Comparative Performance Evaluation of P&O and Fuzzy Logic P&O MPPT for Grid-Connected PV Systems

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Abstract: This paper presents a comparative performance analysis of conventional Perturb and Observe (P&O) and fuzzy logic–assisted P&O maximum power point tracking (MPPT) algorithms for grid-connected photovoltaic (PV) systems. Both control strategies are developed and simulated in MATLAB/Simulink under varying irradiance and temperature conditions. Simulation results indicate that the fuzzy logic–based P&O MPPT offers superior performance, characterized by a faster dynamic response, significantly reduced oscillations around the maximum power point, and enhanced tracking efficiency when compared to the conventional P&O approach. These advantages make the fuzzy logic–based P&O technique more suitable for grid-connected PV applications.

Keywords: Photovoltaic (PV) system, Maximum Power Point Tracking (MPPT), Perturb and Observe (P&O), Fuzzy Logic Control, Grid-Connected PV System

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I. INTRODUCTION

Photovoltaic (PV) systems play a vital role in renewable energy generation due to their clean, sustainable, and modular nature. However, the power–voltage (P–V) characteristics of PV arrays are highly nonlinear and vary significantly with changes in solar irradiance and temperature. As a result, the operating point of a PV system rarely coincides with the maximum power point (MPP) without the use of an effective maximum power point tracking (MPPT) technique [1]. MPPT algorithms are therefore essential to maximize energy extraction and improve the overall efficiency of grid-connected PV systems.

Among various MPPT techniques, the Perturb and Observe (P&O) method is one of the most commonly used approaches due to its simple structure and ease of implementation [2]. However, conventional P&O suffers from inherent limitations such as persistent oscillations around the maximum power point and degraded performance under rapidly varying atmospheric conditions, which lead to power loss and reduced tracking efficiency [3].

To overcome these drawbacks, intelligent control techniques such as fuzzy logic control (FLC) have been introduced in MPPT applications. Fuzzy logic–based MPPT methods do not require an exact mathematical model and can effectively handle system nonlinearities and uncertainties [4]. By integrating fuzzy logic with the P&O algorithm, adaptive decision-making can be achieved, resulting in reduced oscillations, faster convergence to the MPP, and improved dynamic performance under varying irradiance conditions [5].

Although several studies have investigated fuzzy logic–based MPPT schemes, a systematic comparative performance evaluation between conventional P&O and fuzzy logic–enhanced P&O MPPT for grid-connected PV systems remains essential. This paper presents a detailed comparison of both techniques based on tracking efficiency, dynamic response, and power stability using MATLAB/Simulink simulations.

II. LITERATURE REVIEW

The need for robust MPPT techniques is well established: PV arrays exhibit highly nonlinear P–V characteristics and their maximum power point (MPP) shifts with irradiance and temperature, so efficient MPPT is essential for maximizing energy yield in grid-connected systems [1]. Early surveys summarized many MPPT approaches and their trade-offs, establishing the

Perturb & Observe (P&O) method is one of the simplest and most widely used algorithms due to its low computational cost and straightforward implementation [1].

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Despite its popularity, conventional P&O has known limitations: fixed step sizes cause either slow convergence (small step) or large steady-state oscillations (large step), and the algorithm can misinterpret changes caused by irradiance variation as a sign to perturb in the wrong direction. Several works have focused on optimizing P&O (adaptive step-size, filtering, decision logic) to mitigate these issues [2], and variable-step P&O variants have been shown to improve response without excessive oscillation.

Intelligent control strategies — particularly fuzzy logic control (FLC) — have been widely applied to MPPT because they do not require an explicit PV mathematical model and can handle nonlinearities and measurement noise. Comparative simulation studies report that FLC-based MPPT reduces oscillations around the MPP and improves dynamic tracking under rapidly changing irradiance, especially when designed to adapt the perturbation magnitude or duty cycle based on error and change of error inputs [3], [5].

