PERFORMANCE EVALUATION OF TRADITIONAL (P&O) AND AI-BASED (FLC) MPPT ALGORITHMS FOR SOLAR PV SYSTEMS ON-GRID: A COMPARISON UNDER DYNAMIC LOAD

[1]AHMED M ALMAWLA,[2]AFRAH T. ABDULLAH, [3]SAAD RAAD SABEEH, [4]MARWAN J. HUSSEIN

[1,2,3,4]Construction and Projects Department, Mustansiriyah University, Baghdad, Iraq.
E-mail: [1]ahmed.majid@uomustansiriyah.edu.iq

Abstract - The rising global demand for electricity and the decline of non-renewable resources highlight the urgent need for sustainable energy solutions. Solar energy is a strong contender due to its abundance, environmental benefits, and falling technological costs. However, photovoltaic (PV) systems face efficiency challenges in varying weather conditions. Maximum Power Point Tracking (MPPT) techniques are vital for optimising PV performance.This paper compares two MPPT approaches: the traditional Perturb and Observe (P&O) method and an innovative Artificial Intelligence (AI)-based Fuzzy Logic Control (FLC) technique for a PV MPPT system, On-grid connected to an R-L Dynamic Load. A mathematical model of the PV system has been presented, along with a detailed methodology and practical implementation. Simulation results demonstrate that AI-based methods significantly outperform conventional techniques in changing environments, offering a promising path toward more efficient solar energy utilization.

Keywords - PV, MPPT, (FLC) Fuzzy Logic Control, Perturb and Observe (P&O), Dynamic Load**.**

I. INTRODUCTION

The increasing demand for electricity underscores the urgent need for renewable energy solutions. As nonrenewable resources diminish, transitioning to sustainable sources like solar power becomes essential [1]. Solar energy is not only free and abundant but also significantly reduces air and water pollution, offering a healthier environment [2]. Currently, solar power accounts for just 1.7% of global energy consumption, yet it is expected to exceed 1 TW in capacity by 2025. This shift is vital for many countries in the Middle East, where the expanding industrial sector demands clean, reliable energy. Embracing solar energy is essential for a sustainable and prosperous future [3,4]. In recent years, the utilization of solar energy has advanced in areas with high amounts of solar radiation due to the fossil fuel pollution problem and low prices of photovoltaic modules. Additionally, the efficiency of photovoltaic modules is decreased, which causes a reduction in the cost-benefit ratio of renewable energy systems [5]. The most important method to optimize photovoltaic modules' efficiency is to apply a maximum power point tracking MPPT technique under different weather conditions [6]. The photovoltaic module voltage and current change to generate different power values, The MPPT technique could effectively track the varying operation points to produce the highest amount of output power, which optimizes the photovoltaic efficiency [7].The photovoltaic maximum power point tracking MPPT could be obtained using different methods and strategies, such as perturb and observe (P&O) and incremental conductance INC [8].The P&O algorithm is considered a conventional methodology in which the operating point of the PV system periodically perturbs and observes certain variations in output power. [9]. However, the P&O control approach results in more energy losses and enables PV module inefficiency because of the oscillations around MPPT [10]. SMC is capable of efficiently managing PV module nonlinearities [11]. on the other hand, Fuzzy Logic controller FLC is one of the modern techniques that provides more flexible control and employs a set of fuzzy rules and variables for making decisions [12]. the FLC approach is considered a smooth control method since it raises the PV module efficiency by reducing the oscillation around MPPT [13]. The combining of P&O and FLC algorithms optimizes the PV module efficiency for instance, FLC could determine variable step sizes in P&O to decrease oscillations around MPPT and raise the overall system performance [14]. Each of these algorithms has advantages and disadvantages, the choice of MPPT approach is based on the specific needs of a photovoltaic module, including complexity, precision, and response time [15]. Many researchers have discussed their MPPT algorithm findings and compared different MPPT approaches for photovoltaic modules under uniform solar irradiance [16,17,18]. Also, the last studies have attempted to combine the traditional MPPT approaches and advanced AI technologies [19,20,21]. PV connected to the grid without batteries is less expensive and requires less upkeep [22]. Grid-connected PV does not require batteries because the generated power is uploaded to the gridfor direct transmission, distribution, and consumption[23,24]. these include issues with power quality, reverse power flow, overvoltage along distribution feeders, trouble controlling voltage, phase imbalance, and increased reactive power islanding detection [25].Islanding occurs when a solar system supplies power to a load without grid electricity, which can

