

ENVIRONMENTAL FACTORS' EFFECTS ON SOLAR CELL PERFORMANCE AND MAXIMUM POWER POINT TRACKING APPLICATION

Zirata, K.B.* and Gulak, L.L.

^{1,2}Department of Electrical/Electronic Engineering, Adamawa State Polytechnic, Yola, Nigeria

*Corresponding email: bzkamaunji@gmail.com

ABSTRACT

Photovoltaic (PV) systems play a pivotal role in meeting the escalating global demand for clean and sustainable energy. However, the efficiency of these systems is significantly influenced by the inherent variability in solar irradiance and environmental conditions. With the variation of the operating conditions, the voltage at which the maximum power can be obtained from also changes. In this paper, a PV model is used to simulate the actual PV module behavior, and then a Maximum Power Point Tracking (MPPT) method using fuzzy logic is proposed in order to control the DC-DC converter. Furthermore, the proposed fuzzy logic technique is compared with the conventional Perturb and Observe (P and O) MPPT method. Simulation result shows that the proposed fuzzy logic MPPT method gives better response than the conventional P and O method under variations of operating conditions. The fuzzy controller presented shows better performance and stability with less oscillation as compared with the Perturb and Observe algorithm which has much oscillation around the MPP which may lead to loss of power. The results also show that fuzzy controller performs better having a maximum power point of 22.79W at 1000W/M² irradiance and 1.89W on solar irradiance level of 100W/m² than the Perturb and Observe algorithm having a maximum power point of 22.57W at 1000W/M² and 1.49W on solar irradiance level of 100W/m² but with much oscillation around the MPP. Furthermore, the results show that fuzzy controller has a higher average tracking efficiency of 91.30% than the Perturb and Observe algorithm which has an average tracking efficiency of 79.89%. FLCs often require manual tuning of membership functions and rules, which can be time-consuming and challenging, especially for complex systems. Future research could focus on developing automated or semi-automated tuning methods to simplify this process.

Keywords: Environmental factors, Solar cell performance, Maximum Power Point Tracking, P and O, Fuzzy Logic Control, DC-DC converter.

1 INTRODUCTION

Solar energy has emerged as a promising alternative to conventional fossil fuels, offering a sustainable and renewable source of power [1]. The global shift towards renewable energy sources has led to a growing interest in solar photovoltaic (PV) systems as a clean and efficient means of electricity generation [2]. However, the efficiency and performance of solar cells, which are the basic units of solar PV systems, are significantly influenced by various environmental factors [3]. These factors include solar irradiance, temperature, shading, dust accumulation, and atmospheric conditions [4]. Solar irradiance refers to the amount of solar radiation received per unit area on a surface, and variations in solar irradiance throughout the day and across different seasons directly impact the output of solar cells [5]. Temperature also plays a critical role, as the efficiency of solar cells decreases with rising temperatures [6]. In addition

to these direct effects, shading caused by nearby objects such as buildings or vegetation, as well as partial shading due to cloud cover, can result in non-uniform illumination of solar panels [7]. This phenomenon leads to what is known as the "partial shading effect," where some parts of the solar panel produce less power than others, reducing the overall output of the system [8]. Furthermore, environmental factors such as dust and debris accumulation on the surface of solar panels can create a barrier to sunlight, reducing the amount of light absorbed by the solar cells [9]. This decreases the efficiency of the panels and can ultimately impact the overall performance of the solar PV system [10]. To address these challenges and optimize the performance of solar PV systems, effective maximum power point tracking (MPPT) techniques are crucial [11]. MPPT is a method used to maximize the power output of solar panels by continuously adjusting the operating point of the system to track the point where the panel produces the maximum power [12]. Various MPPT algorithms, such as Perturb and Observe (P&O), Incremental Conductance (INC), and the Fuzzy Logic Control (FLC) algorithm, have been developed to achieve this optimization [13]. In this context, this research focuses on evaluating the impact of environmental factors on solar cell performance and exploring the application of MPPT techniques, particularly the FLC algorithm, to enhance the efficiency of PV systems. The study utilizes MATLAB/Simulink to develop a program that models a 20W photovoltaic module based on mathematical equations, allowing for the prediction of the module's behavior under different environmental conditions. The results obtained from the simulations provide insights into how the FLC algorithm compares to the traditional P&O controller, highlighting its potential to improve system performance by reducing oscillations around the Maximum Power Point. Through this investigation, the research aims to contribute to the optimization and advancement of solar PV technology for sustainable energy generation.

2 METHODOLOGY

2.1 System Description

The system comprises a photovoltaic (PV) module, a Buck-boost DC/DC converter, and a control unit. The PV module generates DC voltage, which fluctuates based on environmental conditions. The Buck-boost converter regulates the PV module's output voltage to maintain maximum power, adjusting PWM signal voltage references as needed. A controller generates high-frequency PWM signals based on PV panel output and load, employing a Fuzzy Logic Control algorithm for Maximum Power Point Tracking (MPPT). Sensors monitor panel and converter parameters, feeding data to a Microcontroller Unit (MCU), which customizes pulse signal duty cycles to achieve the desired output. The block diagram of the proposed solar PV system is shown in Figure 1.

