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MAXIMUM POWER POINT TRACKING USING FUZZY LOGIC CONTROLLER IN SOLAR PV SYSTEMS

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Abstract— This study conducts a comparative analysis between the conventional Perturb and Observe (P&O) method and fuzzy logic control (FLC) to determine the superior approach for maximizing power extraction in solar photovoltaic (PV) systems. The P&O method, frequently employed for Maximum Power Point Tracking (MPPT), demonstrates significant oscillations upon reaching the maximum power point (MPP) and necessitates a considerable duration to achieve stability. The dynamic performance of the PV system output is examined by utilizing MATLAB simulations of P&O method while considering different irradiance levels. To overcome the use of the P&O method, a fuzzy logic controller is employed to manage the constraints and evaluate the system. The experiments were conducted in different irradiance and the output performance of both FLC, and P&O was noted such as at 800 W/m^2 irradiance, FLC stabilizes at a voltage of approximately 258 V but P&O continues to show significant oscillations with lower voltage around 240 V to 250 V. The findings indicate that FLC significantly mitigates variations at the MPP and achieves a greater output value with a more rapid response time while the P&O algorithm exhibits significant oscillations and delayed responses, particularly under higher irradiance levels. The study's findings indicate that FLC is a superior and more dependable solution for MPPT in PV systems, resulting in enhanced overall reliability and efficiency.

I. Introduction

Energy is essential for both our economy and our daily lives. The industrial revolution has led to a rise in our energy requirements. The developing nation primarily derives its energy from non-renewable sources. The depletion of hydrocarbons, fossil fuels, and other resources is causing developing nations' civilizations to exceed their sustainable limits. Furthermore, traditional energy generation releases greenhouse gases. Global reduction of greenhouse gas emissions, such as Carbon dioxide (CO_2), is necessary to guarantee affordable, safe, and clean energy [1]. Solar, geothermal, biomass, photovoltaic (PV), and wind energy can mitigate the release of CO_2 and other greenhouse gases derived from fossil fuels. Solar energy mitigates greenhouse gas emissions and averts climate change, safeguarding ecosystems, wildlife, and human well-being. Solar energy enhances air quality and minimizes water consumption. PV technology harnesses the power of sunlight and transforms it into electrical energy, making it a commonly utilized method today. In 2017, PV generating systems produced 402 gigawatts (GW), an increase from the 303 GW generated in 2016. The projected increase in PV generation penetration by 2030 is estimated to be between 1760 and 2500 GW [2].

PV cells convert solar radiation into electrical energy. Light induces an electric field between layers of cells, resulting in the generation of electric current. PV systems are inherently variable and vulnerable to changes in temperature and irradiance, thus posing certain difficulties. The primary concerns are decreased efficiency and unpredictable output behavior [3]. Enhancing the performance of PV systems is crucial for optimising electricity generation. Numerous techniques are available to enhance the efficiency of PV systems. A suboptimal power management strategy can decrease the efficiency of a solar photovoltaic PV system.

Maximum power point tracking (MPPT) is an evolving power management system. The MPPT method calculates the ideal voltage and current values for a solar module to achieve maximum power output, taking into account specific temperature and irradiance conditions. This system utilises MPPT, an advanced algorithm, and a direct current-to-direct current (DC-DC) converter. MPPT and a DC/DC boost converter enhance power transfer efficiency between a PV system and a load [3]. The prime methods for power point tracking include Incremental Conductance (INC), Hill Climbing, and Perturb and Observe (P&O). During power tracking, the P&O algorithm remains unaffected by the characteristics of the PV system, such as temperature and radiation. The P&O MPPT method is susceptible to atmospheric conditions due to its oscillation at the maximum power point (MPP), which leads to persistent disturbances and reduced efficiency [3]. We have employed the MPPT technique to enhance the efficiency of power extraction. Irradiance and temperature influence the output of solar panels. As a result, a controller is required to ensure the system's reliability [4, 5].

