Hybrid MPPT technique using fuzzy logic and P&O of solar power system

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ABSTRACT

This paper introduces an enhanced perturb and observe (P&O) technique with a variable step size utilizing fuzzy logic to address the limitations of the traditional P&O technique, particularly under rapidly fluctuating solar radiation conditions. The performance of the suggested variable step size FLC-P&O maximum power point tracking (MPPT) and the constant step size P&O techniques is simulated and evaluated under various operating scenarios using MATLAB/Simulink software. The suggested technique was successfully validated using a boost converter connected to a Canadian Solar CS6P-240P photovoltaic (PV) model. The results demonstrate that the FLC-P&O technique improves response accuracy and reduces steady-state terminal voltage fluctuations. Moreover, the findings show that the suggested technique provides a faster response and higher MPPT efficiency compared to the traditional P&O technique, particularly during sudden variations in solar irradiance.

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1. INTRODUCTION

Maximum power point tracking (MPPT) algorithms are a key component of photovoltaic systems, enabling their efficiency and energy production to be optimized by adjusting the operating point of the solar panels in real time. The main goal of using MPPT is to ensure optimal power extraction from photovoltaic (PV) modules regardless of environmental factors, particularly variations in irradiance and temperature. Previous studies have highlighted several MPPT strategies, including the incremental conductance method [1], [2], and perturb and observe (P&O) [3], [4]. However, these methods have notable limitations. The operation of PV modules requires nonlinear current-voltage characteristics when disconnected from temperature influences. Additionally, works on fuzzy logic (FL) [5], [6], artificial neural networks (ANN) [7], [8], genetic algorithms (GA) [9], [10], and hybrid models of these approaches are also available.

The traditional P&O method often shows inefficiencies under rapidly changing environmental conditions like fluctuations in solar irradiance and temperature. By combining fuzzy logic with a variable step size strategy, the FLC-P&O technique aims to increase accuracy and efficiency in optimizing electrical power. strategy is a popular technique, valued for its fluidity and flexibility of integration. However, it often fails under rapid environmental changes. To improve upon these shortcomings, we propose a modified P&O technique with a changeable step size informed by the application of fuzzy logic. This approach enhances MPPT accuracy and minimizes steady-state voltage oscillations, offering improved performance in varying atmospheric conditions. Previous studies have suggested modified P&O MPPT techniques to address the limitations of the standard P&O technique [11], [12]. According to [13], the advanced P&O control incorporates an FLC, which regulates the DC-DC converter by using power and current variations as inputs and duty cycle adjustments as outputs. Yüksek and Mete [14] introduce a P&O-based MPPT technique featuring an adaptive step size tailored for photovoltaic systems, where the step size is dynamically modified in each cycle based on the power difference. A fuzzy MPPT controller is presented in [15] that uses two inputs: the PV voltage's fixed perturbation step size and the real-time instantaneous slope of the PV power. A fuzzy MPPT controller with error (E) and variation of error (ΔE) as inputs and a single output that represents the duty cycle change is examined in [16]-[18].

This paper introduces a modified P&O technique using a changing step size based on fuzzy logic for tracking maximum power under diverse weather conditions. The fuzzy logic controller reduces oscillations around the MPP using a two-input fuzzy logic controller based on (ΔPpv) and (ΔVpv) to search for a variable voltage step size. Through a comparative analysis, this paper aims to demonstrate which technique, the adjustable step size FLC-P&O MPPT controller or the constant step size P&O conventional MPPT controller, performs better.

The study is organized as follows: i) Section 2 elucidates the principle P&O MPPT system technique with presents a suggested hybrid FLC-P&O MPPT technique; ii) Section 3 details the modeling of the PV panel and boost converter; iii) Sections 4 and 5 illustrate the simulation observations, discussions, and conclusions.

