are simpler and faster, making them common in practical applications. However, their accuracy diminishes under complex scenarios, such as partial shading or rapidly changing environmental conditions (Pamuk, 2023). To address these limitations, this study proposes a hybrid control system combining IT-2FLC and the Inc-Cond algorithm.

The Inc-Cond algorithm determines the operating point relative to the Maximum Power Point (MPP) by continuously comparing the conductance (I/V) with its rate of change (dI/dV). If $-dI/I/V < dI/dV$, the duty cycle decreases; if $-I/V > dI/dV$, it increases (Abbes et al., 2014; Bouchafaa et al., 2011; Rezoug et al., 2018). Meanwhile, the IT-2FLC generates a reference voltage, which is then utilized by the Inc-Cond block to refine the MPP tracking process. This hybrid approach capitalizes on the strengths of both methods, improving overall control efficiency.

In this system, the Inc-Cond algorithm serves as the primary input generator for the fuzzy logic controller. It monitors variations in power and voltage, producing key parameters for inputs into the fuzzy logic system. The IT-2FLC processes these inputs, leveraging its ability to handle uncertainties, nonlinearities, and challenging conditions such as partial shading (Kumar & Balakrishna, 2024). The fuzzy logic system outputs a refined tracking direction and optimized duty cycle. This optimized output is subsequently fed back into the Inc-Cond system, which adjusts the PV system's operating point more effectively toward the true MPP. The hybrid system combines the rapid response of Inc-Cond with the precision of fuzzy logic, ensuring reliable performance in both standard and complex environments. This synergy reduces energy losses, enhances tracking accuracy, and delivers dynamic adaptability to environmental changes, significantly improving the efficiency of the photovoltaic system (Bogaraj et al., 2014; Rezoug et al., 2018).

The recommended method diagram is illustrated in Figure 6. The IT-2FLC diagram highlights its resemblance to the T-1FLC, with the primary distinction being the "Output Processing" segment (Mendel, 2007). In this study, the IT-2FLC was implemented using the Sugeno approach, which is particularly suited for applications requiring computational efficiency. The system operates by transforming discrete inputs into fuzzy sets through a fuzzification process. The inputs considered were the changes in power (ΔP_{PV}) and voltage (ΔV_{PV}), while the output generated was the change in reference voltage (ΔV_{ref}). This structured approach ensures accurate adjustments of the photovoltaic system under dynamic conditions, enhancing its performance and adaptability (Altin, 2013).

$$\Delta P = P(k) - P(k - 1) \quad (6)$$

$$\Delta V = V(k) - V(k - 1) \quad (7)$$

$$\Delta V_{ref} = V_{ref}(k) - V_{ref}(k - 1) \quad (8)$$

The IT-2FLC utilizes triangular membership functions that correspond to seven linguistic variables: 'NB' (Negative Big), 'NM' (Negative Medium), 'NS' (Negative Small), 'Z' (Zero Approximately), 'PS' (Positive Small), 'PM' (Positive Medium), and 'PB' (Positive Big) as shown in Figure 7. These

variables effectively capture input variations and provide a structured representation of the system's behavior. During the inference stage, a fuzzy rule base is established, comprising 49 If-Then rules that define the relationships between input and output parameters. These rules, summarized in Table 3, serve as the guiding framework for decision-making under varying conditions. The "Output Processing" phase differentiates the IT-2FLC from its T-1FLC counterpart. This step employs a

type reducer followed by a defuzzifier. The type reducer first converts the Interval Type-2 Fuzzy Set (IT-2FS) into a Type-1 Fuzzy Set (T-1FS). Subsequently, the defuzzifier transforms the T-1FS into crisp, non-fuzzy output values. This two-step process ensures that the controller produces precise outputs while retaining its ability to handle uncertainties effectively. (Liang & Mendel, 2000; Mendel, 2007).