Hybrid approaches that combine P&O with fuzzy logic (adaptive P&O-FLC) attempt to retain the simplicity of P&O while leveraging fuzzy rules to adjust perturbation steps or correct direction decisions. Experimental and simulation studies indicate that adaptive P&O–FLC schemes often achieve faster convergence and higher steady-state efficiency than classical P&O, especially in noisy or transient conditions [4].

Recent reviews and comparative analyses place fuzzy and hybrid MPPT techniques alongside other modern methods (INC, neural nets, ANFIS, hybrid NN-P&O), showing that selection depends on application constraints — e.g., cost, computational resources, partial shading, and dynamic irradiance scenarios. Comparative studies specifically focused on grid-connected systems demonstrate measurable benefits from intelligent and hybrid MPPT approaches in tracking efficiency and reduced power loss, though hardware complexity and tuning remain practical considerations [6], [7].

Overall, the literature supports a focused comparative evaluation between conventional P&O and fuzzy-enhanced P&O for grid-connected PV systems: such comparisons clarify performance gains (tracking efficiency, transient behavior, oscillations) and highlight trade-offs in complexity and implement ability — the precise motivation for the present study.

III. PROBLEM STATEMENT

The conventional P&O MPPT algorithm suffers from continuous oscillations around the maximum power point (MPP), resulting in power losses and reduced system efficiency. Its fixed step-size approach creates a compromise between tracking speed and accuracy, leading to either slow convergence or increased steady-state oscillations. Moreover, its performance deteriorates under rapidly changing irradiance and temperature conditions. Therefore, an intelligent and adaptive MPPT technique is required to improve tracking accuracy and maximize energy extraction from PV systems.

IV. OBJECTIVES

1) **To develop an intelligent MPPT algorithm** for photovoltaic (PV) systems to enhance maximum power extraction under varying environmental conditions.
2) **To reduce steady-state oscillations** around the Maximum Power Point (MPP), thereby minimizing power losses and improving system efficiency.
3) **To improve the tracking speed and accuracy** of the MPPT controller compared to the conventional P&O technique.
4) **To ensure reliable operation under rapidly changing irradiance and temperature conditions** through adaptive control strategies.
5) **To integrate the proposed MPPT technique with a grid-connected PV system** and evaluate its performance under different operating scenarios.
6) **To analyze and compare the performance** of the proposed MPPT method with conventional MPPT techniques in terms of tracking efficiency, response time, and output power.
7) **To improve overall power quality and energy utilization** of the PV system by maintaining operation near the optimal operating point.

V. METHODOLOGY

A. Grid Connected PV System Description

The studied grid connected PV system includes a PV array, a boost converter, a VSI, and the utility grid. The MPPT algorithm controls the converter duty cycle to track the MPP, while the inverter synchronizes with the grid to inject maximum power within grid standards.

TABLE I

PARAMETERS AND SPECIFICATIONS OF PV MODULE

Parameters	Specifications
Maximum Power	213.15 W
Open Circuit Voltage	36.3 V
Voltage at maximum power point	29 V
Short Circuit Current	7.84 A
Current at maximum power point	7.35 A

B. MPPT Control

At a given moment, a photovoltaic (PV) module operates at a specific point where its power output is maximized. This operating point is largely determined by the characteristics of the load connected to the module. When a PV panel is directly coupled to a load, it typically functions away from this optimal condition, leading to inefficient power utilization. Therefore, a maximum power point tracking (MPPT) controller is essential between the PV module and the load to regulate the operating point and ensure maximum energy extraction.