2. PROPOSED MPPT

2.1. P&O MPPT

The perturb and observe technique is employed in photovoltaic systems to identify the MPPT, continuously adjusting the operating voltage to maximize power output. Periodically, the algorithm modifies the voltage and tracks how it affects power output; if the new power surpasses the previous value, it keeps going in that way; otherwise, it reverses. Although this method requires a constant step size, voltage adjustment remains the core process. This is generally the most prevalent method used for MPPT. Figure 1 illustrates the schematic for P&O MPPT [5], [19].

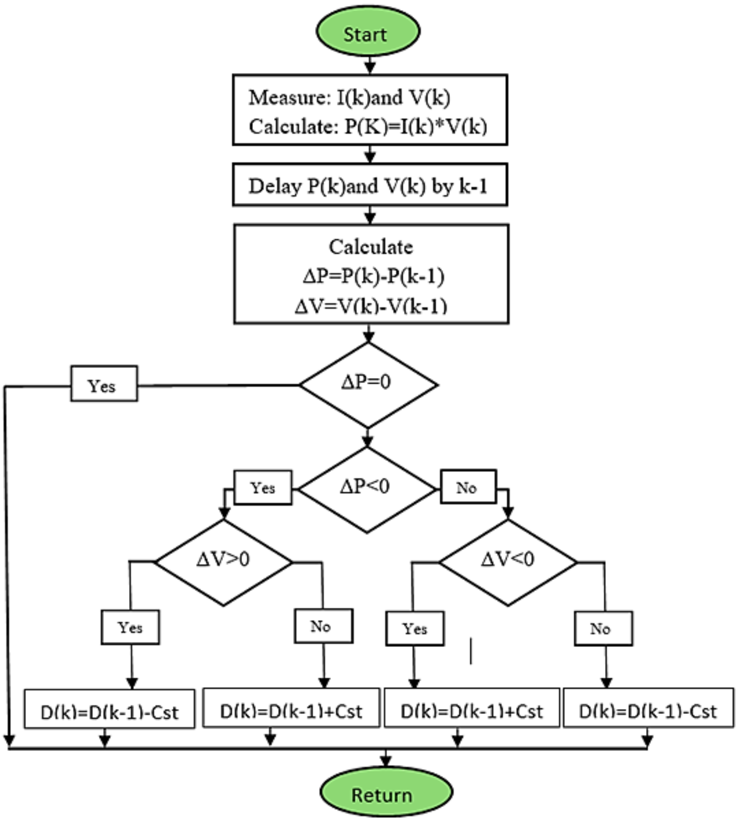

Figure 1. Flowchart of the P&O MPPT technique

2.2. Suggested hybrid FLC-P&O MPPT

Some researchers have refined the P&O technique to mitigate specific shortcomings. The solution adjusts the step size dynamically during MPPT operation based on the insolation level or temperature coefficient. Thus, we propose a modified P&O technique with a changeable step size informed by the application of fuzzy logic, as depicted in Figure 2. In the PV system, the FLC-based MPPT technique is increasingly common. Typically, the FLC configuration includes three stages: Fuzzification, fuzzy inference engine, and defuzzification. In the inference engine stage, the Mamdani fuzzy logic controller method uses min-max fuzzy compositional rules to generate the output fuzzy set. We suggest FLC-P&O, a modified algorithm, to enhance and overcome the limitations of the traditional P&O approach, which has a fixed step size. A fuzzy logic approach is employed to determine the variable step size (ΔD), allowing for automatic adjustment of PV array operating points. The fuzzy logic system uses two inputs based on power variance (ΔPpv) and voltage variation (ΔVpv) to determine the changeable step size (ΔD), as depicted in Figure 3. Figure 4 illustrates the five triangular MFs [6] that are used by both inputs and outputs: negative big (NB), negative small (NS), zero (ZE), positive big (PB), and positive small (PS). The fuzzy rule base, inspired by the P&O method, enables adaptive step-size adjustments for faster convergence. This improves tracking performance while maintaining system stability. The choice of five membership functions provides an optimal balance between precision and computational complexity, ensuring accurate MPPT control. Fewer membership functions make control coarser, while increasing the number unnecessarily increases complexity without a significant gain. This choice ensures sufficient granularity to differentiate between power and voltage variations, while maintaining fast and efficient execution suitable for embedded systems. Table 1 displays the fuzzy regulation base, which consists of 25 variable controls.

