Enhancing Photovoltaic System Efficiency Through Fuzzy Logic-Based Maximum Power Point Tracking

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Abstract – *This study utilizes a fuzzy logic controller (FLC), a type of computational intelligence tool, for determining a photovoltaic (PV) system's maximum power point (MPP). The solar PV system comprises of a PV module, an MPP controller, all of which are designed to monitor and optimize the highest point of energy generation in a photovoltaic system and a DC-DC boost converter. FLC is the core methodology employed in this study for maximum power point tracking (MPPT) within the converter-supplied PV system. The MPPT process involves the analysis of system parameters, including current error and the rate of change of errors, which serve as the input to the fuzzy logic system. The FLC continuously processes these inputs to adjust the duty cycle of the DC-DC boost converter, ensuring that the PV system operates at its highest energy generation potential. The 1Soltech 1STP-215-P PV model is utilized for this study, and it is representative of the PV model used in simulation studies. Photovoltaic systems are inherently nonlinear and respond to various external factors, making them less efficient. Therefore, the proposed intelligent control method, based on artificial intelligence principles, offers an easily implementable solution and provides valuable feedback. It exhibits robust performance even when solar irradiance levels fluctuate and excels at tracking MPPs, among other advantages. To simulate and evaluate the maximum power point tracking in a solar system, a PV system incorporating a fuzzy logic controller is designed and simulated using MATLAB/Simulink. The simulation results confirm the effectiveness of the proposed fuzzy logic controller in maximizing electricity generation from the PV panels while maintaining their operating voltage at an efficient level.*

Keywords*: DC-to-DC boost converter, Fuzzy logic controller (FLC), MATLAB/Simulink, maximum power point (MPPT), photovoltaic (PV) system*

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I. Introduction

In addition to causing environmental issues, the depletion of non-renewable energy sources like fossil fuels poses threats to human health. These energy sources are responsible for greenhouse gas emissions, hindering economic progress and causing air pollution. On the other hand, renewable energy is derived from resources that are both sustainable and continuously replenished, including sunshine, wind, rain, tides, geothermal heat, and biomass [1]. Furthermore, renewable energy is not only environmentally friendly but also aligns with the nation's goals for sustainable development (SDG). In Malaysia, solar photovoltaic systems, often referred to as PV systems, are particularly favored among these resources due to the abundant solar irradiation [2]. Solar cells within PV modules convert sunlight into electricity by utilizing semiconductors, resulting in the generation of direct current (DC). Among the notable advancements in PV power systems, Maximum Power Point Tracking (MPPT) stands out [3]. The Maximum Power Point (MPP) represents a specific point on the I-V or P-V curve where the entire PV system (including the array, converter, and controller) operates with the highest efficiency, generating its maximum output power [4]. However, maintaining MPP operation consistently across varying irradiance levels and seasons, without altering system parameters, poses a challenge due to the MPP's fluctuations. To address this issue, an intermediate DC-DC converter equipped with an intelligent Maximum Power Point Tracking (MPPT) method using a Fuzzy Logic controller is proposed as a solution. Various approaches for tracking the MPP have been extensively explored in prior research [5] and [6]. These approaches differ in terms of algorithms, complexity, and implementation costs. Nonetheless, the primary objective of all these approaches is to enhance tracking performance and reduce oscillations around the MPP, making the tracking process quicker and more accurate.

In the Perturb and Observe (P&O) MPPT approach [8], voltage serves as a reference point, incrementally increasing and decreasing with a predefined step size in order to determine the MPP. This process continues until the MPP is reached. However, at an equilibrium state, the operating point tends to oscillate back and forth around the MPP. To address this, a variable perturbation step size is proposed in [7] to minimize oscillations and enhance response speed. Despite its simplicity in implementation, this method lacks precision and efficiency as it does not account for the impacts of irradiance and temperature variations [8]. In an alternative approach known as the Incremental Conductance (IC) or (dV/dI method) [9]-[11], the MPP is determined by examining the slope of the PV power curve. The PV panel operates at the MPP when the slope is zero. The duty ratio should be increased if the change in conductance is greater than the negative conductance values and the slope of the PV power curve is positive; otherwise, it should be decreased [12]. However, the IC approach faces similar limitations to the P&O approach concerning oscillations and trade-offs in speed.