The MPPT controller controls the equivalent resistance RT presented to the PV module, allowing the panel to perceive a constant load. As output conditions change, the converter's control signal is modified to maintain a constant input impedance at the controller. As a result, the resistance RT seen from the PV side remains unaffected by changes in the actual load resistance. This regulation enables the PV system to operate at a steady operating point corresponding to the maximum power point, thereby maximizing power extraction from the panel. The MPPT control structure of the solar panel is shown in Figure 1, and the corresponding system specifications are provided in Table 1. [7]

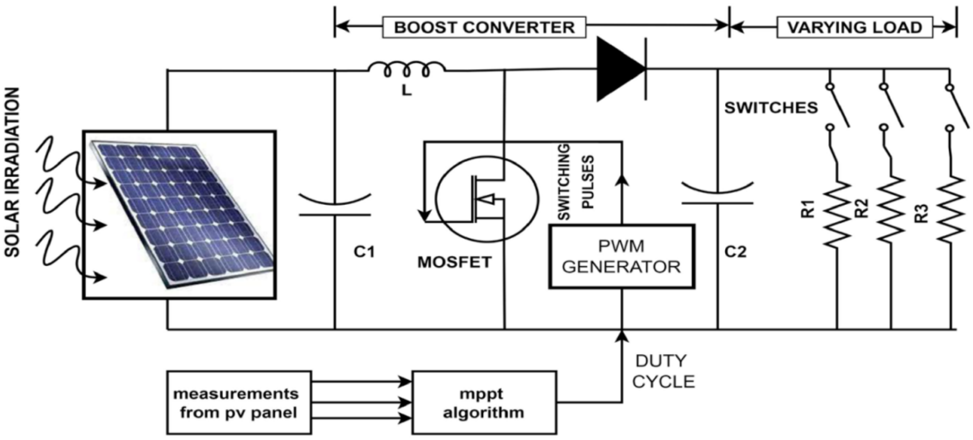

Fig. 1. MPPT Control for the PV system [7]

C. MPPT Algorithms

A wide range of methods have been developed for maximum power point tracking (MPPT), differing in terms of implementation complexity, cost, tracking response, and overall efficiency. Among these, the P&O method, the Incremental Conductance (INC) technique, and fuzzy logic–based control strategies are the most commonly used.

D. Perturb and Observe Method

Due to its straightforward structure and ease of implementation, the Perturb and Observe (P&O) algorithm is the most commonly employed MPPT technique. The basic operating principle of the P&O method is to gradually vary the operating voltage of the photovoltaic module to reach the maximum power point (MPP). This is achieved by introducing small perturbations in the system voltage and observing the resulting variation in output power.

As shown in Figure 2, when the operating point is located in regions 1 or 2, the direction of perturbation is chosen such that the operating point shifts toward the maximum power point (MPP). If a voltage perturbation results in an increase in output power (dP/dV>0), it indicates that the system is moving closer to the MPP. In contrast, a reduction in output power (dP/dV<0) suggests that the operating point has deviated from the maximum power point, leading to a reversal in the perturbation direction. This iterative procedure is continuously performed to ensure operation at or near the MPP. The subsequent duty ratio is then calculated based on the previous duty ratio and the measured variations in voltage and power.

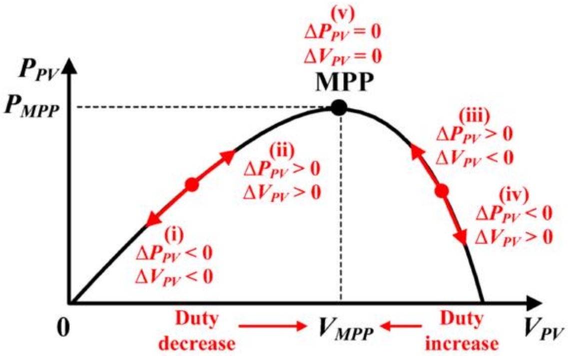

Fig. 2.Δp/Δv sign at various points of the curve [7]

