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Design and Analysis of P&O and Fuzzy Logic MPPT Techniques with Boost Converter for PV Optimization

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ABSTRACT- This paper presents a comparative analysis of the Perturb and Observe (P&O) and Fuzzy Logic Control (FLC) methods for Maximum Power Point Tracking (MPPT) in photovoltaic (PV) systems with a boost converter. Both methods were simulated with MATLAB/Simulink, and the performance was compared on the basis of parameters such as response time, overshoot, steady-state error, and Power Extracting Efficiency for different conditions standard, Variable radiation, Partial shading, variable temperature and variable load. It was observed that the P&O approach is simple to realize, yet it possesses some drawbacks and limitations like, slow response, power fluctuations, relatively high overshot and steady state error, which are accountable for system inefficiency. Nevertheless, the FLC approach presented quicker response time, lesser overshoot, and greater stability compared to the P&O and greater efficiency in tracking the MPP. These advantages position FLC as an optimum tool for maximizing the stability and performance rating of photovoltaic systems in the face of varying environmental conditions.

Keywords: MPPT, Perturb and Observe (P&O), Fuzzy Logic Control (FLC), PV, Boost converter.

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1. INTRODUCTION

As there has been a growing demand for renewable energy, photovoltaic (PV) systems have become the leading technology for the generation of renewable energy. As PV system performance is environmentally dependent, Maximum Power Point Tracking (MPPT) methods regulate the operating point to achieve maximum power extraction under all conceivable environmental conditions [1]. Perturb and Observe (P&O), a simple yet widely used MPPT method with slow convergence in mixed conditions, and Fuzzy Logic, an artificial intelligence-based method with fast tracking potential is compared here by simulations for guiding real-world practical applications in renewable energy [2].

The system comprises a photovoltaic (PV) panel, DC-DC boost converter, two MPPT controllers (Perturb and Observe (P&O) and Fuzzy Logic Controller (FLC)), and a load as depicted in *figure 1*. The PV converts sunlight into direct current (DC) electricity that changes with the environmental conditions. A DC-DC boost converter steps up the PV output voltage to the level needed by the load, as controlled by the MPPT algorithms of P&O or FLC controllers. The two controllers are independent; however, they track the MPP in parallel and adjust the setting in the boost converter for maximum power extraction. The maximum power point then feeds the load where one can witness the P&O and FLC performance in real time, fault tolerance, but at the cost of more complex power electronics and motor cost.

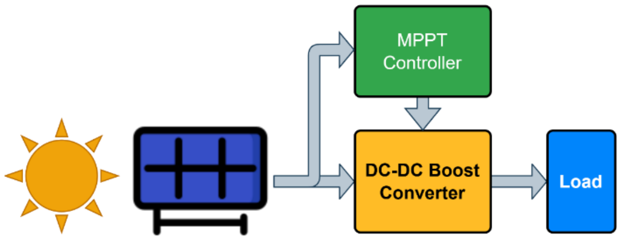

Figure 1. Block diagram of the system

2. BACKGROUND

Photovoltaic systems make use of semiconductor material to transform solar energy into electricity through the generation of direct current (DC) power, which is further invertible into alternating current (AC) using an inverter. The performance of PV systems is influenced by various parameters like solar irradiance, temperature, and shading, thus necessitating the optimization of performance as vital in lowering the costs of solar energy utilization while enhancing long-term sustainability [3]. Maximum Power Point Tracking (MPPT) is a technique used to maximize energy generation through continuously adjusting the

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system operating point on the current-voltage (I-V) characteristic curve so that it matches the maximum power point (MPP). Because of the constant change in environmental parameters, MPPT controllers need to update parameters, such as converter duty cycles, in order to reach optimality [4]. Dynamic conditions, nevertheless, pose difficulties—partial shading, for instance, generates several local maxima, and temperature changes displace the MPP. Conventional techniques such as Perturb and Observe (P&O) might find it hard to deal with such intricacies, making it necessary to implement sophisticated MPPT algorithms to maximize efficiency under varying conditions [5].