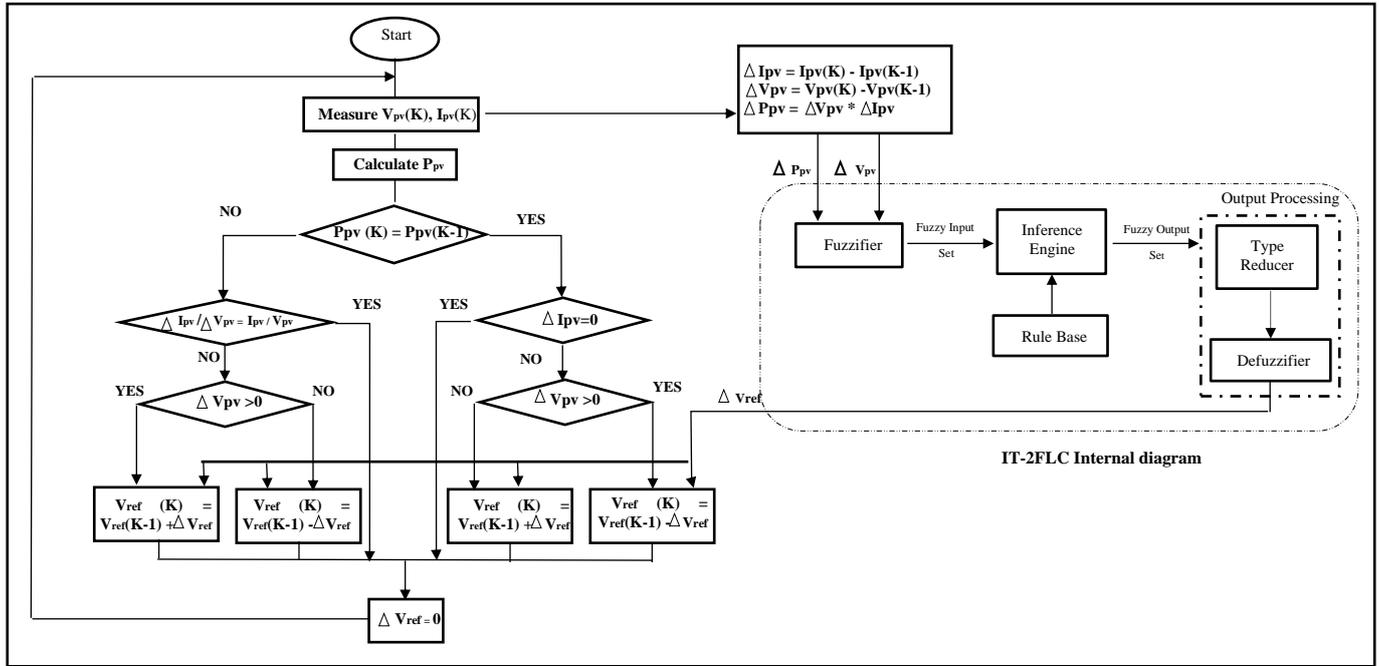


Figure 6. Hybrid algorithm (Inc-Cond-IT-2FLC).

Table 3. Rule base.

ΔV_{ref}	ΔV_{PV}							
	NB	NM	NS	Z	PS	PM	PB	
NB	NL	NL	NM	Z	PM	PL	PL	
NM	NL	NM	NM	Z	PM	PM	PL	
NS	NM	NM	NS	Z	PS	PM	PM	
Z	Z	Z	Z	Z	Z	Z	Z	
PS	PM	PS	PS	Z	NS	NS	NM	
PM	PL	PM	PM	Z	NS	NM	NL	
PB	PL	PL	PM	Z	NM	NM	NL	

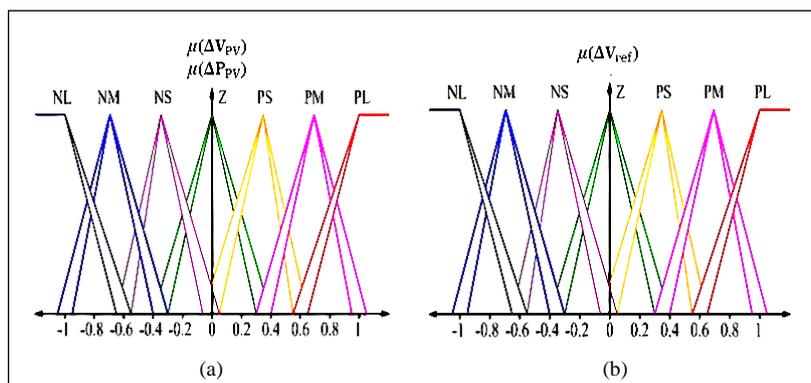


Figure 7. MFs for: (a) input variables and (b) output variable.

In the following section, the simulation results for both the IT-2FLC and the proposed algorithm, which combines the classical Inc-Cond method with IT-2FLC, are presented. The performance of these algorithms will then be compared to the results introduced in (Benyoucef et al., 2022).

4. RESULTS AND DISCUSSION

The PV system examined and the MPPT approaches analyzed were tested through simulations, conducted in two parts. In the first part, the temperature was kept constant at 25°C, while the irradiance varied between 900 and 1000 W/m², as shown in Figure 8. The period during which the irradiation was maintained at 900 W/m² can be interpreted as a uniform shading condition. The results are compared to the approaches suggested by (Benyoucef et al., 2022) based on multiple factors, and their interpretations are also provided. In the study of (Benyoucef et al., 2022), hybrid controllers that combined the strengths of Inc-Cond and P&O with T-1FLC were applied, and their performances were evaluated in the same case study presented in this paper. In the second part of the study, the proposed controller will be evaluated under more complex partial shading conditions to assess its ability to handle uncertain circumstances.