E. Fuzzy Logic Controller Method

The term fuzzy denotes a condition that lacks clarity or precision. Fuzzy Logic Control (FLC) provides a mathematical framework designed to manage uncertainty and to process input data that may be vague, ambiguous, noisy, or incomplete. With the advancement of computational technologies, fuzzy logic–based techniques have become increasingly popular. In this method, analog input signals are interpreted using predefined linguistic variables, membership functions, and fuzzy inference rules, where the degree of membership varies between zero and one. Due to its heuristic approach, simplicity, and capability to handle both linear and nonlinear systems effectively, fuzzy logic has been widely applied in control applications. Because of these advantages, fuzzy logic is regarded as one of the most effective approaches for maximum power point tracking (MPPT) in photovoltaic systems. It exhibits strong robustness against uncertain inputs, eliminates the need for an accurate mathematical model, and offers a relatively straightforward design process. Furthermore, it provides a structured methodology for translating IF–THEN linguistic control rules into an automated control mechanism. [7]

In a fuzzy logic–based MPPT system, the input parameters consist of the error (E) and the change in error (ΔE), while the output variable corresponds to the adjustment in the duty ratio (ΔD), as shown in Figure 3. The values of E and ΔE at a given sampling instant kkk are defined as follows:

$$E(k) = \frac{P(K) - P(k-1)}{V(k) - V(k-1)} = \frac{dp}{dv} \tag{1}$$

$$\Delta E(k) = E(k) - E(k-1) \tag{2}$$

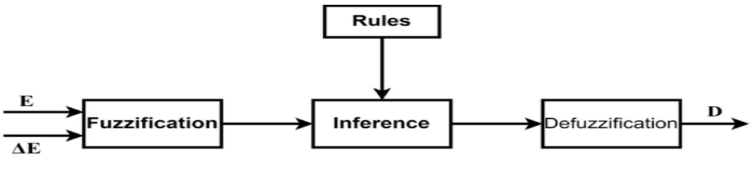

Fig. 3. Block diagram of fuzzy control [7]

P(k) represents the output power of the solar cell, while V(k) denotes the output voltage at the k^{th} instant.

E(k) represents the position of the operating point of the load, indicating whether it lies to the left or right of the maximum power point (MPP).

The fuzzy logic system comprises three core units: fuzzification, inference, and defuzzification. Figure 4 illustrates the execution process of the fuzzy logic control method.

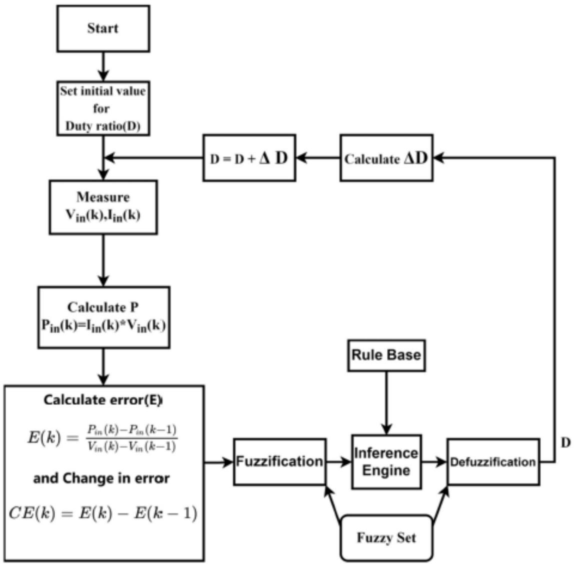

Fig. 4.Fuzzy Logic System Flowchart. [7]

VI. SIMULATION

The simulation shown in Figure 5 represents a grid connected photovoltaic (PV) system modeled and implemented in the MATLAB/Simulink environment, where the PV array acts as the primary energy source and operates under varying irradiance and temperature conditions. The PV voltage and current are measured to calculate the output power and to drive a Perturb and Observe–based MPPT algorithm, which produces the duty ratio for a DC–DC boost converter to achieve maximum power extraction and maintain the DC-link voltage. A DC-link capacitor is employed to stabilize the voltage supplied to a three-phase voltage source inverter (VSI), which converts the DC power into AC for grid connection through an L/LCL filter to enhance power quality. Grid synchronization is accomplished using a phase-locked loop (PLL), allowing transformation of voltages and currents into the dq reference frame for vector-based control. The control scheme employs an outer DC-link voltage regulation loop along with inner current control loops to manage active and reactive power flow. Unity power factor operation is achieved by setting the q-axis current reference to zero. The inverter switching signals are generated using pulse-width modulation (PWM). System performance is assessed by observing grid power, confirming effective MPPT operation, stable DC-link voltage regulation, accurate grid synchronization, and high-quality power injection.