Fuzzy logic control (FLC) is the most suitable method for achieving MPPT because of the fuzzy-based MPPT algorithm's reliability, simplicity of development, precision, and quick adaptability to dynamic environmental changes [4].

To improve the performance of a PV system, the temperature and irradiance factors must be considered and optimized. To enhance efficiency, it is necessary to conduct a study on MPPT utilizing FLC.

This paper aims to design and simulate a comprehensive MPPT system using a FLC and a Buck-Boost converter. Once the FLC is developed, it will be compared and tested against the conventional MPPT method known as P&O Method. Finally, assess the performance under different temperature and irradiance conditions and thoroughly analyze the results. This study does not include an analysis of partial shading conditions.

II. MPPT Study

A systematic research methodology and design procedure have been devised to streamline the project. The process primarily comprises project preparation, component selection and design, and software implementation.

A. Perturb and Observation

The perturbation and observation method, commonly called P&O, is a widely employed for tracking the MPP. This method involves perturbing the system by adjusting the duty cycle of the DC-DC converter, both increasing and decreasing it, and subsequently monitoring the resulting impact on the output power. The purpose of this observation is to potentially rectify the duty cycle in order to optimize power generation [10]. Based on the MPPT technique, the initial step involves measuring the voltage and current values at the starting operating point, followed by calculating the equivalent power value (P1). A slight variation in voltage is introduced, and the resulting power Pnew is computed [9] while Pold is the power achieved before the variation of the voltage.

After comparing Pnew and Pold, the subsequent perturbation is determined. If the value of Pnew is greater than Pold, the perturbation will be continued in the same direction until the MPP is attained. In the scenario of reverse case perturbation, the perturbation is applied in the opposite direction. The methodology commonly employed in PV modules to achieve optimal power extraction is widely recognized as the most popular method [9].

Its tracking velocity and steady-state oscillations determine the efficacy of the P&O approach as mentioned in Figure 1, primarily contingent upon the magnitude of the perturbation step size. Using

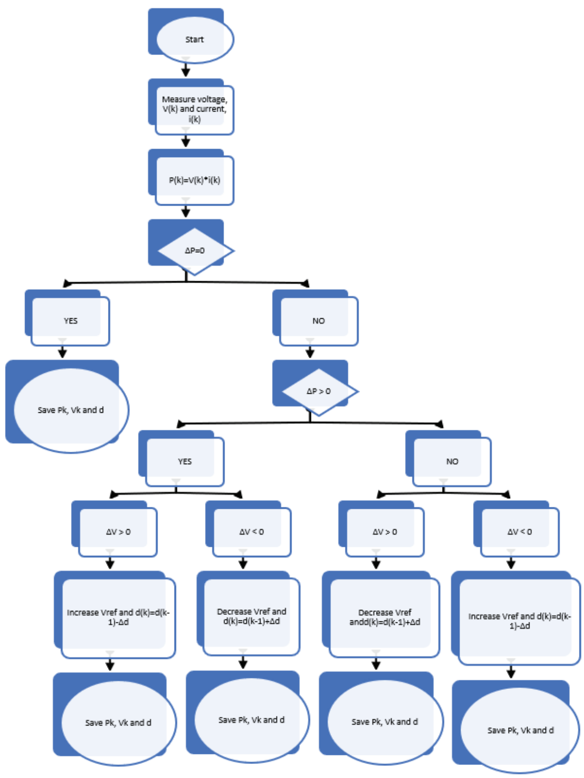

Figure 1: Flowchart of the P&O method [11]

a larger perturbation step size accelerates the tracking time but also leads to significant oscillations in the steady state. A decrease in the magnitude of the perturbation step size leads to a reduction in the amplitude of steady-state oscillations. However, it also results in a decrease in the system's responsiveness or agility. Hence, it is imperative to select the perturbation magnitude with caution in order to minimize steady state oscillations while concurrently enhancing the speed of reaction [9].