The study will be carried out in two parts:

The first part focuses on uniform shading and time response during rapid climatic variations. It consists of three stages:

- **Stage 1:** Performance evaluation of Inc-Cond, T-1FLC, and IT-2FLC techniques.
- **Stage 2:** Comparison of the proposed hybrid controller with each of its sub-controllers.
- **Stage 3:** Inc-Cond-based IT-2FLC versus Inc-Cond-based T-1FLC.

The second part addresses partial shading and includes three study scenarios.

4.1. Uniform shading

4.1.1. Performance evaluation of Inc-Cond, T-1FLC, and IT-2FLC techniques

In the preliminary stage, the three algorithms — Inc-Cond, T-1FLC, and IT-2FLC — are compared. Figures 9(a) and 9(b) present the progression of PV voltage and PV power of the MPPT methods over the entire simulation domain (0-0.8s), during the change mode and at the irradiance variation point (0.4s), where the irradiance shifts from 900 to 1000 W/m². The results indicate some convergence in processing for the fuzzy logic methods in terms of reduced vibration and faster response speed, compared to the Inc-Cond method. The Inc-Cond method is significantly affected by the variation, causing critical oscillations, particularly near the radiation change point, resulting in a notable loss of energy. Therefore, it can be concluded that the fuzzy logic methods performed better. Among these, IT-2FLC excels.

When the PV panel is irradiated with 900 W/m², it is observed that Inc-Cond exhibits large oscillations. The tracked MPP for Inc-Cond, T-1FLC, and IT-2FLC is determined to be 7.691e⁴ W, 7.693e⁴ W, and 7.742e⁴ W, respectively. After the rapid change in irradiance, the settling time — which refers to the amount of time required for the system to stabilize or reach a steady state after a change in operational conditions — is 0.01s for IT-2FLC, while T-1FLC settles after 0.017s. When the irradiance is increased to 1000 W/m², the panel's performance improves, with the MPP values reaching 8.442e⁴ W, 8.448e⁴ W, and 8.451e⁴ W for Inc-Cond, T-1FLC, and IT-2FLC, respectively.