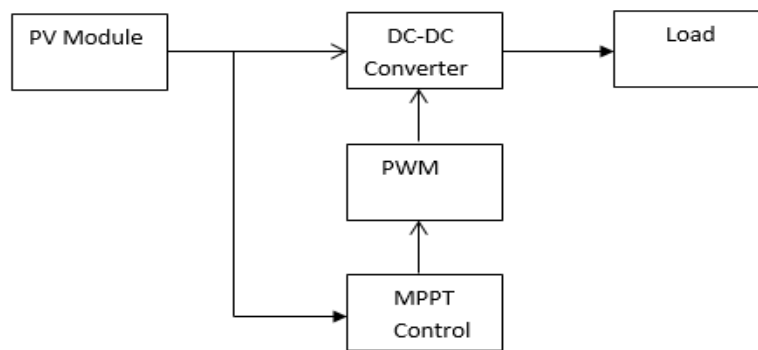


Figure 1. Block diagram of solar PV system

2.2 Mathematical Modeling of PV Cell

For the Modeling and Simulation of the Photovoltaic cell in Figure 2, equations 1 to 10 were used to model the PV module under different environmental parameters.

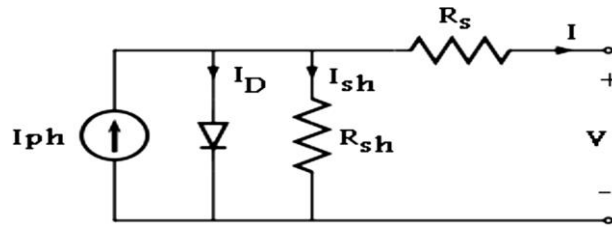


Figure 2. PV Cell equivalent circuit

The mathematical model for the photovoltaic (PV) module was developed using the equivalent circuit of a PV cell with one diode and two resistors [14]. This model is known as a single diode model of a solar cell. The photo generated current of photovoltaic cell is expressed by Kirchhoff's current law as:

$$I_{ph} = I_D + I_{sc} + I \tag{1}$$

From equation (1), the output current is expressed as:

$$I = I_{ph} - I_D - I_{sh} \tag{2}$$

$$I_{ph} = (I_{sc} + K_i (T - T_r)) G / G_r \tag{3}$$

$$I_D = I_o (e^{(V/nV_t)} - 1) \tag{4}$$

$$I_{sh} = (V + IR_s / R_p) \tag{5}$$

Substituting I_D in equation (2), the output current becomes:

$$I = I_{ph} - I_o (e^{(V/nV_t)} - 1) \tag{6}$$

The thermal voltage of the diode is expressed as:

$$V_t = N_s K T / q \tag{7}$$

Equation (6) becomes;

$$I = I_{ph} - I_o (e^{(qV/KT)} - 1) \tag{8}$$

The module saturation current varies with the cell temperature and is expressed as:

$$I_o = I_{rs} ((T/T_r) e^{3}) e^{(qE_g/nK) * ((1/T_r) - (1/T))} \tag{9}$$

The modules reverse saturation current is expressed as:

$$I_{rs} = I_{sc} / e^{(qV_{oc}/nKT N_s)} - 1 \tag{10}$$

Where $q = 1.6 \times 10^{-19}$ C is electron charge, I_{sc} is short circuit current (A), V_{oc} is open-circuit voltage (V), n is an ideality factor of the diode, I_{sh} is the shunt current, I_D is the diode current, V is module output voltage (V), R_s is series resistor (Ω), R_p is parallel resistor (Ω), N_p is the number of modules connected in parallel, N_s is the number of cells connected in series, T_r is Reference temperature (K), T is operating temperature (K), G is actual solar irradiation (W/m^2), G_r is Reference solar irradiation (W/m^2). E_g is Band gap energy for silicon. The PV model parameters of Solarland SLP20-12U are presented in Table 1.

Table 1. Photovoltaic model Parameters

P_{max}	V_{max}	I_{max}	V_{oc}	I_{sc}
20 W	17.5V	1.16A	21.6V	1.31A

2.3 Maximum Power Point Tracking Techniques

PV generators have nonlinear I-V characteristics. So, there is a unique MPP at which the PV generator operates at its maximum output power. On the other hand, current and voltage generated by PV generators depend on atmospheric conditions[15].

2.3.1 Perturb and Observe (P and O)

This algorithm functions by regularly adjusting and modifying the power and voltage levels of an array at the (k + 1)th moment, comparing them to the previous adjustment cycle at the kth moment [16] as illustrated in Figure 3. If the change in power (ΔP) is zero, the algorithm repeats the comparison. However, if ΔP is non-zero and both the Power and voltage are positive during the same interval; the algorithm increases the step size (ΔD) to be added to the duty cycle. Otherwise, it adjusts in the opposite direction.