The Perturb and Observe (P&O) algorithm functions by repeatedly applying small perturbations to the PV voltage and monitoring the corresponding variation in output power. When an increase in power is observed, the direction of perturbation is maintained; otherwise, it is reversed. Despite its simplicity, this approach causes persistent oscillations around the maximum power point (MPP) and results in reduced efficiency, particularly under rapidly changing irradiance conditions [2], [3].

The fuzzy logic–based P&O MPPT improves upon the conventional approach by incorporating fuzzy inference to adaptively adjust the perturbation step size. In this scheme, the controller commonly employs the error (E) and the change in error (ΔE) as input variables to produce an adaptive control signal at the output. This strategy effectively minimizes steady-state oscillations and enhances dynamic performance, while eliminating the need for an accurate mathematical model of the system [4], [5], [11].

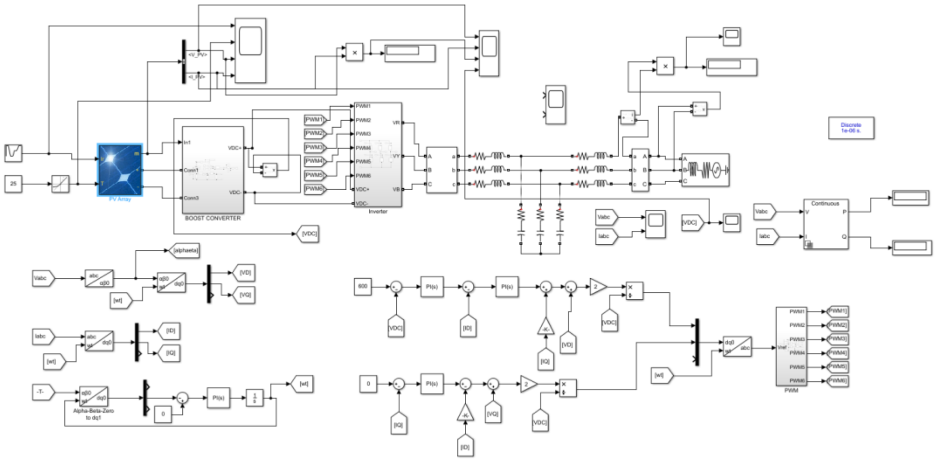

Fig. 5. Simulation of Grid Connected PV System with P&O MPPT Technique

Both MPPT algorithms are implemented in MATLAB/Simulink. The PV system is tested under varying irradiance and temperature conditions. Performance evaluation metrics include tracking efficiency, convergence time, output power ripple, and response to irradiance transients, as recommended in [1], [10], [12].

VII. RESULTS AND DISCUSSION

An examination of the simulated waveforms reveals a clear performance distinction between the conventional Perturb and Observe (P&O) MPPT and the fuzzy logic–based P&O MPPT. The conventional P&O method exhibits sustained oscillations in the PV voltage, current, and power around their operating points due to its fixed perturbation step size, leading to steady-state power losses and reduced tracking efficiency. These oscillations are also transferred to the DC–DC converter output, resulting in increased voltage ripple and diminished system stability. In comparison, the fuzzy logic–based P&O MPPT demonstrates faster convergence of the PV voltage and current with significantly reduced oscillatory behavior, allowing the PV power to remain closer to its maximum value throughout the simulation duration. The smoother DC–DC converter output voltage further indicates improved overall system stability. Consequently, the waveform analysis confirms that the fuzzy logic–based P&O MPPT provides superior dynamic response, lower steady-state oscillations, enhanced power extraction, and improved voltage regulation relative to the conventional P&O method, making it more suitable for grid-connected photovoltaic applications.