endanger utility workers who might unknowingly interact with energized circuits.[26] .

This study examines an advanced grid-connected photovoltaic (PV) system that employs (MPPT) with (FLC) to evaluate the effects of integrating PV systems into the gridConnected to an efficient single-phase DC/AC converter, the inverter is modeled using a sophisticated PWM-controlled single-phase full-bridge IGBT module (H-bridge),The Maximum Power Point Tracking (MPPT) controller expertly integrates fuzzy logic control to compare with conventional perturb and observe technique to optimize energy extraction, the PWM generator employs bipolar modulation.By varying the load, we can effectively analyze the behaviour of the Maximum Power Point Tracking (MPPT) control technique and determine the time it takes to achieve a stable operating state. This understanding is vital for optimizing PV system performance and efficiency as shown in Figure 1.

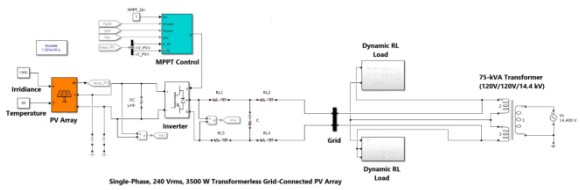


Figure 1: Design PV MPPT System connected to Dynamic Load.

II. MATHEMATICAL MODELLING

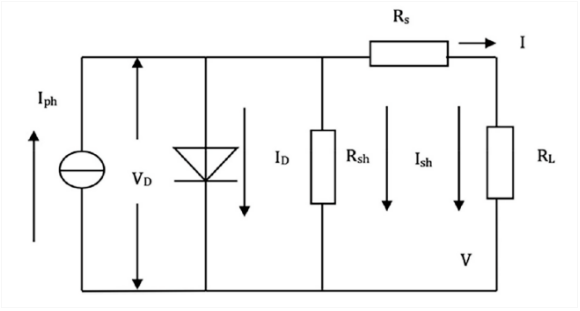


Figure2: PV cell equivalent model.

Figure 2 illustrates the equivalent circuit of a solar cell, which includes the following components:

I_{ph}:This represents the optical current, I_{sh}: This is the diode current,

I: This is the current that flows through the series resistance.
The external load resistor is denoted by Rs, and the internal resistor by R_{ush}, $V_D$the diode voltage, V is the output voltage across the load.

$$I = I_{ph} - I_D - \frac{V_D}{R_{sh}} \quad (1)$$

we can obtain ID and VD, respectively

$$V = V + I R_s \quad (2)$$

$$I_D = I_o = (\exp\left(\frac{q V_D}{A K_T}\right) - 1) \quad (3)$$

Now, we can substitute in eqn. (1) to get:

$$I = I_{ph} - I_O \left[\exp\left(q\left(V + \frac{I R_s}{A K_T}\right) - 1\right)\right] - V + IR_s / R_{sh} \quad (4)$$

Where:

- q is electron charge, $q = 1.6 * 10^{-19} C$
- K is the Boltzmann constant, $K = 0.86 * 10^{-4} (\frac{ev}{K})$
- T is the absolute temperature,
- A is the curve constant of the PN junction.