2.3.2 Fuzzy Logic Control (FLC)

This article introduces a novel approach utilizing a fuzzy logic controller (FLC) as an intelligent maximum power point tracking (MPPT) technique for photovoltaic (PV) systems operating amidst varying external conditions. Unlike traditional methods, many fuzzy-based MPPT algorithms determine the optimal point by analyzing the slope of the power-current characteristic and its changes. This constitutes a nonlinear control strategy aimed at incorporating the expertise of experienced users into the design of fuzzy-based controllers, typically depicted in Figure 3. Generally, the fuzzy logic approach comprises three main stages [17]: a) Fuzzification: converting crisp values into input fuzzy sets; b) Rule formulation: establishing rules using a series of IF-THEN statements; c) Defuzzification: converting output fuzzy values into crisp values.

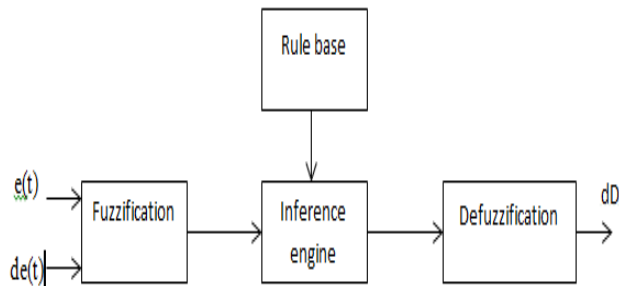


Figure 3. General diagram of a fuzzy controller

During fuzzification, numerical input variables “crisp” are converted into linguistic variables based on a membership function. For this MPPT, the inputs of the fuzzy logic controller are taken as error (e) (the differential variation of power with respect to variation of voltage) and the changing of error (de) at sample time k. The equations for e and de are given as follows.

$$e(t) = P(k) - P(k-1) / V(k) - V(k-1) \tag{11}$$

$$de(t) = e(t) - e(t-1) \tag{12}$$

Fuzzy rule base represents in a structured way the control policy in the form of a set of production rules such as: If <process state > then < control action>. The ‘if’ of the rule refers to the antecedent and the ‘then’ refers to the consequent. The rules are summarized in the matrix look-up table in Table 2. This type of fuzzy conditional statement is often called a Mamdani-type rule. This method uses minimum operator as a fuzzy implication operator, and max-min operator for the composition.

Table 2. Fuzzy Rule Base

		CE				
		NB	NS	ZE	PS	PB
E	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

2.4 Dc-Dc Buck-Boost Converter

Dc-dc converter can be used as a switching-mode regulator to convert a dc voltage, normally unregulated to a regulated dc output voltage [18, 19]. The regulation is normally achieved by PWM and

the switching device is normally an insulated gate bipolar transistor (IGBT). Buck-boost dc-dc converter is used in this system, Figure 4. It consists of a boost inductor, controlled switch, diode and a filtering capacitor. The power switch is responsible for modulating the energy transfer from the input source to the load by varying the duty cycle D .

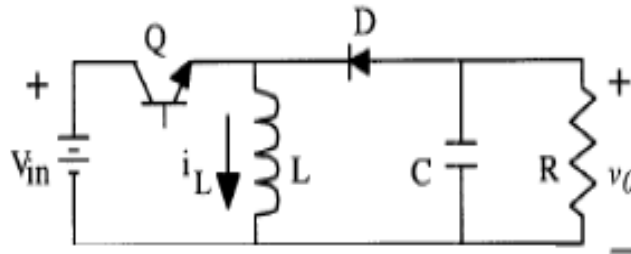


Figure 4. DC-DC Buck-Boost Converter

2.5 Development of Simulink Model

To evaluate the performance of the Perturb and Observe (P and O) and Fuzzy Logic Control (FLC) methods, the nonlinear current-voltage (I-V) and power-voltage (P-V) characteristics of a photovoltaic (PV) module was simulated using the models illustrated in Figures 6 and 7. The inputs for this simulation are the voltage and current of the PV module, with the output being the duty cycle (D) of the buck-boost converter. This duty cycle calculation is crucial for regulating the buck-boost converter effectively. The simulation includes the fuzzification, decision-making, and defuzzification processes. The parameters of an SLP20-12U PV module, which has a rated power of 20W was utilized. The voltage and current sensors monitor the values at the solar panel's output and the buck-boost converter's output, transmitting this data to the controller unit. Figures 5 and 6 depict the models comprising the PV system, Maximum Power Point Tracking (MPPT) controllers, and the buck-boost converter. The block diagram representing the fuzzy logic and P and O controller simulates the respective MPPT algorithms. The duty cycle ($D(k)$) necessary for driving the converter is determined by updating the previous value using $D(k-1)$.