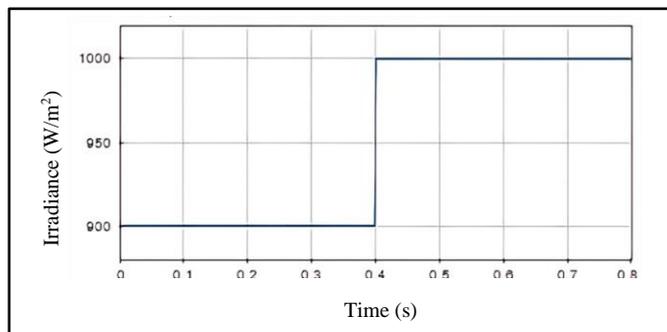


Figure 8. Solar irradiance variation

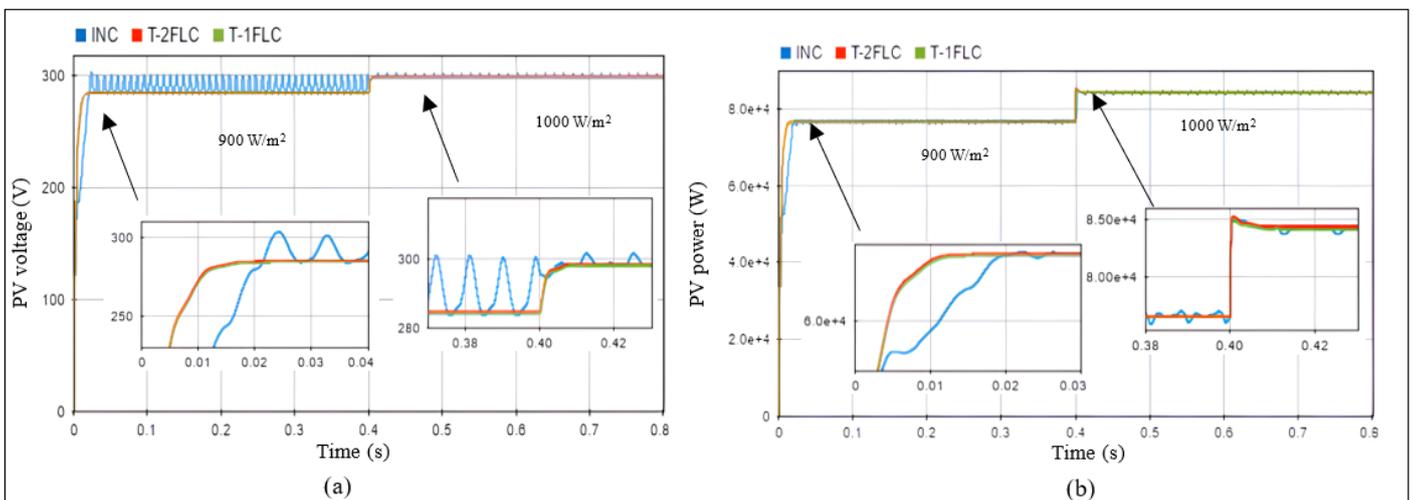


Figure 9. MPPT methods: (a) Photovoltaic voltage and (b) Photovoltaic power.

4.1.2. Contrast of the proposed hybrid controller (INC-IT-2FLC) and each of its sub controllers

In the second stage, the comparison results between standard Inc-Cond algorithm, IT-2FLC and Inc-Cond based IT-2FLC algorithm are presented in Figure 10 (a) and (b). The goal is to assess the performance of these methods under similar meteorological circumstances, concerning photovoltaic voltage (V) and power (P). Simulations show that combining the two methods, rather than using them individually, improved the tracking performance significantly with a faster convergence rate and steadier state compared to standard Inc-Cond, which has considerable fluctuations. Accordingly, there was a power gain of 950 W and an augmented accuracy and efficiency with a percentage of 0.54% and 1.1% respectively, when irradiance is 900 W/m². A power gain of 450 W, as well as increased accuracy with a rate of 0.21% and efficiency by 0.51% is obtained when irradiance is 1000 W/m² as illustrated in Table 4.

4.1.3. Inc-Cond based IT-2FLC vs Inc-Cond based T-1FLC

The last stage of the first part includes a comparison between the outcomes of the Inc-Cond-based IT-2FLC controller suggested in this paper and those of the hybrid controller (Inc-Cond-based T-1FLC) featured in (Benyoucef et al., 2022), as shown in Figure 11. It is concluded that the Inc-Cond-based IT-2FLC has proven its effectiveness in both cases. When the irradiance is 900 W/m², the tracked MPP values are 7.767e4 W for Inc-Cond-based T-1FLC and 7.786e4 W for Inc-Cond-based IT-2FLC, with accuracy values of 90.49% and 91%, and efficiency levels of 91.37% and 91.6%, respectively. When the irradiance is 1000 W/m², the tracked MPP is 8.466e4 W for Inc-Cond-based T-1FLC and 8.487e4 W for Inc-Cond-based IT-2FLC, accuracy is 96.57% for INC-T-1FLC and 96.64% for INC-IT-2FLC, and efficiency is 99.6% for INC-T-1FLC and 99.84% for INC-IT-2FLC, with the settling times shown in Table 4 and Figure 12. One explanation for this is that, unlike T-1FLC, which uses a single fuzzy set for each input variable, IT-2FLC employs two fuzzy sets, allowing it to capture more intricate correlations between the input and output variables. Additionally, IT-2FLC has more parameters to adjust, enhancing its flexibility for adapting to changing environments, making it a more effective tool for online control than T-1FLC. Consequently, when both IT-2FLC and T-1FLC are implemented using the Inc-Cond algorithm, Inc-Cond-based IT-2FLC performs better.

4.2. Partial shading

After demonstrating the effectiveness of the proposed control system in uniform shading and rapid variations in climatic conditions compared to other control systems, this part of the study tests its effectiveness under more challenging conditions, namely partial shading.

A PV system with a power of 2.55e5 W was evaluated through three scenario studies. In each scenario, the results of the proposed system were compared with those of other controllers based on several criteria. The photovoltaic generator consisted of three identical solar panels. Figure 13 illustrates the proposed PV system for this part of the article. Figure 14 represents the different cases to be studied while Figure 15 displays the power versus voltage curves obtained in each case study, the results of which will be analyzed and discussed.

Study Scenario 1: The first scenario evaluates the proposed system under standard test conditions, where the temperature is 25°C and all PV panels are irradiated with 1000 W/m². From the obtained results in Figure 16(a), it is observed that the proposed controller outperforms both Inc-Cond and Inc-T-1FLC, achieving a global MPP of about 2.503e5 W, with an efficiency and accuracy of 98.43% and 97.12%, respectively, as shown in Table 5.