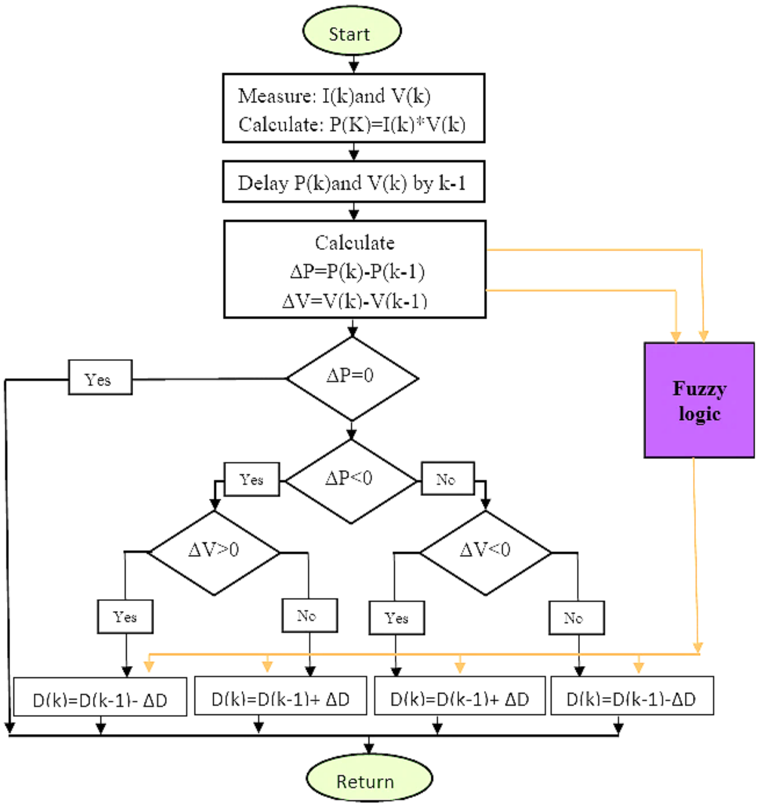

Figure 2. Flowchart of suggested hybrid FLC-P&O MPPT technique

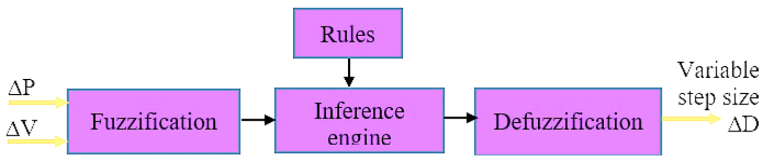

Figure 3. Block diagram of a FLC

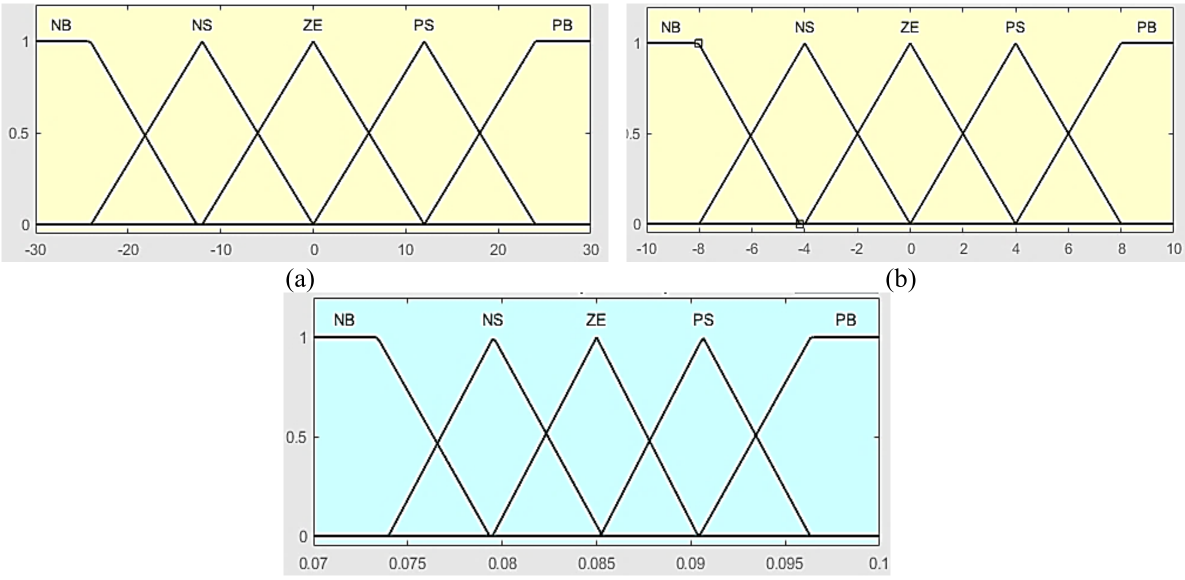

Figure 4. Membership functions for suggested fuzzy controller: (a) ΔPpv, (b) ΔVpv, and (c) ΔD

Table 1. Rule base table with 25 rules

Δv Δp	NB	NS	ZE	PS	PB
NB	NB	NB	NB	NS	ZE
NS	NB	NB	NS	ZE	PS
ZE	NB	NS	ZE	PS	PB
PS	NS	ZE	PS	PB	PB
PB	ZE	PS	PB	PB	PB

The fuzzy controller determines the changeable step size (ΔD) using two input variables. The differential voltage and differential power used by the FLC are calculated using (1) and (2).

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

$$\Delta V(K) = V(K) - V(k-1) \quad (2)$$

To perform inference, Mamdani's Max-Min composition method is applied. Defuzzification is executed via the center-of-gravity method, converting the fuzzy subset of the variable-step-size into real integers, as demonstrated by (3) [20], [21].

$$\Delta D = \frac{\sum_{j=1}^{n} \mu(\Delta D_j) * \Delta D_j}{\sum_{j=1}^{n} \mu(\Delta D_j)} \quad (3)$$

3. MODELLING OF PV ENERGY CONVERSION SYSTEM

3.1. Modelling of PV panel

The most widely used equivalent electrical circuit of a real solar cell is most likely the one-diode model, which includes one diode (D), a current source (Iph), parallel resistance (Rp), and series resistance (Rs). This equivalent model is illustrated in Figure 5. It is appropriate for simulations and performance studies because it offers a good combination of accuracy and simplicity.