B. Fuzzy Logic Controller

Fuzzy logic approaches have become widely employed across various industries, demonstrating their applicability in the operation of wind turbines equipped with nonlinear models. The fuzzy logic structure comprises three sub-blocks: fuzzification, inference, and defuzzification [3].

1. Fuzzification

In the initial phase of fuzzification measurement, the fluctuations in the output voltage and current of the PV panel are used to ascertain the input membership functions of the fuzzy logic-based MPPT controller. During the interference process, linguistic rules based on FLC are employed to determine the control action by establishing logical connections between the input and output membership. The stage of rule evaluation involves the generation of a fuzzy output membership function for each type of subsequent action of the input membership function. The defuzzification stage is responsible for transforming linguistic variables into crisp variables [4]. There are two input variables used in fuzzification in this experiment: voltage and current. This input characterises the rate at which the output voltage and current vary. This factor is crucial in a real-time control strategy for enhancing the system's time response [2].

In fuzzy control, there are subsets in odd quantities. Fuzzy subsets are employed to assign membership function values to linguistic variables in linguistics [4]. The subsets are the margin of quantity in a linguistics manner.

In this FLC, five subsets are used which are Very Low (VL), Low (L), Medium(M), High (H), and Very High (VH) as referred to in Figure 2. Figure 2 shows the two inputs voltage and current and the output duty cycle membership functions along with the subsets value.

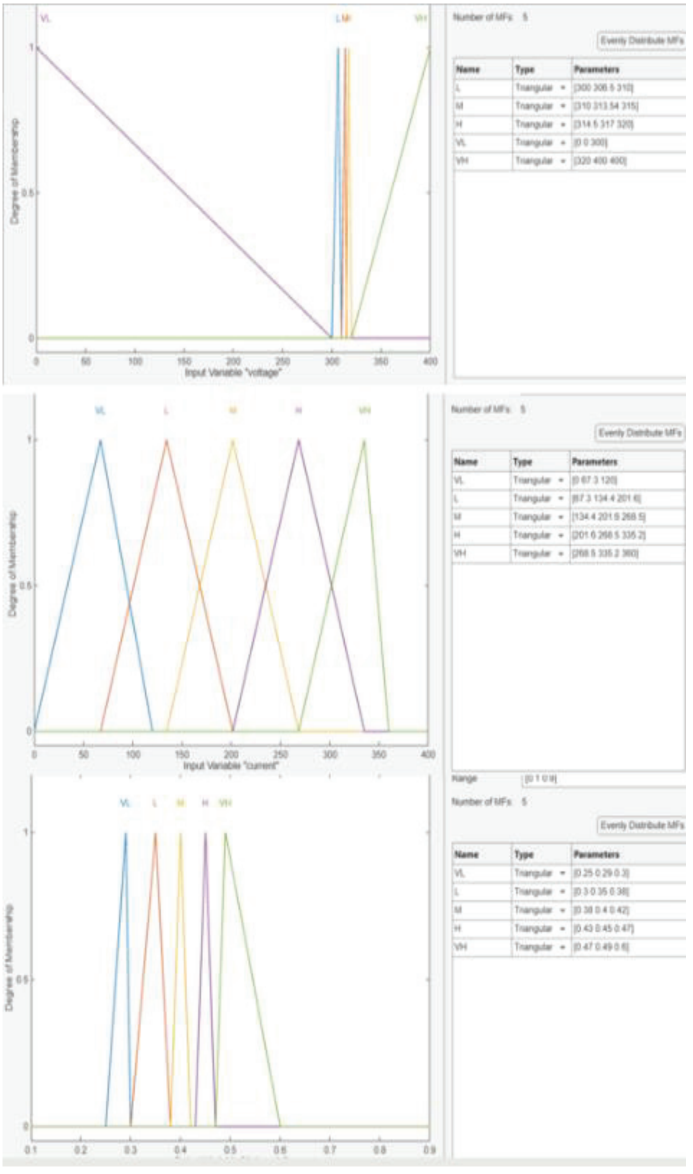

Figure 2: Membership function for (a) input Voltage, (b) input Current and (c) output Duty Cycle

2. Fuzzy Rule Base

Fuzzy logic primarily encompasses the fundamental components of fuzzy sets and operators, commonly called "If-Then" rule statements. These principles are utilized throughout developing the "If-Then" conditional statements that serve as the fundamental base of fuzzy logic.