Finally, the modified current equation can be written as follows:

$$I = I_{ph} - I_o \left[\exp(\frac{q (v+IR_S)}{A KT} - 1\right] \quad (5)$$

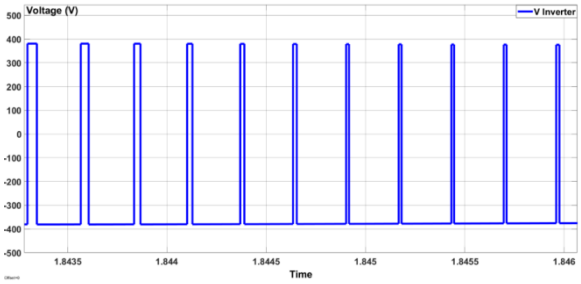


Figure 3: Voltage waveform for Cascaded two-level H-Bridge Inverter.

In Figure 3, the waveform is a modulated square wave, filtered by the H-Bridge output of two-level inverters using Pulse Width Modulation (PWM)indicating efficient two-level switchingPWM control employs high-frequency switching, ensuring precise control of the output voltage profile.For an H-Bridge inverter, the output voltage V_{ab} across the load terminals is:

$$V_{ab}(t) = V_{dc} . S(t) \quad (6)$$

Where $S(t)$is a switching function alternating between +1, 0, and −1 depending on the modulation strategy (e.g., bipolar or unipolar PWM). In a single-phase full-bridge inverter, this gives:

$$V_{ab}(t) = \begin{cases} +V_{dc} \text{ when switches } S1 \text{ and } S4 \text{ are } ON \\ -V_{dc} \text{ when switches } S2 \text{ and } S3 \text{ are } ON \end{cases} \quad (7)$$

The inverter is directly connected to a photovoltaic (PV) array, The Cascaded Two-Level H-Bridge inverter effectively converts this fluctuating DC power into AC energy.

III. METHODOLOGY

The characteristic curve of a photovoltaic (PV) array demonstrates that the cells behave nonlinearly,

primarily influenced by changes in irradiance and temperature [28-32]. This variability complicates the task of identifying and calculating the maximum power point (MPP) at any load, as it shifts throughout the day. To maximise efficiency, it is essential to dynamically adjust the operating point to match the MPP. [33,34].We highlight the advantages of the DC-DC Boost converter and DC/AC converter, particularly their low switching losses and reduced inductance, which lead to minimised current ripples and lower system stress during operation [35,36]. Fuzzy Logic Control Technique is vital for navigating this process effectively, making it essential for achieving peak performance in PV systems.

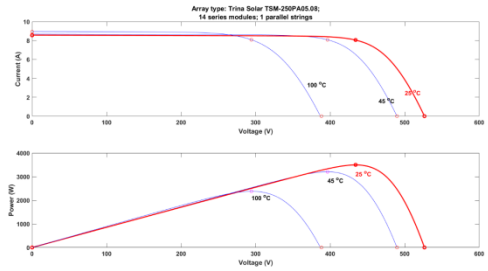


Figure 4: PV Curves (Current-Voltage-Power).

PV characteristics as shown in Figure 4, which describe the PV Panel curves about Temperature increase, which are related to Voltage and current variation. Perturb and Observe (P&O) techniques are commonly used to track the Maximum Power Point (MPP) in photovoltaic (PV) systems due to their ease of use and minimal reliance on system parameters.The P&O algorithm is particularly effective in situations where atmospheric conditions fluctuate continuously or gradually, which can lead to power losses in the PV system.

The effectiveness of the P&O approach is influenced by the I-V and P-V characteristic curves, as well as the step size of the voltage perturbation. In this method, the voltage of the PV array is gradually changed, and the corresponding power response is assessed. Suppose an increase in operating voltage leads to higher power output. In that case, the operating point is to the left of the MPP, indicating that further voltage increases are necessary to reach the optimal point. Conversely, if an increase in voltage results in a decrease in power, the operating point is to the right of the MPP, requiring voltage reductions to converge towards the MPP.

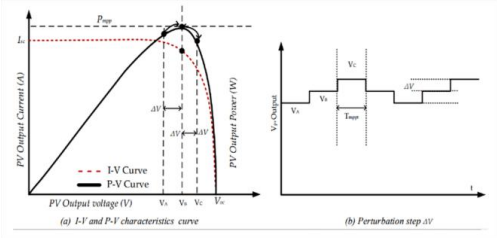


Figure 5: P&O MPPT Operation.