3. LITERATURE REVIEW

Alkhayyat and Aiwa (2024) research paper discusses the application of an FLC-based MPPT method for PV systems and also describes the performance of FLC in reacting to environmental condition changes and keeping the system reliable and stable[6]

A research work carried out by Mutlag et al. (2024) analyzed the application of P&O with boost converters and FLC controllers to enhance the performance of PV systems under varying light conditions. This research pointed out the advantages of using P&O with fuzzy logic to improve the tracking efficiency during poor conditions.[7]

Rupesh and Vishwanath (2021) presented a research paper on the application of FLC in PV systems through a boost converter, illustrating the excellence of fuzzy logic-based systems in delivering maximum energy output. In this research, it was concluded that FLC is viable in maintaining the stability and efficiency of PV systems under different conditions.[8]

Alkhayyat et al. (2024) report the application of a fuzzy logic adaptive MPPT controller in a stand-alone PV system for a symmetrical multilevel boost converter. The outcome shows the capacity of the controller to track the maximum power point without oscillation under changing solar radiation conditions.[9]

Babu and Kalavathi (2024) in their paper highlighted that MPPT using FLC with a boost converter greatly enhanced the efficiency of the PV system since the design parameters of the converter were optimized in real-time according to the environmental parameters.[10]

Recent research has concentrated on creating hybrid MPPT techniques that merge P&O and FLC or other global search techniques to maximize performance under partial shading. GA and PSO have been applied with FLC and P&O techniques for maximum system performance assurance. Sharma et al. (2024) presented a paper on the application of hybrid optimization algorithms for MPPT control in PV systems that dramatically improved the response time and accuracy of the system under adverse conditions like shading and temperature variations [11].

4. SYSTEM ARCHITECTURE OVERVIEW

Figure 2 shows the four main components of the photovoltaic (PV) system modeled in MATLAB: a PV array, a boost converter, and two MPPT controllers—Perturb and Observe (P&O) and Fuzzy Logic Control (FLC). The setup is designed to maximize tracking of the Maximum Power Point (MPP) with varying environmental conditions for maximum energy harvesting and optimum efficiency in the photovoltaic system.

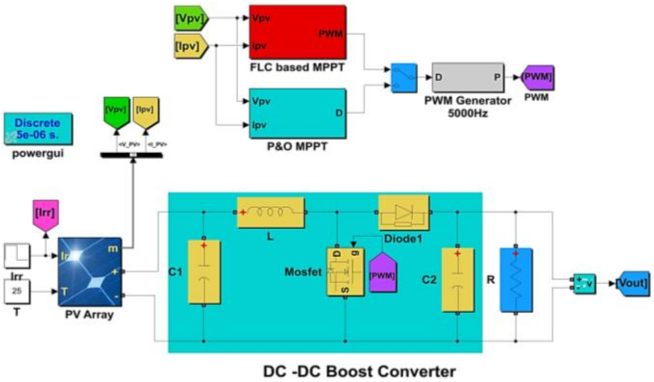

Figure 2. System Architecture in MATLAB

4.1. PV Array Design

The PV array is the focal source of energy in this system, which transforms sunlight into DC energy. Its functionality is described on the basis of the I-V (current-voltage) and P-V (power-voltage) characteristics of the array, which are functions of parameters like temperature and irradiance. For the purpose of this analysis [12].

Table 1 demonstrate the properties of a module advance Solar Hydro Wind Power AP1156P-210 which used in this simulation, the PV array is modeled using the single-diode equivalent circuit model. Initial parameters like short-circuit current (Isc), open-circuit voltage (Voc), temperature coefficients, and maximum power point (MPP) behaviors are utilized to simulate the response of the array under various conditions, the PV array is exposed to various irradiance levels (*i.e.*, 200 W/m², 500 W/m², 1000 W/m²) and temperatures (*i.e.*, 25°C, 45°C) to see its output and the efficiency of MPPT methods under these conditions.

Table 1. Properties module advances Solar Hydro Wind Power AP1156P-210

Parameter	Symbol	Typical Value	Unit
Maximum Power	P_{max}	210	W
Open Circuit Voltage	V_{oc}	36.55	V
Short Circuit Current	I_{sc}	7.79	A
Voltage at Maximum Power	V_{mpp}	28.63	V
Current at Maximum Power	I_{mpp}	7.33	A
Maximum System Voltage	V_{max}	1000	V
Nominal Operating Cell Temperature (NOCT)	-	45	°C

To obtain a power output of 5000 watts and an output voltage of 150-200 volts from the solar panel system, as outlined in the design parameters, a series connection of 6 panels must be established, followed by connecting Four of these series configurations in parallel. Consequently, a total of 24 PV panels of the specified type is required.