3.2. Modelling of DC-DC boost converter

To produce a greater output voltage, a boost converter is used to increase the input voltage. It is frequently employed when the photovoltaic panel's voltage is less than what the load requires. As seen in Figure 6, this converter interconnects the PV module with the load, making it an essential part of PV systems [22], [23]. The following are the boost converter's essential parameters: an inductor (L) of 100 mH, switching frequency (fs) of 20 kHz, and capacitors, C_1 = 390 µF and C_2 = 470 µF.

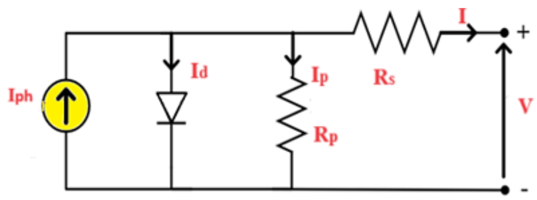

Figure 5. One-diode equivalent circuit

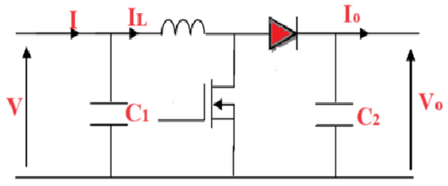

Figure 6. Equivalent circuit of the boost converter

4. RESULTS AND DISCUSSION

This part supplies the simulation results for the suggested approach, implemented in the MATLAB/Simulink environment, as depicted in Figure 7. The suggested hybrid FLC-P&O MPPT technique is based on the classic P&O process, incorporating a variable step size dynamically calculated by the FLC, contrasting with the traditional constant step size P&O MPPT technique. The electrical parameters for the Canadian Solar CS6P-240P PV panel utilized in the simulations are presented in [18]. The PV cell's I-V and P-V voltage characteristics for the Canadian Solar CS6P-240P are displayed in Figures 8 and 9 at different irradiation intensities of 400, 300, 200, and 100 W/m^2.