The FLC procedure involves collecting input data from several sensors, which are subsequently inputted into the control system [11]. Table 1 contains 25 inference rules for various combinations of the linguistic variables' voltage and the output D to get the necessary reference signals [3]. The rule based FLC table is given in Table 1.

Table 1: FLC rule-based table

VI	VL	L	M	H	VH
VL	VL	VL	L	H	VH
L	VL	VL	L	L	VH
M	VL	L	L	M	VH
H	VL	VL	L	H	VH
VH	VL	VL	M	VH	VH

3. Defuzzification

Defuzzification is a method employed to convert the fuzzy output of an inference engine into a well-defined output by utilizing membership functions similar to those employed by the fuzzifier [11].

The DC-DC converter necessitates an appropriate control parameter in order to effectively regulate the output of the FLC from fuzzy data to non-fuzzy data. The process of converting fuzzy sets into crisp sets is commonly referred to as defuzzification. During the process of defuzzification, the output of the fuzzy controller is converted from a linguistic fuzzy value into a crisp numerical number.

The topic of interest is DC-DC converters. The PV voltage and PV current are utilized as input parameters in our maximum power point tracking MPPT controller, namely the FLC. The resultant output corresponds to the duty cycle (D) of the initial direct current (DC) to DC converter [3].

III. Methodology

The P&O and Fuzzy Logic Controller design is simulated using MATLAB Simulink. The flowchart sequence of actions undertaken in this project is depicted in Figure 3.

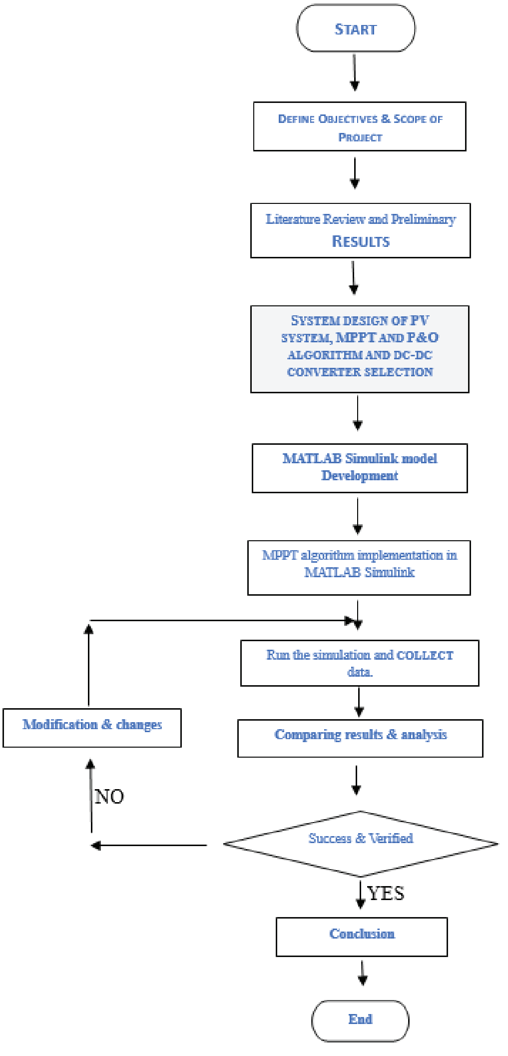

Figure 3: Project Flowchart

After the development of Buck Boost DC-DC converter, MPPT P&O algorithm and selecting the manufacturer of PV module, the overall model was developed in Simulink as given below in Figure 4.