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4.2. Boost Converter Design

A boost converter shown in *figure 3* and its specifications design shown in *table 2* is used to increase the PV array's voltage to meet grid or load needs. In order for the MPPT controllers to maximize power extraction from the PV array, the boost converter is essential for controlling the voltage output., the boost converter is designed with parameters such as input/output voltages, inductor value, and switching frequency. The converter's duty cycle is adjusted by the MPPT controllers to maintain the system at the MPP[13].

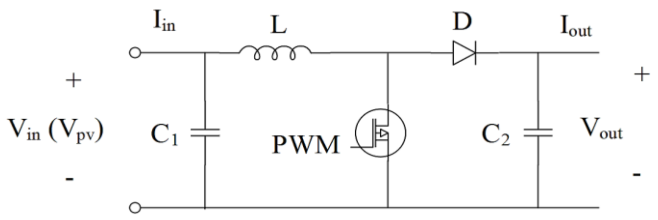

Figure 3. Boost Converter

Table 2. Specifications of boost converter design

Parameter	Symbol	Typical Value	Unit
Input Voltage	Vin	150-200	V
Output Voltage	Vout	400	V
Rated Power	Pout	5	KW
Switching Frequency	FSW	5	KHz
Current Ripple	ΔI	4%	
Voltage Ripple	ΔV	2%	

Based on the boost converter limitations tabled above and using the design laws, it is possible to calculate the values of the basic parameters in the design[14].

Output Current (I_{out}): $V_{in} = 200V$

$$I_{out} = \frac{P_{out}}{V_{out}} = \frac{5000W}{400V} = 12.5A$$

Current Ripple (ΔI_L): The ripple is 4% of the output current:

$$\Delta I_L = 0.04 \times I_{out} = 0.04 \times 12.5A = 0.5A$$

Inductor Value (L): the minimum input voltage is chosen to be $V_{\text{in}} = 150V$. The inductor is calculated based on general energy storage principles during switching.

$$L = \frac{V_{in} \cdot (V_{out} - V_{in})}{f_s \cdot V_{out} \cdot \Delta I_L}$$

$$L = \frac{150 \cdot (400 - 150)}{5000 \cdot 400 \cdot 0.5} = \frac{150 \cdot 250}{1000000} = 37.5mH$$

Capacitors Value C_1 and C_2 Using the formula:

$$C_1 \geq \frac{I_{\text{out}} \cdot D}{f_s \cdot \Delta V_{\text{in}}} = \frac{12.5 \cdot 0.5}{5000 \cdot 4} = \frac{6.25}{20000} = 312.5\mu F$$

$$C_2 \geq \frac{I_{\text{out}} \cdot D}{f_s \cdot \Delta V_{\text{out}}} = \frac{12.5 \cdot 0.5}{5000 \cdot 8} = \frac{6.25}{40000} = 156.25\mu F$$

4.3. P&O MPPT Design

One popular Maximum Power Point Tracking (MPPT) method for maximizing the effectiveness of photovoltaic (PV) systems is the Perturb and Observe (P&O) algorithm [15]. As seen in *figure 3*, it works by varying the PV system's voltage or current on a regular basis and tracking the change in output power that results. The algorithm continues to make adjustments in that direction if the operating point changes, and in the opposite direction if the power changes.[16].

The algorithm's primary goal is to keep the PV system operating at or near the maximum power point (MPP) despite changes in sunlight or load conditions. Although it's simple and cost-effective to implement, P&O may experience oscillations around the MPP under steady-state conditions and may temporarily track inaccurately under rapidly changing environmental conditions [17].