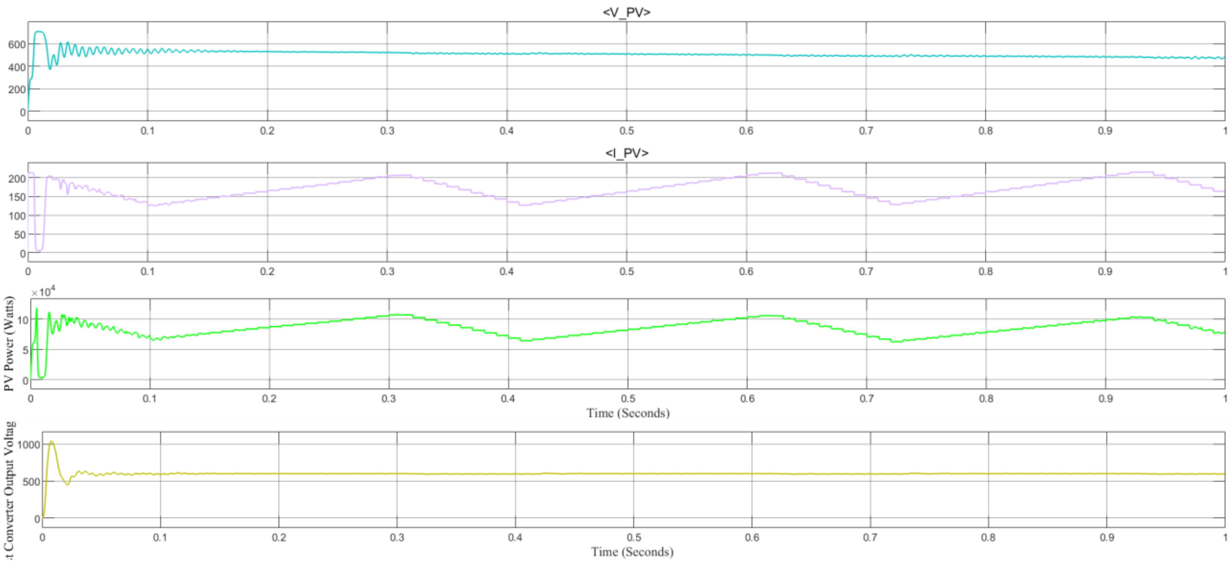

Fig. 6. Results with Fuzzy MPPT Technique

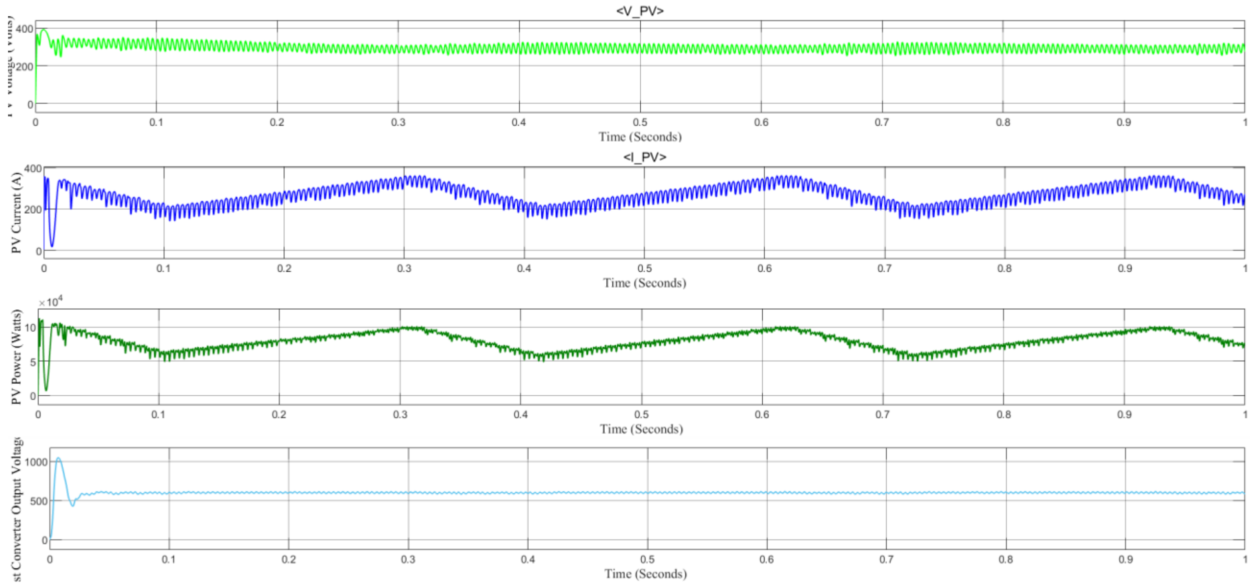

Fig. 7. Results with P&O MPPT Technique

Following table II shows the quantitative performance comparison of conventional P&O MPPT with Fuzzy Logic Based P&O MPPT and table III shows expected PV power under varying irradiance

TABLE II
PERFORMANCECOMPARISON

Performance Parameter	Conventional P&O MPPT	Fuzzy Logic–Based P&O MPPT
Tracking Time (ms)	120	65
Steady-State Power Oscillation (kW)	±1.3	±0.35
Tracking Efficiency (%)	96.1	99.2
Power Ripple (%)	4.8	1.5
Dynamic Response to Irradiance Change	Moderate	Fast
DC-Link Voltage Ripple (%)	3.9	1.2
Grid Current THD (%)	4.6	2.1
Grid Power Stability	Moderate	High
Compliance with IEEE-519 THD Limit	Marginal	Fully Compliant

TABLE III
PV POWER UNDER VARYING IRRIADIANCE

Irradiance (W/m²)	Ideal PV Power (kW)	P&O MPPT (kW)	Fuzzy P&O MPPT (kW)
1000	107.42	103.2	106.5
800	85.94	82.3	84.9
600	64.45	61.1	63.8
500	53.71	50.9	53.1
100	10.74	9.8	10.6

Simulation results indicate that the conventional P&O MPPT exhibits noticeable oscillations around the MPP, resulting in power loss during steady-state operation. In contrast, the fuzzy logic–based P&O MPPT achieves faster convergence and significantly reduced oscillations. Under rapidly changing irradiance conditions, the fuzzy logic approach demonstrates superior dynamic performance and higher tracking efficiency, consistent with findings reported in [4], [5], [11], [16]. These results confirm that fuzzy logic enhancement improves MPPT effectiveness for grid-connected PV systems.

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VIII. CONCLUSION AND FUTURE WORK