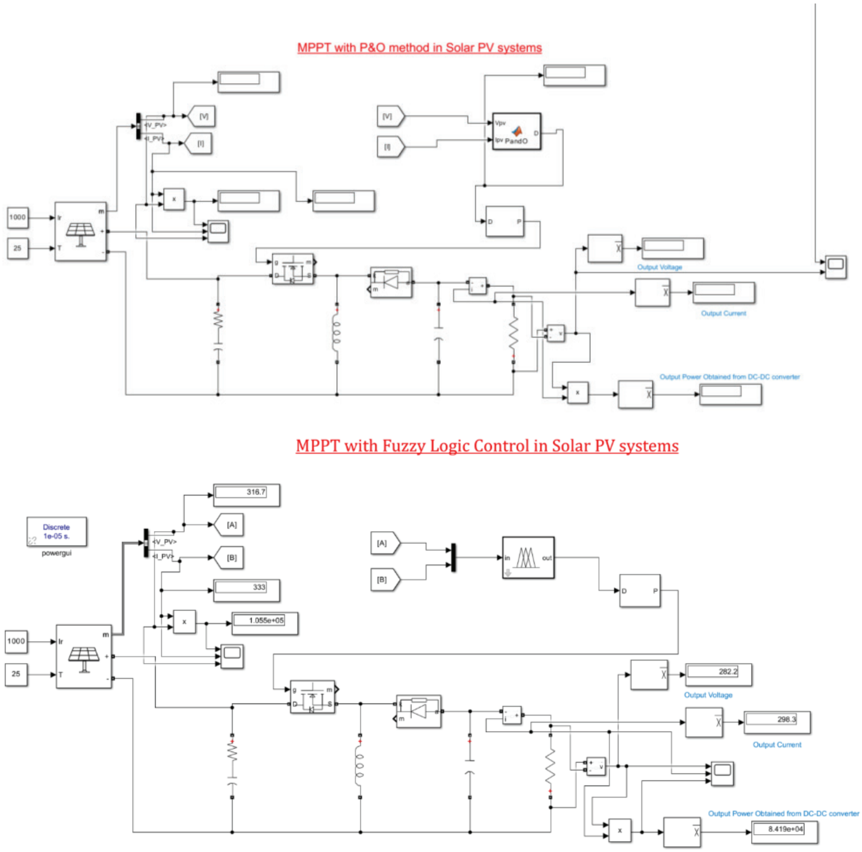

Figure 4: MATLAB Simulink Model for (a) P&O and (b) Fuzzy Logic Controller in Solar PV System

Initially, a two-unit block constant is utilized as the input for the PV array, which in turn serves as the input for both irradiance and temperature. Subsequently, the bus selector block is employed to gather the voltage and current measurements from the PV array. Following this, the unit delay block is utilized in both the voltage and current lines to introduce a single-step delay in the signal. It signifies a time delay that occurs at specific intervals in the simulation. The unit delay block stores the preceding value of a signal and produces that value at the present simulation time step. The block is commonly employed in modelling and simulation to depict systems exhibiting discrete-time behaviour, wherein the output at a specific time is contingent upon the input at the preceding time step. Ultimately, the MPPT P&O algorithm determines the highest voltage, and subsequently, the duty cycle is calculated by subtracting the voltage obtained from the MATLAB function from the PV voltage. The Fuzzy Logic Controller determines the maximum peak point of voltage and current at different irradiance using the fuzzy set rules set by the user.

In addition, Pulse Width Modulator (PWM) is employed in the simulation to regulate the average power delivered to the load by adjusting the duty cycle, which represents the ratio of time the signal is high to the total signal period. The PWM output is sent to the switch of the buck boost converter that is appointed in the Simulink model of both P&O and FLC. The buck-boost converter is employed to enable any load resistance to effectively track the maximum power through the utilization of a maximum power point tracker. The buck-boost converter is employed to regulate the equivalent load resistance, which can vary from zero to infinity while remaining unaffected by changes in the actual load resistance [14]. The buck-boost converter can effectively function in both ways [11].