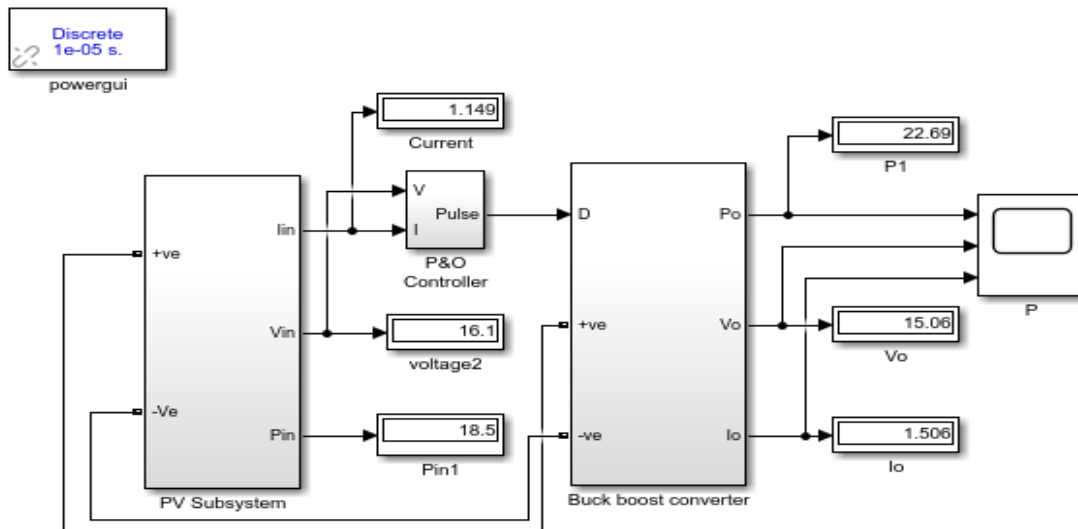


Figure 5. Matlab/Simulink Model of PV System with P&O

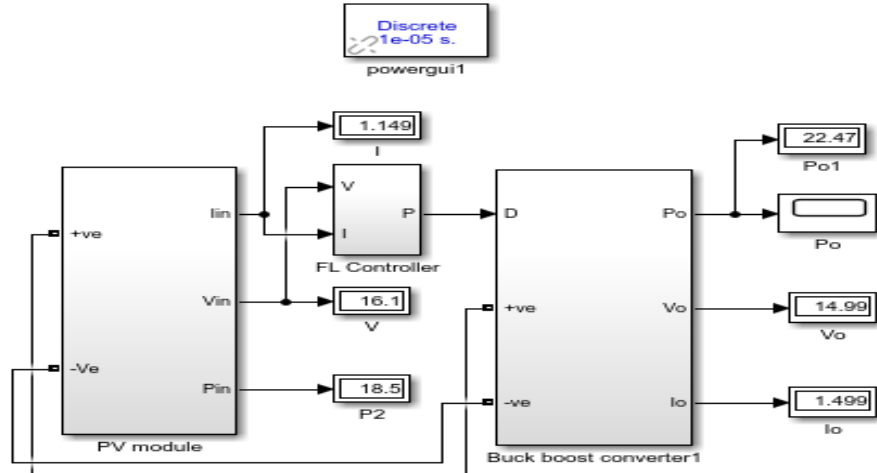


Figure 6. Matlab/Simulink Model of PV System with fuzzy Controller

3 RESULTS AND DISCUSSION

3.1 Varying irradiance with constant Temperature

Simulations were carried out using Matlab code for 20W solar PV module at two conditions: Constant temperature and varying solar radiation intensity; Constant solar radiation intensity and varying module temperature. The results of the response of varying irradiance with constant temperature without controller are shown in Figures 7a and 7b. The system's stable nature is compromised by its nonlinear response during transients, resulting in poor steady state error in command tracking, prompting the need for a controller. This agrees with the works of [3, 4, 5]. The graphs depicted in Figures 7a and 7b illustrates the I-V and P-V traits of the photovoltaic generator under constant temperature conditions of 25°C across various solar irradiation levels. Observably, as solar irradiation levels rise, the PV's output power increases, while reduced irradiance levels notably diminish the current.

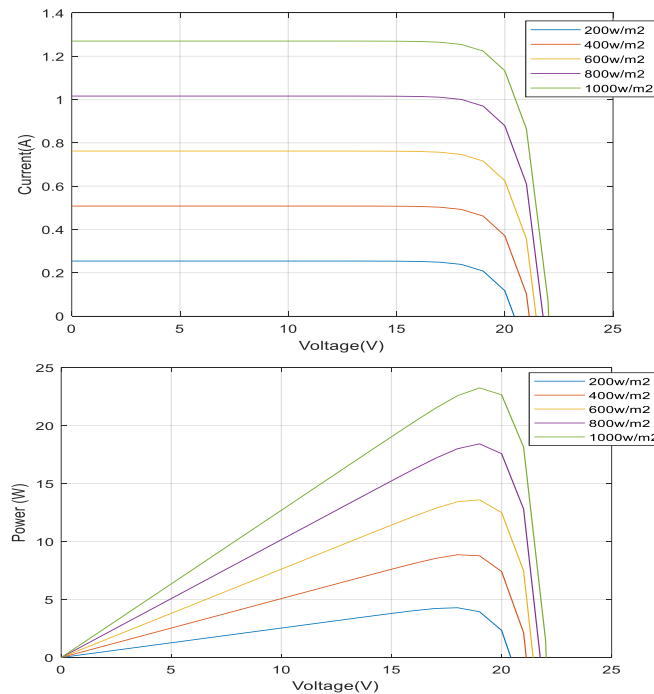


Figure 7. I-V and P-V characteristics of Photovoltaic cell for constant temperature and varying irradiation levels