The simulation results for the Perturb and Observe (P&O) MPPT technique show that the system experiences considerable instability during changes in irradiance. When the irradiance drops from 1000 W/m² to 500 W/m² at around 0.1 seconds, both the PV voltage (Vpv) and current (Ipv) exhibit severe oscillations, including negative spikes, which reflect poor dynamic response and weak damping characteristics. The output power (Pout) also suffers from deep dips, even reaching large negative values, indicating inefficient power transfer and delayed adaptation to the new operating point. Although the output voltage (Vout) eventually stabilizes, it does so with overshoot and relatively slow recovery, highlighting limitations in the ability of P&O to respond rapidly and smoothly to environmental changes.

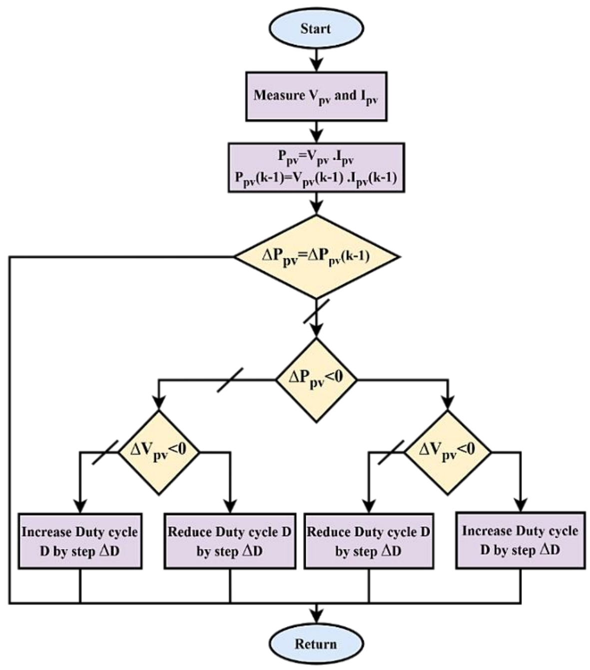

Figure 4. Perturb and Observe MPPT algorithm flow chart

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The P&O algorithm is implemented in the system simulation with a fixed step size. The algorithm continuously adjusts the duty cycle of the boost converter based on the power variations, trying to track the MPP, the algorithm which control to the duty cycle is written as a program language in MATLAB function.

4.4. FLC design and configuration

The Fuzzy Logic MPPT controller offers a more advanced approach, utilizing a rule-based system to handle the non-linear characteristics of the PV system. Fuzzy logic shown in *figure 5* is particularly effective in adapting to rapidly changing environmental conditions and minimizing oscillations around the MPP[18].

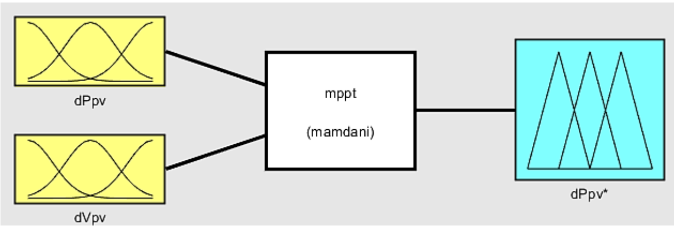


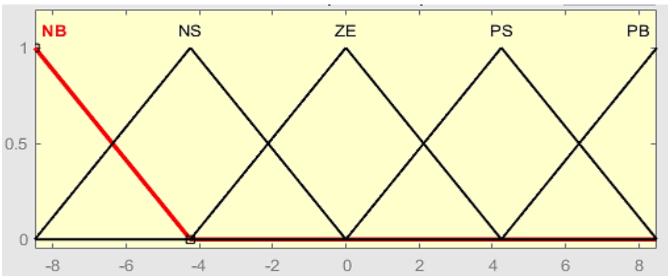
Figure 5. Fuzzy Logic Control Structure for MPPT in PV Systems

In a Fuzzy Logic Control (FLC) system for Maximum Power Point Tracking (MPPT) in photovoltaic (PV) applications, the controller inputs are the change in PV power (dP_{PV}) and change in PV voltage (dV_{PV})[19]. These inputs shown in *figure 6* are converted into linguistic terms such as Big Negative, Negative, Zero, Positive, and Big Positive via membership functions in the fuzzification process, which maps input values to degrees of membership[20]. The FLC then applies a set of fuzzy rules to these inputs to determine the output, represented as an adjustment in the Duty Cycle for the boost converter. Through defuzzification, the linguistic output is translated into a specific numerical Duty Cycle, which adjusts the PV array's operating point, aiming to maintain it at the Maximum Power Point (MPP). This approach provides a responsive, adaptive means of tracking the MPP under changing environmental conditions notice *table 3*, while the *figure 6* refers to the linguistic values of state variables of FLC[21].