Study Scenario 2: In the second scenario, the system was tested under partial shading conditions, where panel n°1 was exposed to radiation of 1000 W/m², while panels n°2 and n°3 received radiation of 800 W/m². From the energy curve in Figure 15, the appearance of both a global maximum and a local one was observed. This is due to the fact that partially shaded panels generate lower currents. It is concluded that Inc-IT-2FLC presented the best performance, while the traditional Inc-Cond showed lower efficiencies, as proven in Figure 16(b) and Table 5.

Study Scenario 3: In the final scenario, each PV panel was exposed to different radiation levels. Panel n°1, panel n°2, and panel n°3 were irradiated with 900 W/m², 700 W/m², and 400 W/m², respectively. Figure 15 depicts the presence of a global maximum value and two local ones. The obtained results clearly confirm the ability of the proposed controller to manage uncertainties better than the other methods.

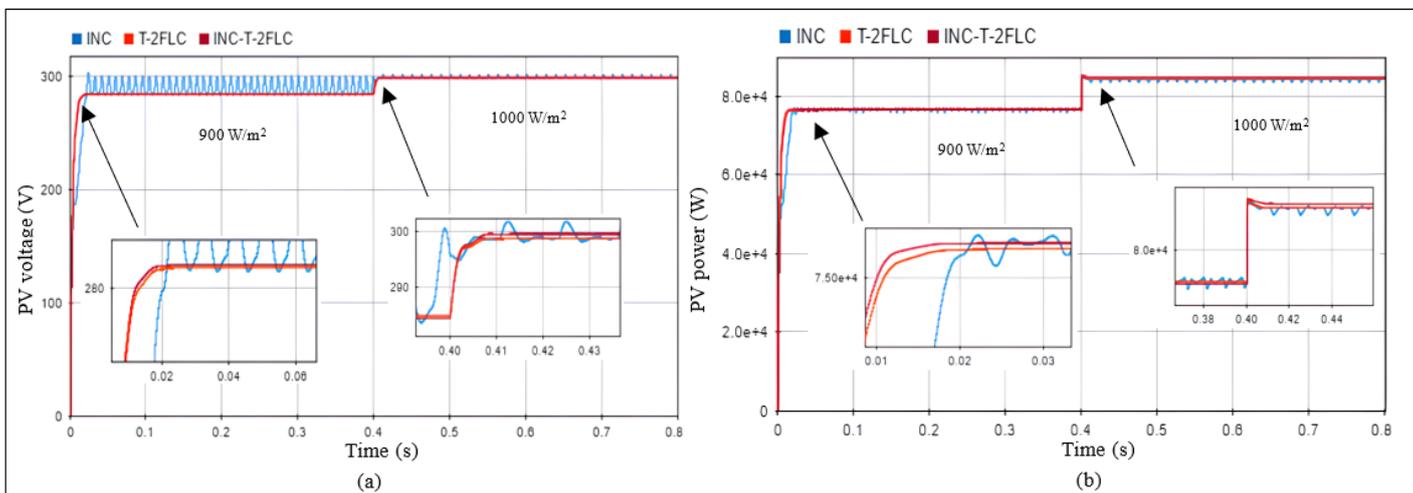


Figure 10. Inc-Cond, IT-2FLC and modified Inc-Cond methods: (a) PV voltage, and (b) PV power.