3.2 Varying module temperature with Constant irradiance

The results of the response of varying module temperature with constant irradiance without controller are shown in the Figures 8a and 8b. The system's stable nature is compromised by its nonlinear response during transients, resulting in poor steady state error in command tracking, prompting the need for a controller. This agrees with the works of [3, 4, 6]. The graphs displayed in Figures 8a and 8b depict the I-V and P-V attributes of a photovoltaic module under a constant irradiation level of $G = 1000$ watts/m² across varying temperature values. Notably, the open circuit voltage of the solar panel diminishes as temperature rises. The complexity of the tracking problem stems from the rapid fluctuations in environmental conditions and the nonlinearity observed in the I-V characteristics of the PV module.

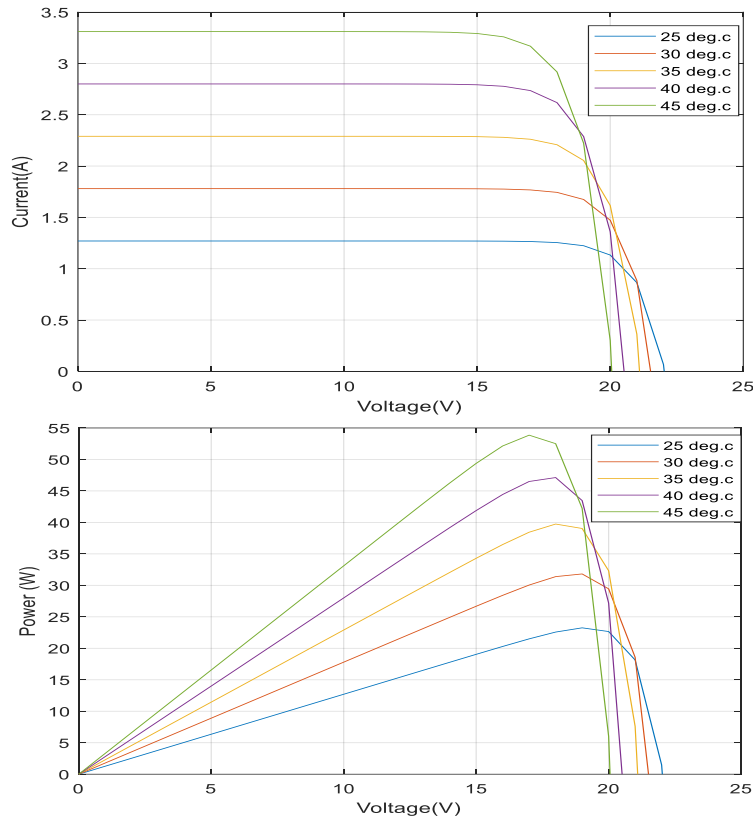


Figure 8. I-V and P-V characteristics of Photovoltaic cell for constant irradiance and varying temperature levels

3.3 Response of the Controlled PV Module output power using P and O controller

The 'P and O' Controller was incorporated into the solar cell model to form a controlled loop using a 10Ω load at varying irradiance. Under the 10Ω load, the output power remained at steady state indicating load match, but with chattering behaviour [16] which may lead to loss of power. Figures 9 and 10 show the results in this case.