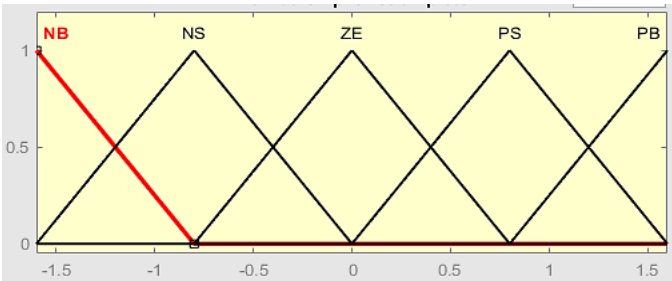
Table 3. Membership of FLC

dPpv \ dVpv	NB	NS	ZE	PS	PB
NB	PS	PB	NB	NB	NS
NS	PS	PS	NS	NS	NS
ZE	ZE	ZE	ZE	ZE	ZE
PS	NS	NS	PS	PS	PS
PB	NS	NB	PB	PB	PS

dPpv (Input 1):	Change in Power	Output dPpv:	Adjusted change in Power
dVpv (Input 2):	Change in Voltage	NB:	Negative Big
NS:	Negative Small	ZE:	Zero
PS:	Positive Small	PB:	Positive Big



(a)



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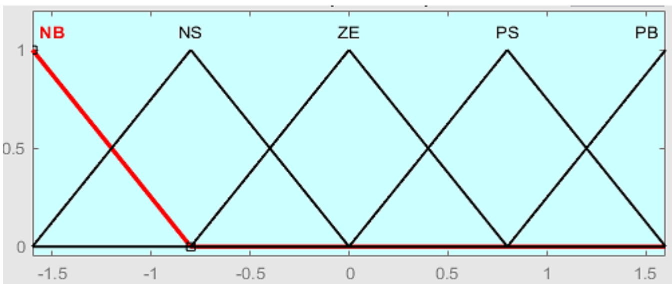

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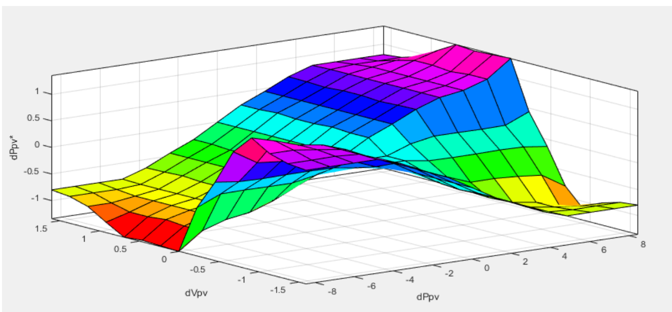

(d)

Figure 7. linguistic values of: *(a)* dPpv input variable; *(b)* dVpv input variable and; *(c)* output variable duty cycle and (d) graphical representation of fuzzy control rules

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The design of an MPPT controller using fuzzy logic (FLC) is based on the principle of maximal power point tracking (MPP) by analyzing the relationship between voltage change and the output power of the solar cell array. Two key input variables are chosen for the system: error (E) and error change (ΔE). Error represents the rate of change of power relative to voltage, while ΔE represents the difference in error value between two successive measurement samples. These two variables reflect the behavior of the curve and its direction of movement towards or away from the MPP. As the power point approaches, E is close to zero, while it carries either a positive or negative sign when the power is increasing or decreasing. The controller's output is ΔD, which represents the required change in the duty cycle of the DC-DC converter. Changing the duty cycle shifts the operating point on the I-V curve until the MPP is reached. The variables E, ΔE, and ΔD were divided into five language groups: NB, NS, Z, PS, and PB. Triangular Membership Functions were used due to their simplicity, speed of implementation, and compatibility with MPPT applications. A fuzzy rule base was then constructed, determining the output value based on the interaction of the two inputs. ΔD increases as power increases and decreases as power decreases. The output is close to zero when E and ΔE are near zero because the system is already close to the MPP. Tuning was achieved by adjusting the membership ranges and increasing the microcontroller's sensitivity by narrowing the PS and NS ranges and widening the Z range to reduce oscillation around the operating point. The inference rule was also improved by increasing the influence of PB and NB to achieve faster access to the MPP while reducing stabilization time and ripple. Finally, the Centroid method was adopted for fuzzy-field-to-scalar defuzzification, providing a smooth and stable response. As a result, the system achieved fast tracking performance with good stability around the maximum power point compared to traditional methods.