The four primary components of a Fuzzy Logic Controller (FLC) are the fuzzifier, knowledge base, inference mechanism, and defuzzifier.

In Fuzzifier, component transforms classical inputs into fuzzy sets using membership functions, which can be Gaussian, trapezoidal, or triangular, depending on the application. In Knowledge Base, defines the system's control logic through IF-THEN rules stored in the knowledge base.In Inference Mechanismprocesses the rules from the knowledge base to generate a fuzzy output. While Defuzzifierconverts the fuzzy output into a clear control signal.

In this study, for regulating the speed of a DC motor using the Mamdani approach by develop a Fuzzy Logic Controller (FLC). With two input variables, such as Error (E) and Sum of Error (ΣE), to corresponding control actionsGaussian membership functionsemployed for fuzzifying the inputs, which allows for smooth transitions and enhances sensitivity to changes. For the output, triangular membership functions are utilized to simplify the defuzzification process and accelerate the system's response.The system's operational logic is encapsulated in a set of 25 fuzzy rules that address various failures and dynamic conditions. The defuzzification process generates accurate output signals suitable for real-time applications.

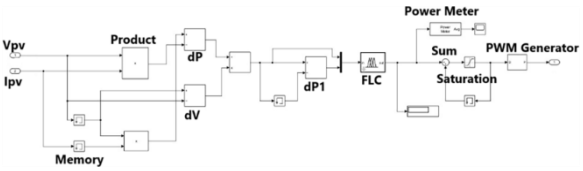


Figure 6: Design of Fuzzy Logic Controller.

The system's ability to adapt effectively to changing operating conditions with more detailed perspective is provided in Figure 7, which employs 3D surface plots to display how adjustments to both error terms produce smooth, continuous changes in the control signal.

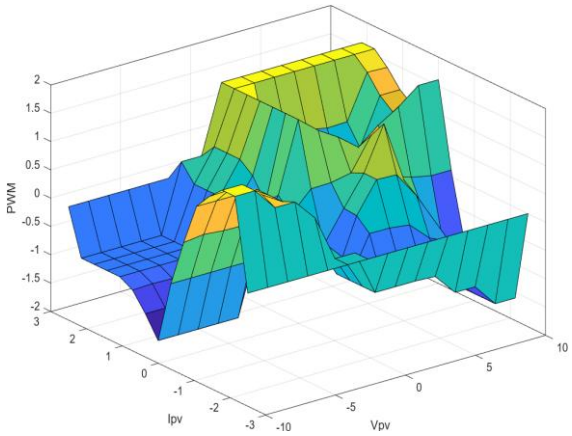


Figure7 :FLC controls the surface.

In Figure 8, The H-Bridge inverter receives DC input from the photovoltaic (PV) array, along with pulse-width modulation (PWM) signals from the fuzzy logic controller (FLC) output.Power is efficiently fed into the grid while supporting a dynamic load, with the inverter output synchronised to the grid's voltage and frequency. As the dynamic RL load, which varies in resistance (R) and inductance (L), changes the current drawn, the fuzzylogic controller (FLC) adjusts the inverter output to maintain the maximum power point (MPP) and ensure grid stability.