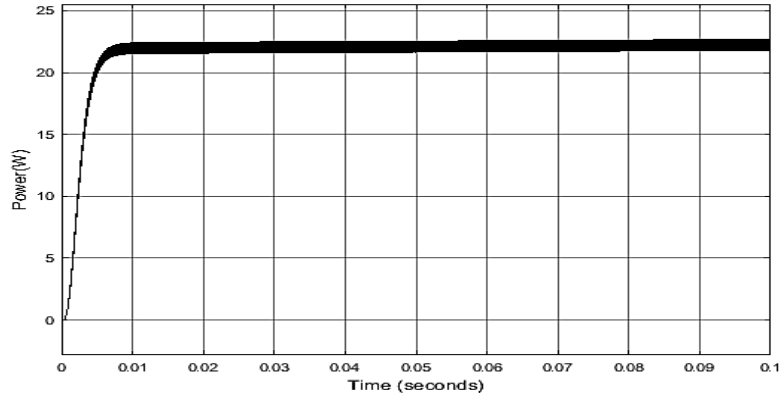


Figure 9. P and O response under a load of 10Ω at 1000w/m^2

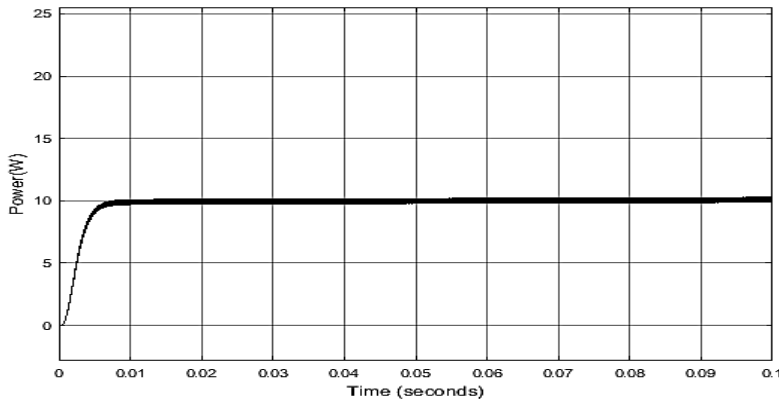


Figure 10. P and O response under a load of 10Ω at 500w/m^2

Under 15Ω load, the output power returned to steady state when affected by the load variation with little overshoot and settling time, while indicating chattering behaviour [16] with some level of power loss. Figures 11 and 12 show the results in this case.

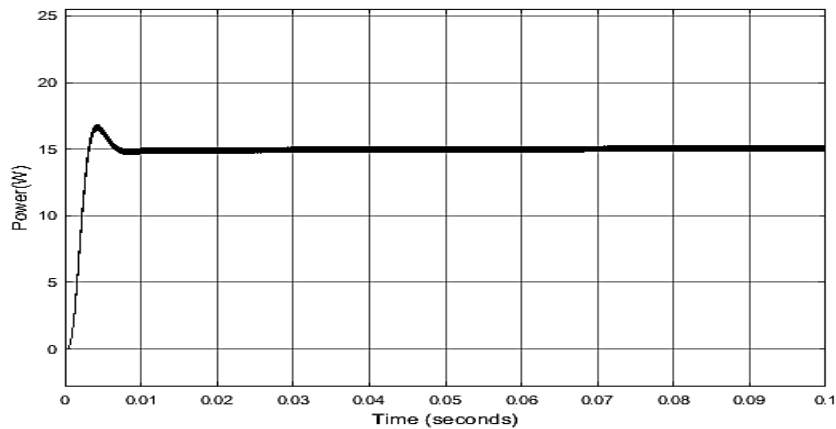


Figure 11. P and O response under fixed load of 15Ω at 1000W/m^2

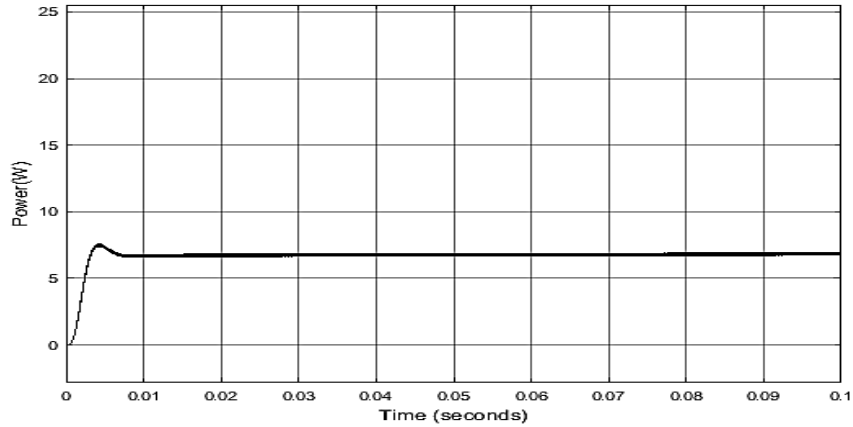


Figure 12. P and O response under fixed load of 15Ω at $500\text{W}/\text{m}^2$

3.4 Response of the Controlled PV Module output power using Fuzzy controller

The fuzzy controller was incorporated into the solar cell model to form a controlled loop using a 10Ω load at varying irradiance. Under the 10Ω load, the output power remained at steady state indicating load match. Figures 13 and 14 show the results in this case.