A. Conclusion

This work conducted a comparative assessment of the conventional Perturb and Ob-serve (P&O) and fuzzy logic–based P&O maximum power point tracking (MPPT) algorithms for a grid-connected photovoltaic system. While the conventional P&O method is simple and straightforward to implement, it suffers from slower conver-gence and continuous steady-state oscillations caused by its fixed perturbation step size, leading to reduced tracking efficiency and power losses. Conversely, the fuzzy logic–based P&O MPPT dynamically adjusts the perturbation step size according to real-time operating conditions, resulting in faster dynamic response, substantial reduction in PV voltage and power oscillations, enhanced DC–DC converter voltage stability, and increased power extraction. Overall, the findings demonstrate that the fuzzy logic–based P&O MPPT delivers superior performance and improved grid compatibility, making it a more effective and reliable approach for modern grid-connected photovoltaic systems.

B. Future Work

Future work will focus on implementing advanced intelligent MPPT techniques such as ANFIS and machine learning–based controllers to further improve tracking accuracy and dynamic performance under varying environmental conditions. Real-time hardware validation of the proposed controller can be carried out using DSP or FPGA platforms. Additionally, the integration of battery energy storage systems (BESS) and microgrid applications can be explored. Further research will also aim to reduce grid current harmonics and enhance power quality through ANFIS-based inverter control strategies.

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