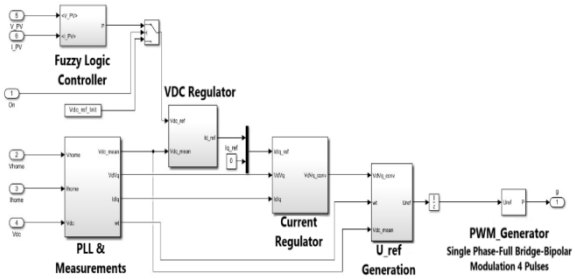
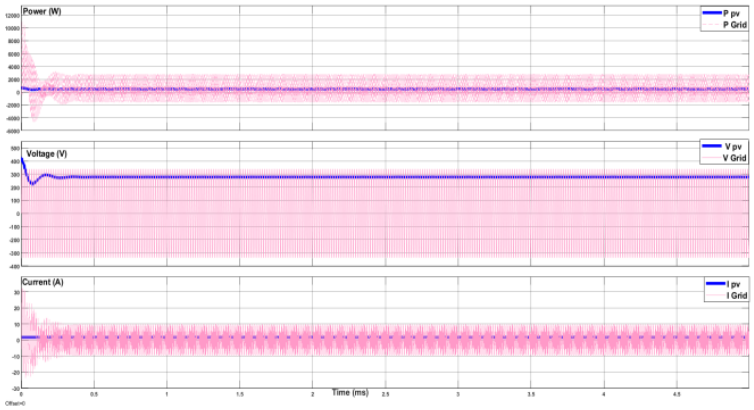


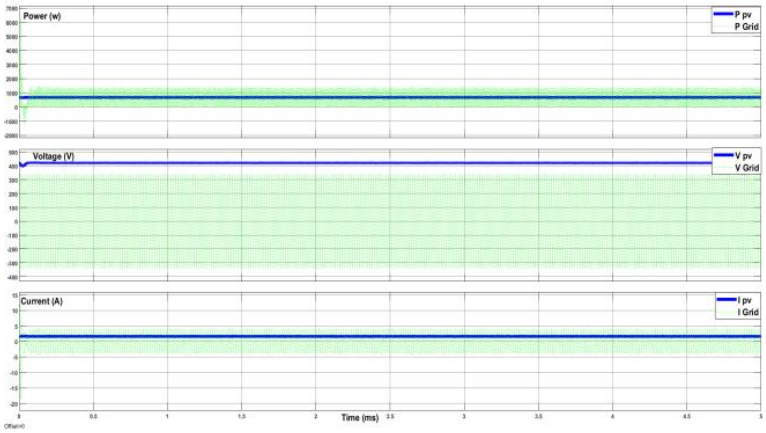
Figure. 8 . H-Bridge Inverter Topology.

IV. RESULT

First Scenario: Irradiance 200 W/m², Temperature 25 C, in Figure 9,(FLC) is highly effective, providing exceptional stability with minimal ripple after initial convergence and ensuring near-constant power delivery.(P&O) method experiences significant oscillations around the Maximum Power Point (MPP) and is less stable under dynamic load changes. FLC managing variations in (R) and (L) smoothly, resulting in fewer fluctuations in current and voltage. P&O, is more sensitive to load changes and exhibits slower response times, resulting in increased ripple.FLC performs optimally under low irradiance and variable loads, achieving impressive efficiencies of approximately 92-96%. P&O achieving lower efficiencies of about 85-90% due to tracking errors and ripple losses. At 200 W/m² irradiance.



A- FLC Power, Voltage and Current Signals.

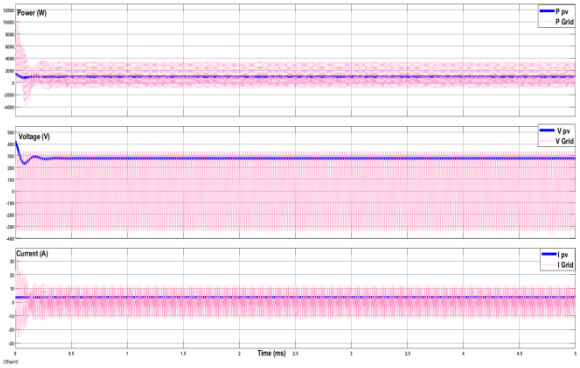


B- P &O Power, Voltage and Current Signals.