We use tracking efficiency (η) statistics to assess how well MPPT approaches operate. Typically, it is described as (4) [13], [24], [25].

$$\eta = \frac{\sum P_{MPPT}(i)}{\sum_{j=1}^{n} P_{Max}(i)} * 100 \quad (4)$$

Where P_{MPPT}: output power of the photovoltaic system using the MPPT controller, and P_{max}: maximum possible output power of the PV system at MPP.

To evaluate the suggested FLC-P&O MPPT technique under a variable irradiance profile with ramp-up and ramp-down conditions, a test was conducted at T = 25 °C, as depicted in Figure 10. The irradiance begins at 400 W/m² and remains constant for the first 0.5 seconds. It then decreases to 150 W/m² between 0.5 and 1.5 seconds. After 1.5 seconds, the irradiance rises to approximately 250 W/m² before gradually declining to 200 W/m².

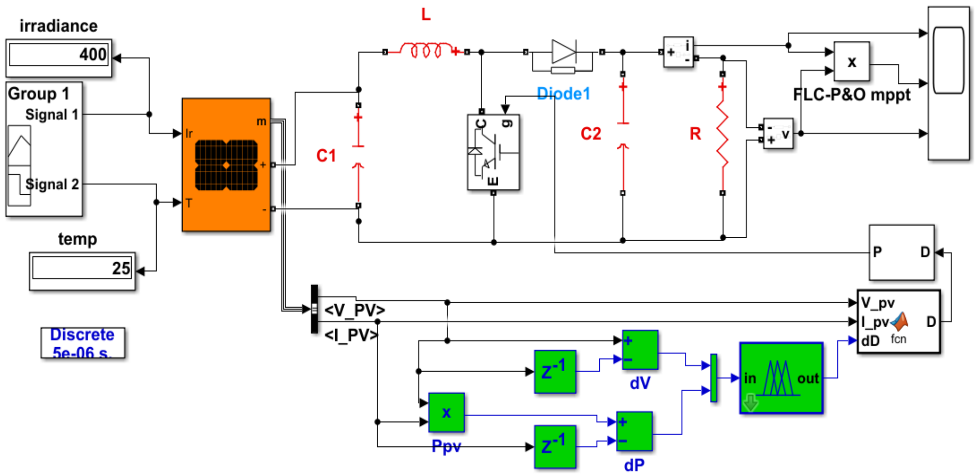

Figure 7. Simulink model of PV system with hybrid FLC-P&O MPPT controller

Figures 11 and 12 depict the PV output current for the suggested FLC-P&O MPPT and a P&O MPPT with constant step size of value 0.04. The suggested MPPT controller has a quicker transient response without oscillations. Figure 13 shows the output power of P&O and the suggested FLC-P&O when irradiances change. In the first case (25 °C, 400 W/m^2), the PV system achieved a maximum power output of 96.4 Watts, corresponding to the envisaged maximum power. Subsequently, at 25 °C and 200 W/m^2, The PV system attained its planned optimal power of 48.6 Watts. Therefore, simulation results indicate that under abrupt changes in solar radiation conditions, the PV system converges very accurately to its optimal power. By integrating FLC and P&O techniques, the suggested approach benefits from the strengths of both techniques. Table 2 summarizes the calculated efficiency, oscillation level, and response time during sudden increase in irradiation. In contrast to conventional P&O, when fluctuations of 1.5 W peak-to-peak power are maintained, the suggested MPPT shows reduced power oscillation, confirming the resolution of conflicts between dynamic response and steady-state oscillation.