IV. Results and Analysis

The study demonstrates that the load resistance and duty ratio graph of many converters provides valuable insights into the performance characteristics of each converter [14]. The graph is presented in the following manner in Figure 5.

The analysis and figure clearly indicate that a buck-boost converter is the optimal choice for efficiently tracking the maximum power output of any load resistance connected to the PV system. The buck converter is used when the load's resistance is less than the internal resistance of

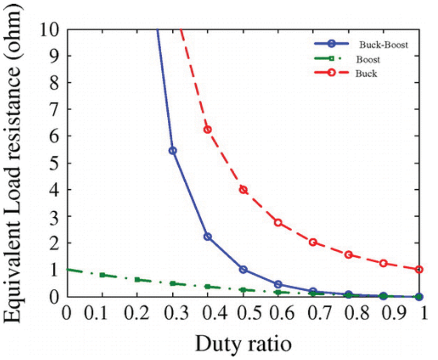

Figure 5: Different duty ratio DC-DC converter load resistance equivalents [14]

the PV array at its MPP. Conversely, the boost converter is used when the load resistance is higher than the internal resistance of the PV array at MPP. When generating pulses to regulate the DC-DC converter, it is crucial to carefully select the control variables, specifically the voltage as the output of the MPP tracker. Inadequate selection of suitable control variables can result in system instability, especially in direct MPP trackers [14]. Therefore, it is advisable to prioritize stability when choosing the voltage as the control parameter in a direct MPP tracker [14].

The buck converter and boost converter are unsuitable for this purpose as they cannot ensure that the operating point will coincide with the maximum power point under all irradiation and temperature conditions. In contrast, the buck-boost converter can autonomously identify the MPP without being affected by the surrounding environmental conditions. In addition, it provides a wider range of operating point perturbation [15]. An MPPT controller's main purpose is to optimize the operating point of the PV array, guaranteeing that it consistently operates at its MPP regardless of changes in environmental conditions [14].

The provided graphs of Figures 6 and 7 compare the performance of P&O and Fuzzy Logic-based MPPT algorithms under various irradiance levels, examining both voltage and power outputs.

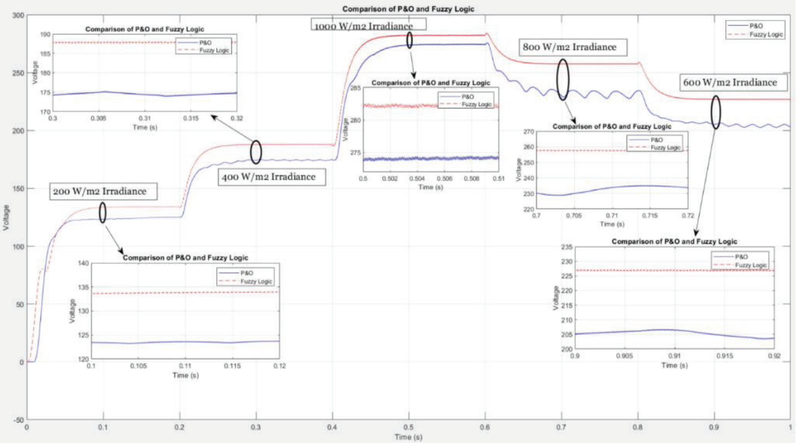

Figure 6: Voltage Comparison of P&O (blue) and FLC (red)