The Fuzzy Logic controller is designed and implemented in the simulation environment as showing in *figure 9*. The system evaluates the inputs and applies the corresponding fuzzy rules to adjust the duty cycle dynamically, improving the response time and efficiency of the system when D is the change in power error (dP/dV) while DE is change in D (Derivative of Error).

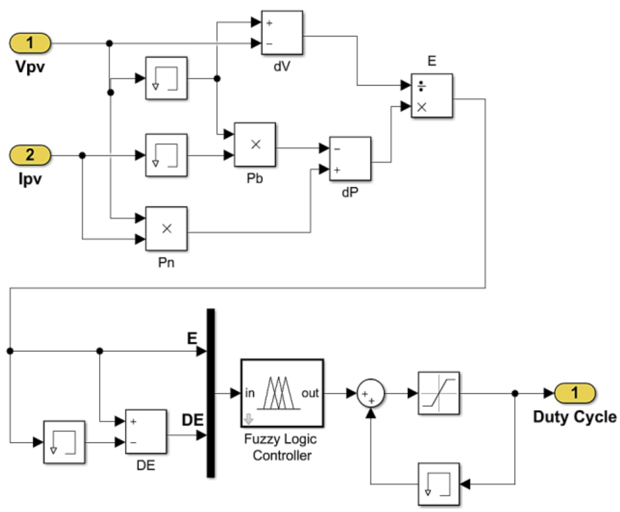


Figure 9. MATLAB Simulink of MPPT FLC

5. RESULTS AND DISCUSSION

The design is simulated in a suitable environment (*e.g.*, MATLAB/Simulink) to compare the performance of P&O and Fuzzy Logic MPPT techniques under identical conditions. The key metrics evaluated in the simulations include tracking speed, accuracy, efficiency, and system stability. Both MPPT techniques are simulated with the same PV array and boost converter under varying irradiance, varying temperature, partial shading and drop load conditions.

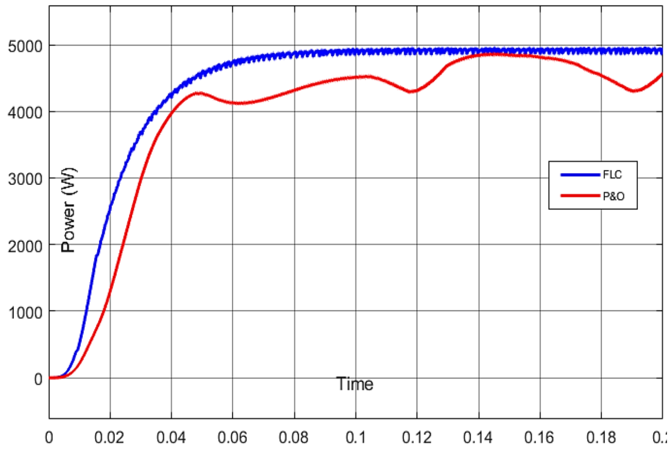
The output response of P&O algorithm and Fuzzy Logic Control (FLC) MPPT techniques for the designed system for all motioned conditions are summarized in *table 4*.

Table 4. Comparing the performance of mppt algorithms (FLC and P&O) under different operating conditions (temperature change, radiation change, load change, and partial shading) based on efficiency, stability, time response and ripple value.