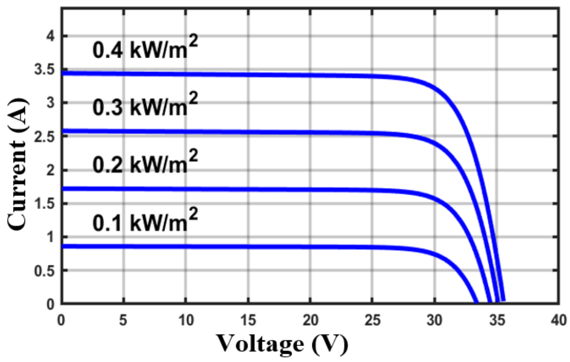

Figure 8. (I-V) Characteristics curves for PV with various Irradiations

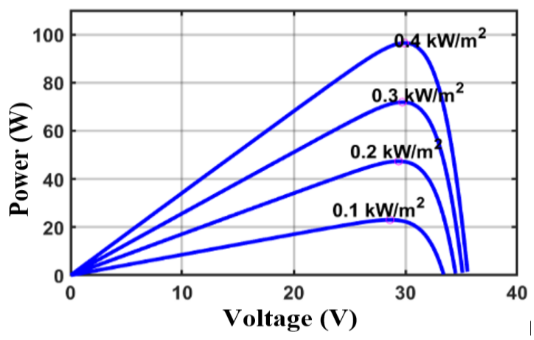

Figure 9. (P-V) Characteristic curves for PV with various Irradiations

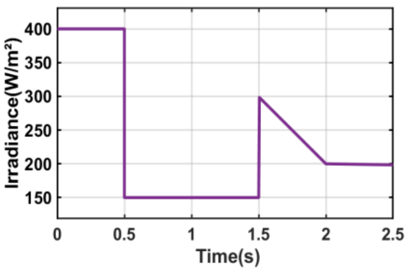

Figure 10. Solar radiation variation

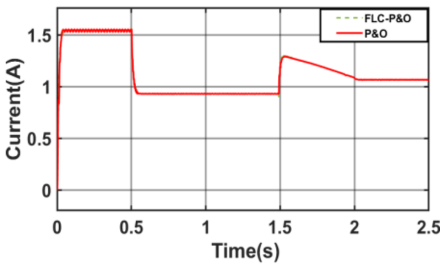

Figure 11. Waveform of output current for P&O and FLC-P&O techniques

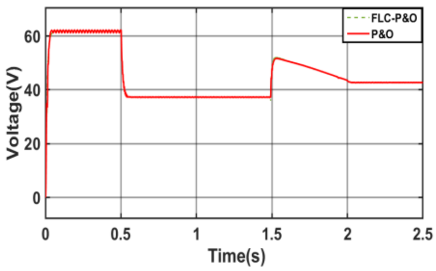

Figure 12. Waveform of the output voltage for P&O and FLC-P&O techniques

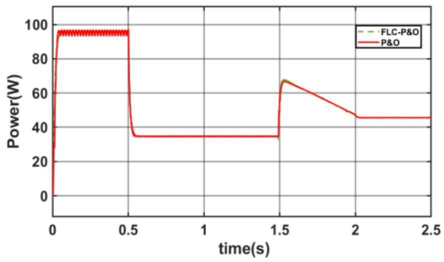

Figure 13. Waveform of the output power for P&O and FLC-P&O techniques

Table 2. Summarizes the comparison of the suggested FLC-P&O technique with the traditional P&O technique

Techniques	Oscillation level	Efficiency (%)	Response time to sudden irradiation increases
Conventional P&O technique	3W	92.50	Medium
FLC technique [22]	8W	96.50	Slow
suggested FLC-P&O technique	Neglected	98.99	fast

The results presented in Figure 14 reveal that the suggested MPPT is more precise than other MPPT techniques in tracking the MPP in different weather conditions. The findings demonstrate that the FLC-P&O MPPT achieves the fastest convergence time to reach a steady state. One of the significant challenges in solar systems is the fluctuation of output power in unstable atmospheric conditions. The P&O technique exhibits greater fluctuations and instability in the waveform, indicating less efficient tracking of the MPP under varying conditions, whereas the FLC-P&O technique displays more stable waveforms, suggesting more accurate and efficient tracking with reduced fluctuations near the MPP.