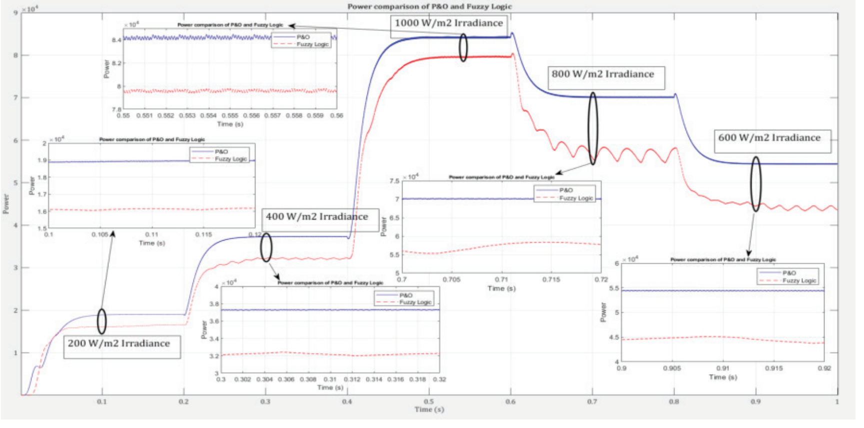

Figure 7: Power Comparison of P&O (red) and FLC (blue)

The voltage comparison graph in Table 2 illustrates the voltage output of the solar PV system at irradiance levels of 200 W/m², 400 W/m², 600 W/m², 800 W/m², and 1000 W/m².

The power comparison graph in Table 3 evaluates the power output of the solar PV system under the same irradiance levels.

The comparison between the P&O and fuzzy logic MPPT algorithms reveals that the fuzzy logic controller consistently outperforms the P&O algorithm in terms of stability and efficiency. The fuzzy logic controller quickly stabilizes the voltage and power outputs with minimal to no oscillations across all irradiance levels. This stability ensures more reliable and efficient performance, maximizing power extraction from the solar PV system.

Table 2: Voltage comparison of FLC and P&O of different irradiance level

Irradiance Level (W/m²)	Fuzzy Logic Control	P&O Method
200	Stabilizes at 134 V with minimal oscillations	Fluctuates between 125-130 V, showing instability
400	Maintains stable voltage around 188 V	Exhibits oscillations and stabilizes around 175 V
600	Steady voltage of about 227 V	Pronounced oscillations, stabilizing around 210-220 V
800	Stabilizes around 258 V	Significant oscillations, stabilizing around 240-250 V
1000	High, stable voltage around 282 V	Larger oscillations, stabilizing around 275 V

Table 3: Power comparison of FLC and P&O of different irradiance level

Irradiance Level (W/m²)	Fuzzy Logic Control	P&O Method
200	Stabilizes at 19,000 W with minimal oscillations	Fluctuates around 18,000-19,000 W, indicating less stable performance
400	Consistently maintains a power output of approximately 37,310 W	Exhibits noticeable oscillations around 36,000-37,000 W
600	Stabilizes at a power output of about 54,490 W	Shows more pronounced oscillations with a lower power output around 53,000-54,000 W
800	Maintains a stable power output around 70,120 W	Continues to show significant oscillations and a lower power output around 68,000-69,000 W
1000	Achieves a high and stable power output of approximately 84,190 W	Demonstrates larger oscillations and a delayed response, with power output fluctuating around 82,000-83,000 W

In contrast, the P&O algorithm exhibits significant oscillations and delayed responses, particularly under higher irradiance levels. These fluctuations can lead to suboptimal power extraction and reduced system efficiency. The fuzzy logic controller's ability to handle non-linearity and variability in environmental conditions makes it a superior choice for MPPT in solar PV systems.

In summary, the analysis of the graphs underscores the advantages of using fuzzy logic for MPPT, including quick stabilization, minimal oscillations, and higher efficiency, thereby enhancing the overall performance and reliability of solar energy systems.

V. Conclusion

In conclusion, this study has demonstrated that the P&O method, while commonly used for MPPT in solar PV systems, is prone to significant oscillations and energy losses, reducing overall system efficiency. By contrast, FLC offers a more stable and reliable alternative, effectively minimizing these issues. The implementation of FLC in MPPT enhances the accuracy and speed of power tracking, making it a promising solution for improving the performance and efficiency of solar PV systems. This research contributes valuable insights toward optimizing solar energy harvesting, supporting the broader adoption of renewable energy technologies.