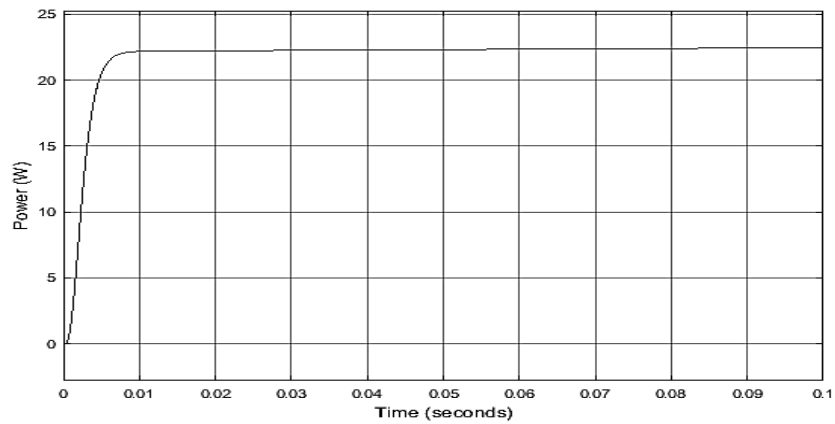


Figure 13. Fuzzy response under fixed load of 10Ω at $1000\text{W}/\text{m}^2$

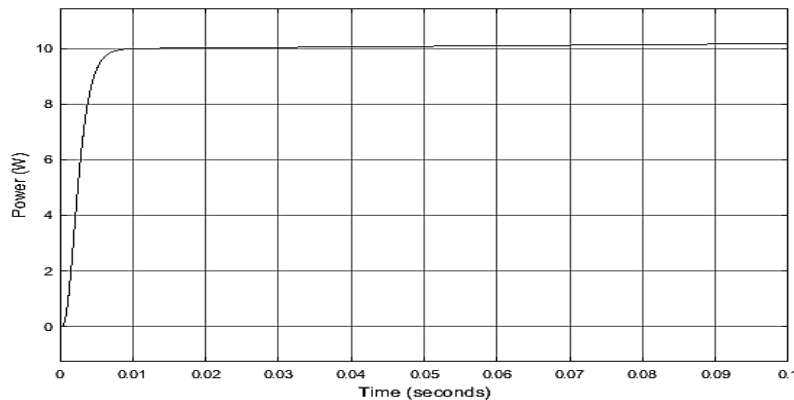


Figure 14. Fuzzy response under fixed load of 10Ω at $500\text{W}/\text{m}^2$

Under 15Ω load, the output power returned to steady state even when affected by the load variation with little overshoot and settling time [17]. Figures 15 and 16 show the results in this case.

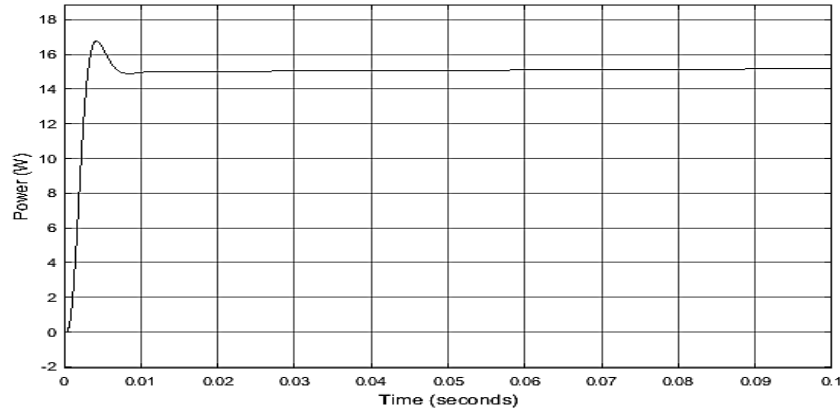


Figure 15. Fuzzy response under fixed load of 15Ω at $1000W/m^2$

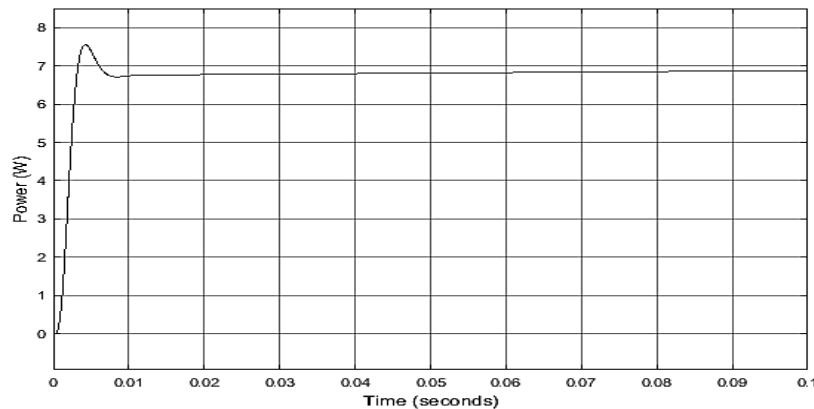


Figure 16. Fuzzy controller response under fixed load of 15Ω at $500W/m^2$

4 CONCLUSIONS

In conclusion, the following were achieved in PV module control using ‘P and O’ and fuzzy controller algorithms. The ‘P and O’ and fuzzy controllers for the PV module control were modeled using Matlab/Simulink. The fuzzy controller presented shows better performance and stability with less oscillation as compared with the Perturb and Observe algorithm which has much oscillation around the MPP which may lead to loss of power. The results also shows that fuzzy controller performs better having a maximum power point of 22.79W at $1000W/M^2$ irradiance and 1.89W on solar irradiance level of $100W/m^2$ than the Perturb and Observe algorithm having a maximum power point of 22.57W at $1000W/M^2$ and 1.49W on solar irradiance level of $100W/m^2$ but with much oscillation around the MPP. Furthermore, the results show that fuzzy controller has a higher average tracking efficiency of 91.30% than the Perturb and Observe algorithm which has an average tracking efficiency of 79.89%. Fuzzy logic requires human knowledge and experience to design the fuzzy rules. This knowledge bottleneck can be eliminated using neural network to learn the rules The Fuzzy logic controller can also be used in conjunction with neural network techniques for further increase in system performance and efficiency.