Fuzzy logic can be implemented on advanced microcontrollers (e.g., STM32, Raspberry Pi), though computational demands may require higher-performance processors. Sensor accuracy and calibration are crucial for reliable operation. To ensure real-time processing, the fuzzy logic rules can be optimized by reducing the complexity of calculations. This will enable efficient MPPT performance while maintaining accuracy. Additionally, minimizing energy consumption, especially for embedded systems powered by renewable sources. Additionally, scaling to larger systems (e.g., photovoltaic farms) introduces challenges like system synchronization and multi-controller coordination. With these considerations, fuzzy logic proves to be a practical, and efficient approach for MPPT implementation.

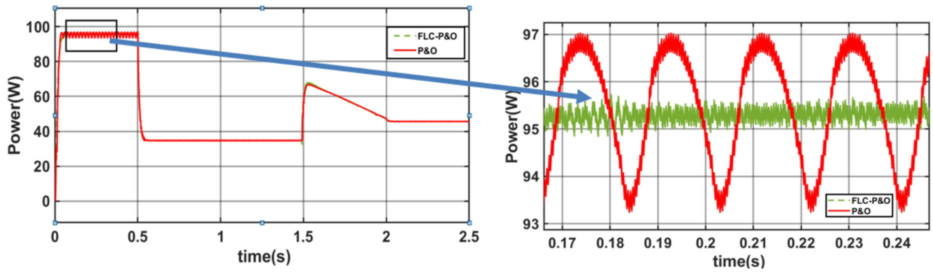

Figure 14. Evaluation of the suggested technique versus the traditional technique under step-variation irradiance conditions

5. CONCLUSION

The suggested FLC-P&O technique has been tested by simulation and evaluated using MATLAB/Simulink, demonstrating considerable enhancements in response time, efficiency, and a decrease in power oscillations surrounding the MPPT in contrast to the typical P&O approach. By incorporating fuzzy logic with the P&O algorithm, the system can automatically adjust the step size, leading to quicker and more precise MPPT. With the suggested FLC-P&O approach, the MPPT's tracking efficiency rises from 96.80% to 98.99%. and achieves minimal fluctuations around the operating point compared to the standard P&O technique. The performance comparison indicates that the suggested technique offers adaptive and variable step size operation, exceptional flexibility in design optimization, minimal output power fluctuations, and faster tracking times relative to the conventional P&O technique.

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AUTHOR CONTRIBUTIONS STATEMENT

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C : **C**onceptualization
M : **M**ethodology
So : **So**ftware
Va : **Va**lidation
Fo : **Fo**rmal analysis
I : **I**nvestigation
R : **R**esources
D : **D**ata Curation
O : Writing - **O**riginal Draft
E : Writing - Review & **E**diting
Vi : **Vi**sualization
Su : **Su**pervision
P : **P**roject administration
Fu : **Fu**nding acquisition

CONFLICT OF INTEREST STATEMENT

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper

DATA AVAILABILITY

The data that support the findings of this study are available on request from the corresponding author, [KE]. The data, which contain information that could compromise the privacy of research participants, are not publicly available due to certain restrictions.

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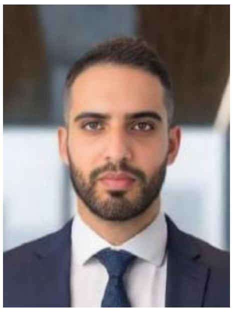

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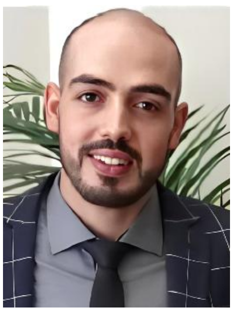

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