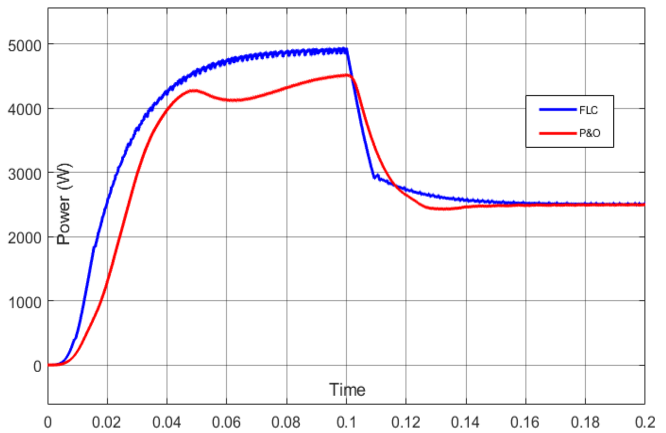
Condition	MPPT Efficiency (%)		Time of response (s)		Voltage Overshoot (%)		Voltage Ripple (V)		Current Ripple (A)	
	P&O	**FLC**	**P&O**	**FLC**	**P&O**	**FLC**	**P&O**	**FLC**	**P&O**	**FLC**
Standard (1000 w/m², 25C°)	88.5	98.32	0.14	0.07	5	1	1.2	4	0.04	0.13
Irradiation (500 w/m²)	55	60	0.12	0.12	4.8	0.6	0.75	4	2.3	0.12
Temperature (50 C°)	82	87.1	0.093	0.086	2.58	0.5	1.1	4.5	2	0.13
Drop Load to Half	89.7	92.87	0.075	0.05	0.46	0.46	1.15	2	0.8	0.1
Patial shading (600, 1000) w/m²	61.94	71.1	0.085	0.08	0.5	0.46	1	5	0.03	0.1

In contrast, the Fuzzy Logic Control (FLC) MPPT technique demonstrates a much more stable and efficient response to the most variable conditions. The PV power curves remain smoother, with only minor and short-lived oscillations, and the transient disturbances are significantly reduced compared to the P&O method. The output power shows quicker recovery and minimal negative deviation, suggesting a more accurate and faster tracking of the maximum power point. Additionally, the output voltage stabilizes swiftly and with less overshoot, indicating better voltage regulation and control. Overall, the FLC MPPT outperforms the P&O technique by providing enhanced stability, faster tracking speed, and more reliable power delivery under dynamic irradiance conditions.

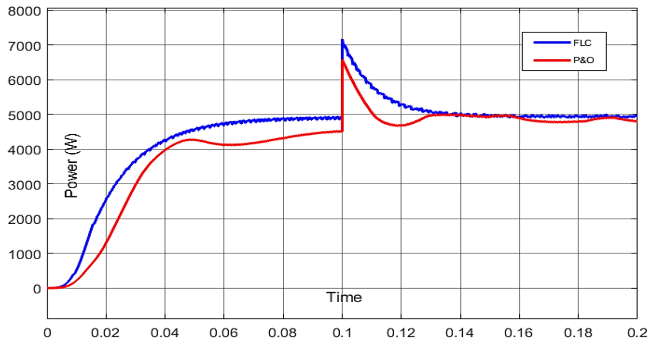
Figure 10 demonstrate the output power response of the designed boost converter controlled by FLC and P&O controller under different conditions.



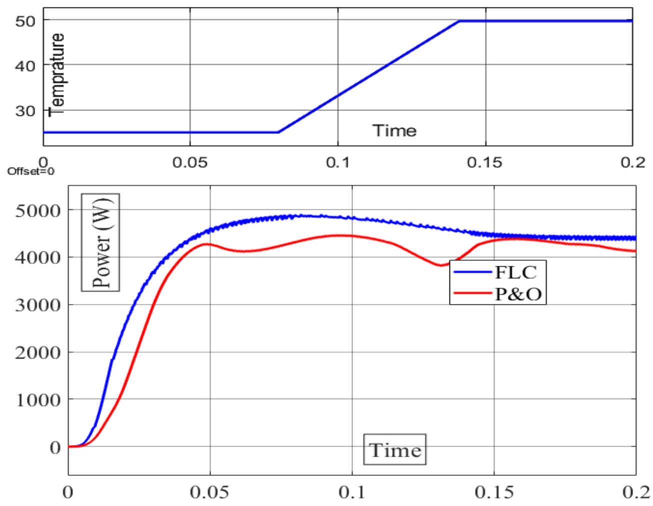
(a) The Output response of the P&O and FLC technique for boost converter output power at standard condition (1000 W/m², 25C°).