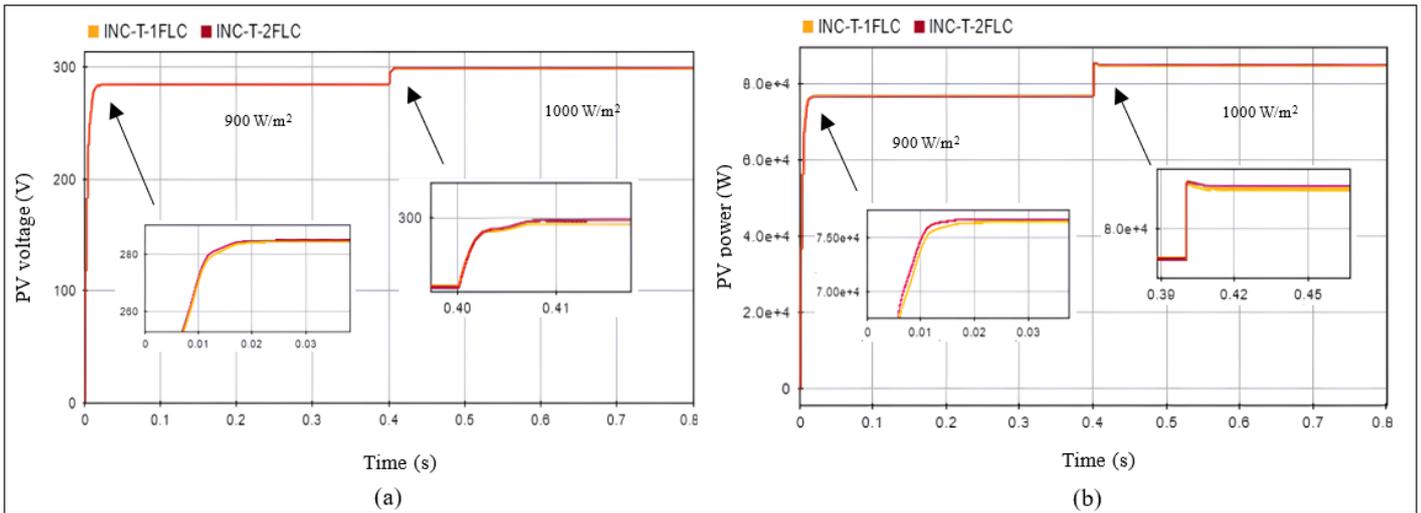


Figure 11. Inc-Cond based T-1FLC and Inc-Cond based IT-2FLC: (a) PV voltage and (b) PV power.

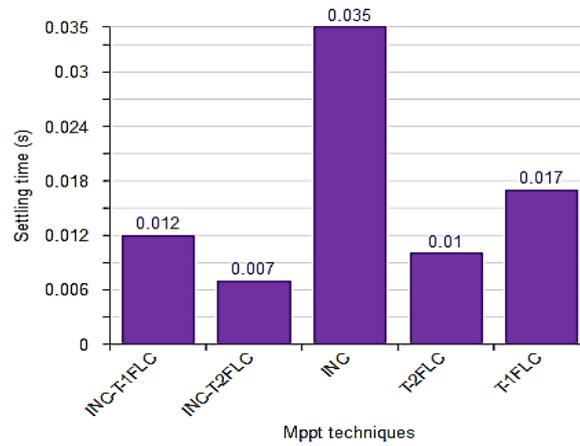


Figure 12. Settling time of MPPT techniques.

Table 4. Evaluation of MPPT approaches.

Temperature at 25 C°							
MPPTs	G = 900W/m ²			Settling time (s)	G = 1000W/m ²		
	MPP (W)	Accuracy (%)	Efficiency (%)		MPP (W)	Accuracy (%)	Efficiency (%)
INC-COND	7.691e ⁴	87.46	90.48	Oscillatory	8.442e ⁴	96.43	99.31
T-1FLC	7.693e ⁴	87.55	90.50	0.017	8.448e ⁴	96.45	99.38
INC-IT-1FLC	7.767e ⁴	88.49	91.37	0.012	8.466e ⁴	96.57	99.6
IT-2FLC	7.742e ⁴	88.62	91.08	0.01	8.451e ⁴	96.54	99.42
INC-IT-2FLC	7.786e ⁴	88.93	91.6	0.007	8.487e ⁴	96.64	99.84

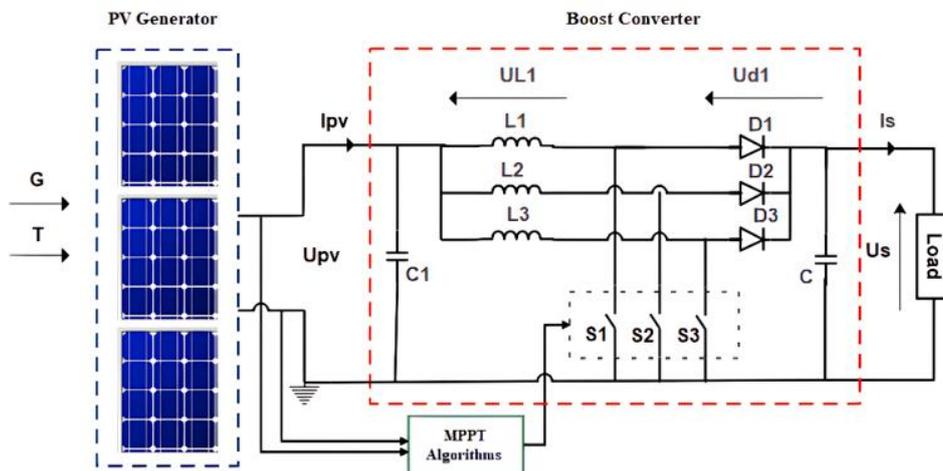


Figure 13. Structure of photovoltaic system.