REFERENCES

1. Lazaroiu, A.C., Gmal Osman, M., Strejoiu, C.V. and Lazaroiu, G. (2023). A Comprehensive Overview of Photovoltaic Technologies and Their Efficiency for Climate Neutrality. *Sustainability*, vol. 15, no. 23. pp. 1-24.
2. Shaikh, M.R.S. (2017). A Review Paper on Electricity Generation from Solar Energy. *Int. J. Res. Appl. Sci. Eng. Technol.*, vol. 5, no. 9, pp. 1884-1889.

3. Kaur, S. and Vig, S. (2023). A Review of different MPPT algorithms for PV System. *Jour. Curr. Res. Eng. Sci.*, vol. 6, no. 1, pp. 1–7.
4. Moayad, H., Alhussain, A. and Yasin, N. (2020). Modeling and simulation of solar PV module for comparison of two MPPT algorithms (P & O & INC) in MATLAB / Simulink. *Indones. J. Electr. Eng. Comput. Sci.*, vol. 18, no. 2, pp. 666–677.
5. Shaik, F., Lingala, S.S. and Veeraboina, P. (2023). Effect of various parameters on the performance of solar PV power plant: a review and the experimental study. *Sustain. Energy Res.*, vol. 10, no. 6, pp. 2-23.
6. Dhass, A.D., Natarajan, E. and Lakshmi, P. (2014). An Investigation of Temperature Effects on Solar Photovoltaic Cells and Modules. *Int. J. Eng.*, vol. 27, no. 11, pp. 1713-1722.
7. Bernadette, D., Twizerimana, M., Bakundukize, A., Pierre, B.J. and Theoneste, N. (2021). Analysis of Shading Effects in Solar PV System Email address. *Int. J. Sustain. Green Energy*, vol. 10, no. 2, pp. 47-62.
8. Chaudhary, A., Gupta, S., Pande, D., Mahfooz, F. and Varshney, G. (2015). Effect of Partial Shading on Characteristics of PV panel using Simscape. *Int. J. Eng. Res. Appl.*, vol. 5, no. 10, pp. 85-89.
9. Abuzaid, H., Awad, M., Shamayleh, A. and Awad, M. (2022). Impact of dust accumulation on photovoltaic panels: a review paper. *Int. J. Sustain. Eng.*, vol. 15, no. 1, pp. 264-285.
10. Rashid, M., Yousif, M., Rashid, Z., Muhammad, A., Altaf, M. and Mustafa, A. (2023). Effect of dust accumulation on the performance of photovoltaic modules for different climate regions. *Heliyon*, vol. 9, no. 12, pp. 1-13.
11. Devarakonda, A.K., Karuppiah, N., Selvaraj, T. and Balachandran, P.K. (2022). A Comparative Analysis of Maximum Power Point Techniques for Solar Photovoltaic Systems. *A Comp. Anal. Maximum Power Point Tech. Sol. Photovolt. Syst.*, vol. 15, no. 8776, pp. 1-30.
12. Singh, J., Singh, S.P., Verma, K.S. and Kumar, B. (2022). Comparative Analysis of MPPT Control Techniques to Enhance Solar Energy Utilization and Convergence Time Under Varying Meteorological Conditions and Loads. *Front. Energy Res.*, vol. 10, no. July, pp. 1-17.
13. Derbeli, M. O. and Barambones, N.C. (2023). A Fuzzy Logic Control for Maximum Power Point Tracking Algorithm Validated in a Commercial PV System. *Energies*, vol. 16, no. 748, pp. 1-14.
14. Boussada, Z., Ben, H.M. and Lassaad, S. (2017). Photovoltaic Cell Mathematical Modelling. *Int. J. Eng. Res. Technol.*, vol. 6, no. 6, pp. 884-887.
15. Ko, J.S., Huh, J.H. and Kim, J.C. (2020). Overview of maximum power point tracking methods for PV system in micro grid. *Electron.*, vol. 9, no. 5, pp. 1-22.
16. Mahdi, A.S., Mahamad, A.K., Saon, S., Tuwoso, T., Elmunsyah, H. and Mudjanarko, S.W. (2020). Maximum power point tracking using perturb and observe, fuzzy logic and ANFIS. *SN Appl. Sci.*, vol. 2, no. 1, pp. 1-9.
17. Narwat, L.K. and Dhillon, J. (2021). Design and Operation of Fuzzy Logic Based MPPT Controller under Uncertain Condition. *Jour. Phys. Conf. Ser.*, vol. 1854, no. 1, pp. 1-12.
18. Zulkifli, M.Z., Azri, M., Alias, A., Talib, N. and Lazi, J.M. (2019). Simple control scheme buck-boost DC-DC converter for stand-alone PV application system. *Int. J. Power Electron. Drive Syst.*, vol. 10, no. 2, pp. 1090-1101.
19. Zaini, Z. and Wulung, W.J. (2023). DC-DC Buck and Boost Converter Design for Energy Control in Hybrid PV Systems. *Andalas Jour. Electr. Electron. Eng. Technol.*, vol. 3, no. 2, pp. 71-80.