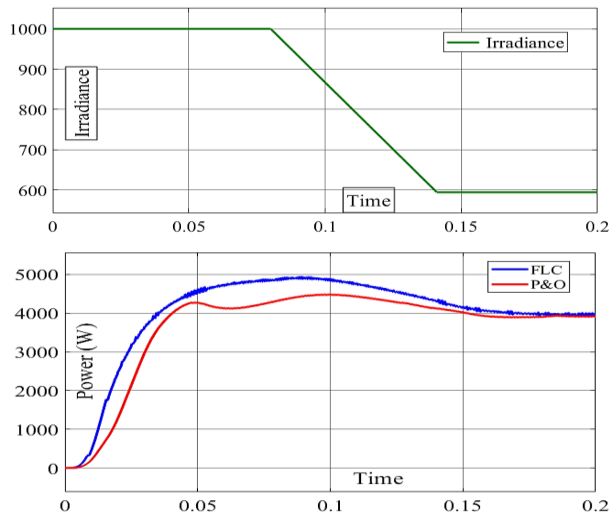
(b) The Output response of the P&O and FLC technique for boost converter output power when the irradiance drops from 1000 to 600 w/m² at constant temperature 25C° after 0.1s of starting.



(c) The Output response of the P&O and FLC technique for boost converter output power when the load value drops from 32 to 10 Ω after 0.1s of starting at standard conditions (1000 W/m², 25C°).



(d) The Output response of the P&O and FLC technique for boost converter output power with variable Temperature at constant irradiance 1000 W/m².



(e) The Output response of the P&O and FLC technique for boost converter output power at partial shading for the half of the PV panels with constant temperature 25 C°.

Figure 9. output power response of the designed boost converter controlled by FLC and P&O controller under different conditions

Table 5. A comparative benchmark study between current work and recent studies on MPPT techniques using FLC and P&O

Research	Technique	Efficiency	Response time (s)	Overshoot, Oscillation (%)	Ripple output, Stability	Conditions
This work	P&O	88.5%	0.14	5	less stable under varying conditions	Standard, Variable Temperature, variable load, partial shading, variable radiation
	FLC	98.32%	0.07	1	More stable under vary conditions	
Maamar, Yahiaoui, et al [22]	P&O	Medium	0.33	More overshoot	Medium	Standard, Variable radiation, variable temperature
	FLC	Very High	0.11	Less Overshoot	Very High	
Abdelsattar, et al [23]	P&O	Low	Varies	---	---	Varying conditions
	FLC	Medium	Medium	---	---	
Pavithra, C, et al [24]	P&O	Lower	Slow	Lower	Stable (at low fixed step size)	variable environmental conditions
	FLC	Higher	Fast	Higher	Stable	
Lamia, Y.,[25]	P&O	Lower	0.14	Large	Less stability	Varying irradiations
	FLC	Higher	0.035	Small	More stability	
Abdelaziz, Y., et al [26]	P&O	Lower	Lower	---	More	partial shading
	FLC	Higher	Faster	---	Less	

7. CONCLUSION

This study evaluated the performance of Fuzzy Logic Control (FLC) and Power-and-Operate (P&O) technologies combined with a boost converter to optimize photovoltaic power systems under varying environmental and operating conditions, such as load variation, solar irradiance variation, partial shading, and temperature variations. The results conclusively demonstrate the superiority of FLC over P&O in both energy extraction and overall system quality. FLC provided faster convergence to the Maximum Power Point (MPP), less oscillation, and stable voltage and current outputs with minimal ripple, resulting in more efficient energy harvesting under varying environmental conditions.

Although P&O is less computationally demanding and easier to use, its slow response time and oscillatory nature around the MPP reduce its efficiency and lead to energy losses. However, FLC's intelligent and adaptive nature makes it more efficient at handling nonlinearity and sudden changes in environmental parameters, making it the ideal choice for applications requiring reliability and precision. These results highlight that FLC technology is the most effective and efficient method compared to P&O technology in high-performance photovoltaic systems. Hybrid methods that leverage the simplicity, flexibility, and improved performance of P&O technology could be the subject of future research.

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