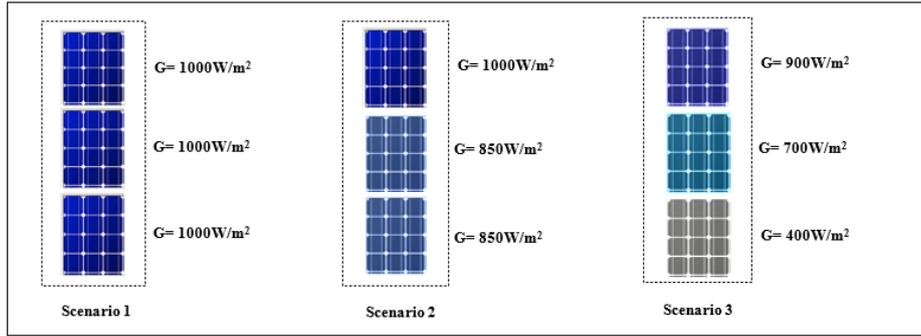


Figure 14. Representation of study scenarios.

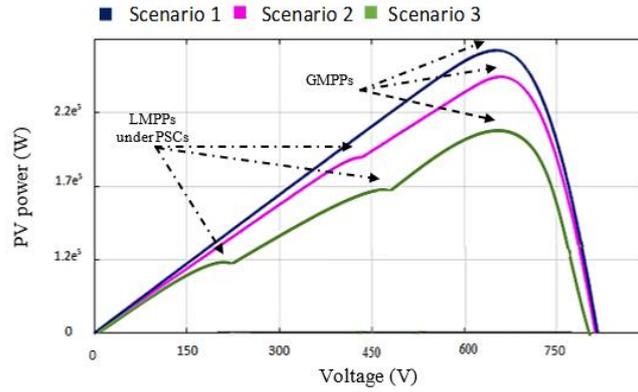
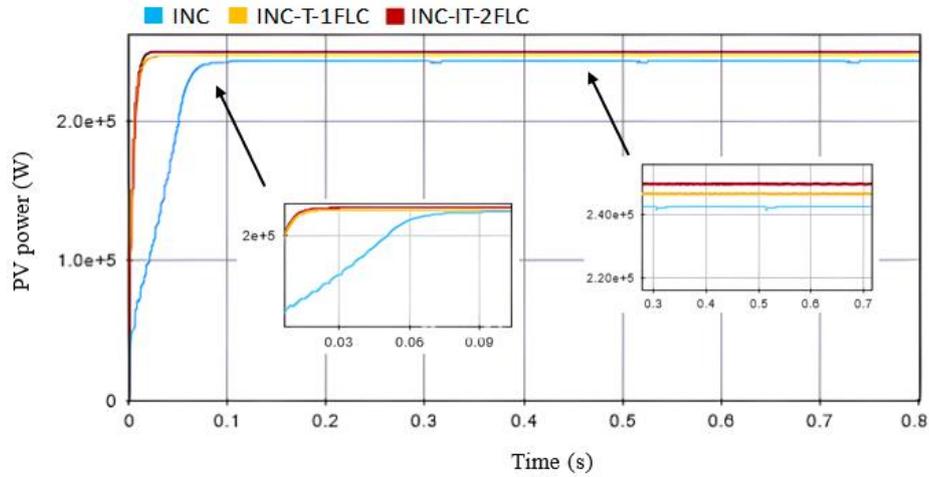
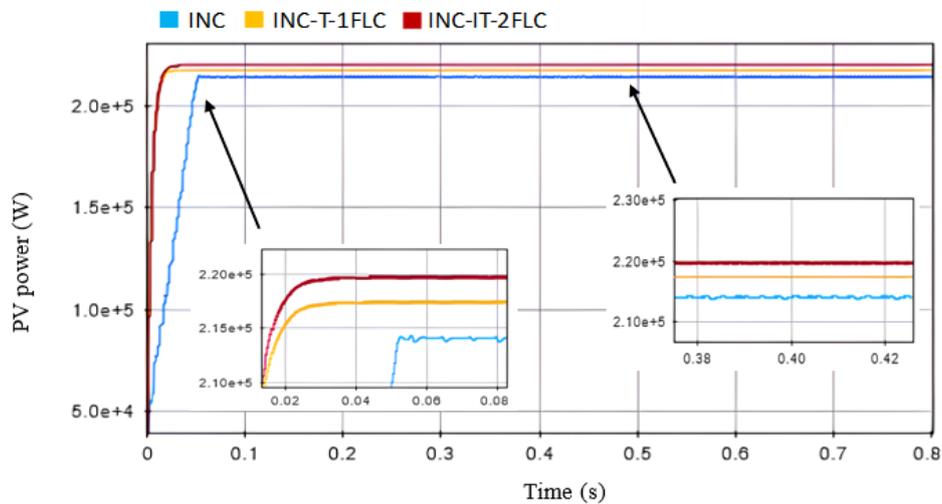