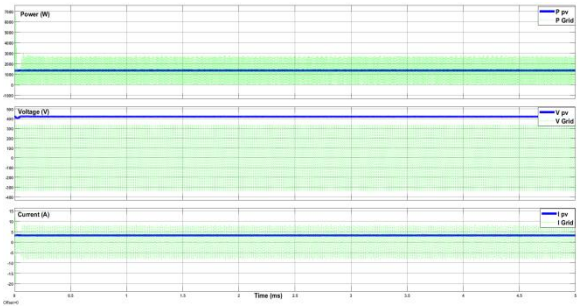
Figure 9: (A- FLC Signals, B- Perturb & Observe In Condition (IR=200 W/m², Temp 25 C).

Second Scenario: Irradiance 400 W/m², Temperature 35 C,Thehigher temperatures may slightly reduce voltage, the efficiency benefits of advanced control methods remain compelling.in Figure 10,(FLC) excels with its rapid convergence, quickly reaching and maintaining the Maximum Power Point (MPP), while Perturb and Observe (P&O) lags with slower response and overshooting issues.FLC consistently delivers stable power output with minimal fluctuations, P&O suffers from greater

variability, especially during load transitions. At 35°C, FLC effectively compensates for voltage drops and adapts to thermal drifts,P&O struggles with voltage oscillations. FLC produces smoother waveforms and superior(THD) performance, in contrast to P&O's noticeable switching ripple and current instability.



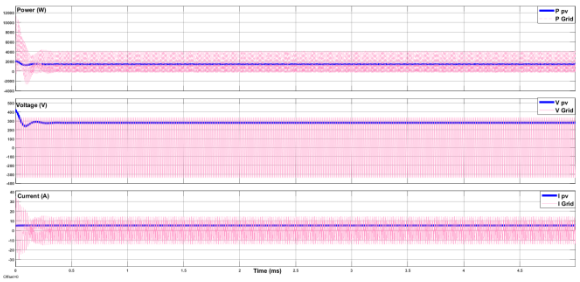
A- FLC Power, Voltage and Current Signals.



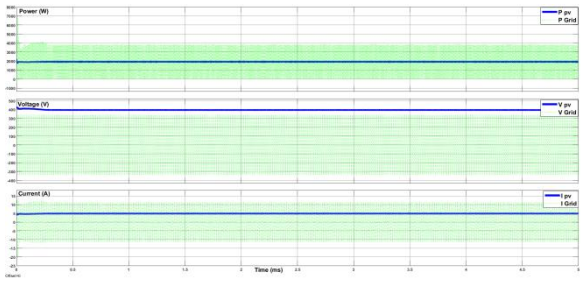
B- P &O Power, Voltage and Current Signals.

Figure 10 (A- FLC Signals, B- Perturb &Observe In Condition (IR=400 W/m², Temp 35 °C)).

Third Scenario: Irradiance 600 W/m², Temperature 45 °C,In Figure 11,(FLC) achieves fast and smooth convergence to the MPP,(P&O) method is slower to find the new MPP and exhibits oscillations and delayed responses.The FLC adapts better to voltage drops due to its adaptive logic, while P&O struggles with voltage instability and rapid thermal effects.the FLC produces smooth outputs with minimal ripple, even under varying loads. The P&O method,shows significant current ripple and reduced damping under high irradiance.the FLC's reducing issues with reactive power and (THD) with high efficiency (94-96%) under thermal stress. The P&O methodwith efficiencies around 83-88%.



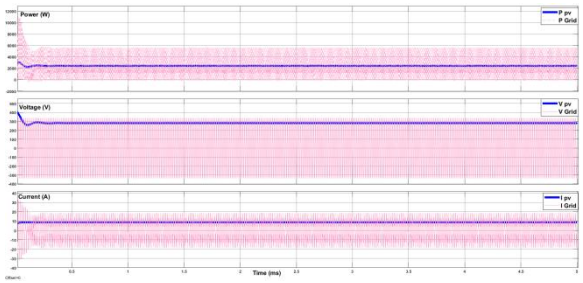
A- FLC Power, Voltage and Current Signals.