VI. References

[1] L. K. Narwat and J. Dhillon, "Design and operation of fuzzy logic based MPPT controller under uncertain condition", *Journal of Physics: Conference Series*, vol. 1854, no. 1, p. 012035, 2021.

[2] H. Rezk et al., "Design and hardware implementation of new Adaptive Fuzzy Logic-based MPPT control method for photovoltaic applications", *IEEE Access*, vol. 7, pp. 106427–106438, 2019.

[3] F. Tahiri et al., "Comparative study of the MPPT methods applied to the PV system; perturbation & observation technique, sliding mode control and Fuzzy Logic Control", in International Conference on Smart Grid, Paris, 2023, pp. 1–6.

[4] R. K. Rai and O. P. Rahi, "Fuzzy logic based control technique using MPPT for solar PV system", in First International Conference on

Electrical, Electronics, Information and Communication Technologies, Trichy, India, 2022, pp. 01–05.

[5] H. Rezk and A. M. Eltamaly, “A comprehensive comparison of different MPPT techniques for photovoltaic systems”, *Solar Energy*, vol. 112, pp. 1–11, 2015.

[6] H. G. Ali et al., “Perturb & observe based adaptive sliding mode MPPT control of Solar Photovoltaic System”, in 2020 IEEE International Conference on Environment and Electrical Engineering and 2020 IEEE Industrial and Commercial Power Systems Europe, Madrid, Spain, 2020, pp. 1–6.

[7] M. N. Ali et al., “An efficient fuzzy-logic based variable-step incremental conductance MPPT method for grid-connected PV systems”, *IEEE Access*, vol. 9, pp. 26420–26430, 2021.

[8] A. Mohapatra et al., “Adaptive Perturb & observe MPPT for PV system with experimental validation”, in IEEE International Conference on Sustainable Energy Technologies, Bhubaneswar, India, 2019, pp. 257–261.

[9] S. Khadidja et al., “Comparative study of incremental conductance and perturb & observe MPPT methods for Photovoltaic System”, in International Conference on Green Energy Conversion Systems, Hammamet, Tunisia, 2017, pp.1–6.

[10] M. A. Sasi, “Fuzzy Logic Control of MPPT Controller for PV Systems”, Ph.D thesis, Memorial University of Newfoundland, 2017.

[11] K. Ishaque et al., “Simple, fast and accurate two-diode model for photovoltaic modules”, *Solar Energy Materials and Solar Cells*, vol. 95, no. 2, pp. 586–594, 2011.

[12] V. Jayasree et al., “Fuzzy logic algorithm based MPPT controller for solar PV Powered Electric Vehicle Charging Station”, in 2022 International Conference on Futuristic Technologies in Control Systems & Renewable Energy, Malappuram, India, 2022, pp. 1–6.

[13] B. Nayak et al., “Selection criteria of DC-DC converter and control variable for MPPT of PV system utilized in heating and cooking applications”, Cogent Engineering, vol. 4, no. 1, p. 1363357, 2017.

[14] Chihchiang Hua and Chihming Shen, “Study of maximum power tracking techniques and control of DC/DC converters for photovoltaic power system”, in PESC 98 Record. 29th Annual IEEE Power Electronics Specialists Conference (Cat. No.98CH36196), vol. 1, pp. 86–93.

[15] I. V. Banu et al., “Comparative analysis of the perturb-and-observe and incremental conductance MPPT methods”, in 8th International Symposium on Advanced Topics in Electrical Engineering, 2013. doi:10.1109/atee.2013.6563483

[16] J. Nazdrowicz et al., “Comparison of photovoltaics system response with constant and variable step MPPT algorithm”, in 29th International Conference on Mixed Design of Integrated Circuits and

System, Wroclaw, Poland, 2022, pp. 127–130.

[17] D. Rastogi et al., “Comparative study of DC-DC converters in PV systems using fuzzy logic MPPT algorithm”, in 2022 IEEE Delhi Section Conference, 2022. doi:10.1109/delcon54057.2022.9753494