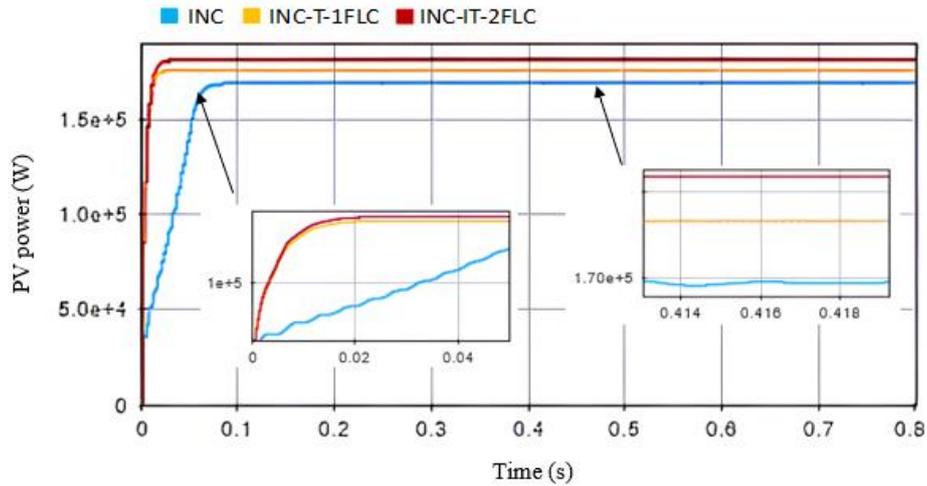
Figure 15. Simulated power versus voltage plots of the suggested system for all study scenarios.



(b) Scenario 1



(c) Scenario 2



(d) Scenario 3

Figure 16. Simulated power versus time graph of the studied methods under standard test condition and various shading scenarios.

Table 5. Analysis of MPPT methods.

MPPTs	Criteria	Scenario 1	Scenario 2	Scenario 3
INC-Cond	GMPP (W)	2.486e ⁵	2.101e ⁵	1.72e ⁵
	LMPP (W)	-	1.652e ⁵	1.161e ⁵ 1.485e ⁵
	Efficiency (%)	97.49	82.39	67.45
	Accuracy (%)	95.86	80.02	64.91
INC-T-1FLC	GMPP (W)	2.499e ⁵	2.181e ⁵	1.782
	LMPP (W)	-	1.699e ⁵	1.221e ⁵ 1.54e ⁵
	Efficiency (%)	98	85.52	69.92
	Accuracy (%)	96.58	83.91	67.48
INC-IT-2FLC	GMPP (W)	2.503e ⁵	2.198e ⁵	1.799e ⁵
	LMPP (W)	-	1.725e ⁵	1.28e ⁵ 1.564e ⁵
	Efficiency (%)	98.43	86.19	70.54
	Accuracy (%)	97.12	85.12	68.35

5. CONCLUSIONS

In this manuscript, a hybrid MPP tracking approach, named Inc-Cond-IT-2FLC, has been applied. The strategy behind the proposed approach is to enhance the tracking process by addressing the limitations of existing methods. The core idea of the investigation was to generalize T-1MFs to IT-2MFs, which has led to an improvement in the PV system's efficiency. Subsequently, IT-2FLC was combined with Inc-Cond. Simulation results demonstrated the superiority of the hybrid controller over the other methods studied. The hybrid system benefits from the simplicity and rapid response time of Inc-Cond while leveraging the adaptive precision of fuzzy logic. This interaction ensures efficient and accurate MPP tracking, which was confirmed by a brief comparison study based on MPP value, accuracy, and efficiency in different scenarios under both uniform and partial shading conditions.

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NOMENCLATURE

MPPT	Maximum Power Point Tracking
Inc-Cond	Incremental Conductance
P&O	Perturb and Observe
FCO	Measurements of open circuit voltage
FCC	Measurements of short-circuit current
PSO	Particle Swarm Optimization

IT-2FLC	Interval Type-2 Fuzzy Logic Controller
INC-IT-2FLC	Inc-Cond based Interval Type-2 Fuzzy Logic Controller
MFs	Membership Functions
T-2FS	Type 2 Fuzzy Set
PV	Photovoltaic
T	Temperature (C°)
G	Irradiance (W/m ²)
ΔV _{PV}	Voltage change (V)
ΔI _{PV}	Current change (A)
ΔP _{PV}	Power change (W)
ΔV _{ref}	Reference voltage change (V)
IBC	Interleaved Boost Converter
STC	Standard Test Condition
PSC	Partial Shading Condition
GMPP	Global Maximum Power Point
LMPP	Local Maximum Power Point

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