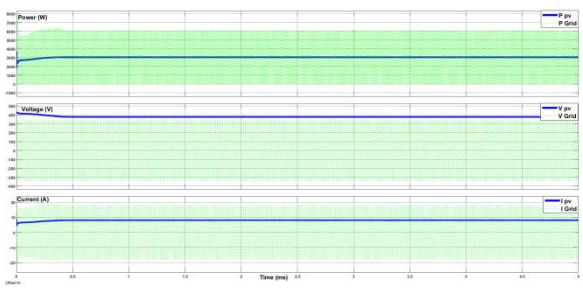
B- P &O Power, Voltage and Current Signals.

Figure.11 (A- FLC Signals, B- Perturb & ObserveIn Condition (IR=600 W/m², Temp 45 C)).

Fourth Scenario: Irradiance 1000 W/m², Temperature 55 C, with dynamic loads ranging from 1000–5000 Ω in resistance and 100–750 H in inductance, the rated power of the PV system is 250 W, yet actual output typically falls between 200–230 W due to temperature losses. Figure 12 illustrates the power, voltage, and current signals, showcasing the superior performance of fuzzy logic control (FLC) in maximizing power point tracking (MPPT).FLC techniques also produce clean, sinusoidal voltage and current waveforms with minimal distortion, outperforming P&O, which experiences higher harmonic distortion. the FLC demonstrates excellent grid-following behavior, making it ideal for inverter integration. In contrast, P&O fluctuations can diminish inverter efficiency andpower quality. Ultimately, FLC achieves an impressive power quality. Ultimately, FLC achieves an impressive efficiency of 95–97%, compared to P&O's 82–87% due to tracking losses and ripple effects. The FLC's advantages clearlyposition it as the superior choice for enhancing photovoltaic system performance efficiency of 95–97%, compared to P&O's 82–87% due to tracking losses and ripple effects.



A. FLC Power, Voltage and Current Signal



B. P &O Power, Voltage and Current Signals.

Figure. 12 (A- FLC Signals, B- Perturb & Observe In Condition (IR=1000 W/m², Temp 55 C

VI . CONCLUDING REMARKS

Benchmark	FLC	P&O
Tracking accuracy	High	Medium
Output power smoothness	Very smooth	Ripple observed
Temperature compensation	Adaptive	Limited
Dynamic load handling	Robust	Weak
On-grid compatibility	Excellent (low THD, stable)	Acceptable (needs filtering)
Use in real-world	Strong	May require

Benchmark	FLC	P&O
systems	candidate	enhancement

Table1: Benchmark Analysis for FLC-P&O.

Fuzzy Logic Control (FLC) significantly surpasses Perturb and Observe (P&O) in on-grid photovoltaic (PV) Maximum Power Point Tracking (MPPT) systems, particularly in conditions were irradiance and load change rapidly.

The summary and conclusion of your On-Grid PV MPPT System, demonstrating the effectiveness of both FLC and P&O techniques under varying irradiance and temperature conditions with a dynamic resistive load, showcasing FLC's superior adaptability and energy optimisation as shown in table 1.

Scenario	Irradiance (W/m^2)	Temperature (°C)	FLC Performance	P&O Performance	Notes on Dynamic Load Response
1	200	25	Stable low power output (~90–100 W), quick tracking, minimal ripple	Under-tracking, visible power oscillations	FLC handles inductive load variation better; P&O shows lag
2	400	35	Improved response, higher power (~150 W), smooth waveform	Moderate oscillations, slow convergence to MPP	P&O more affected by RL changes—unstable power
3	600	45	High efficiency (~93–95%), fast MPP lock-on, low THD	Noticeable ripple in voltage and power, slower tracking	Dynamic R & L cause more instability with P&O
4	1000	55	Maximum power (~220 W), high performance, grid-smooth output	Power ripple, voltage drop due to heat not well handled	FLC compensates for temp-induced drift; P&O less adaptive

Table 2 Comparison of (FLC) & (P&O)Performances According to Different Weather Conditions

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