In addressing the aforementioned challenges in industrial processes, a Fuzzy Logic Controller (FLC) is increasingly employed due to its heuristic nature, which offers simplicity and effectiveness for both linear and nonlinear systems [13]. The notable departure from traditional approaches lies in the absence of a need for a precise system description. Fuzzy logic allows for the formulation of rules using linguistic variables, facilitating relatively straightforward controller adjustments—a departure from conventional design methodologies. Furthermore, given its nonlinearity and adaptability, fuzzy control demonstrates robust performance in various conditions, including parameter variations and fluctuations in load and supply voltage [13]. In this study, fuzzy logic has been employed to track the MPP in a PV system supplied by a boost converter. The fuzzy logic controller utilizes current error and error change as control inputs, with the output being the adjustment of the control signal for the duty cycle.

The performance of MPP tracking is assessed in a PV system employing a fuzzy logic controller under various weather conditions: 1) constant solar irradiance and temperature, and 2) changing solar irradiance and temperature. The paper is structured as follows, comprising five sections. Section II provides a description of the PV system, including the PV generator model and the DC-to-DC converter. Section III introduces the proposed MPP tracking approach based on the fuzzy logic controller for the PV system. Section IV discusses and interprets the simulation results obtained through the MATLAB/Simulink program. Finally, Section V presents the conclusions drawn from the findings.

II. PV System Description

As depicted in Fig. 1, this study examines the performance of MPPT in PV systems using a fuzzy logic-based approach. The system comprises a PV generator, a fuzzy logic controller, and a DC-DC converter. The fuzzy logic controller controls the duty cycle of the DC-DC converter. The PV generator consists of multicrystal silicon solar cells, the DC-DC converter adopts a boost converter configuration, and the MPPT process is overseen by the fuzzy logic controller. Fuzzy logic control involves three primary processes: fuzzification, fuzzy inference rules, and defuzzification.

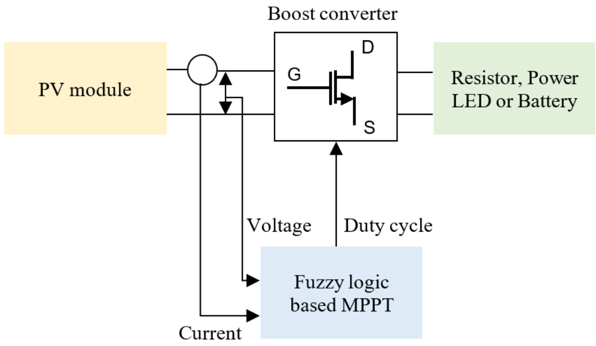


Fig. 1. Block diagram of the PV system along with the MPPT based on fuzzy logic controller

A. PV Generator Model

The PV generator consists of multiple PV cells connected in series and parallel to produce the necessary output voltage and current. Each solar cell comprises a single diode connected in parallel to the photocurrent source. When sunlight hits the surface of the solar panel, it generates photocurrent, and the diode represents the p-n transition region of the solar cell [14]. To enhance the model's accuracy, parallel and series resistors are included in the circuit [15], [16]. Fig. 2 illustrates the equivalent circuit of a PV solar cell based on a single diode.

Therefore, the equation for the I-V characteristic of a PV array can be represented as follows:

$$I_{PV} = I_{ph} - I_o\left[\exp\left(\frac{V_{PV}+R_S I_{PV}}{V_t a}\right)-1\right] - \frac{V_{PV}+R_{sm} I_{PV}}{R_{pm}} \tag{1}$$

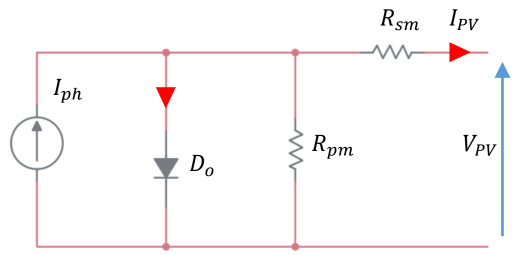


Fig. 2. Equivalent PV solar cell circuit model

Where the variables are defined as follows: V_{PV} represents the output voltage of the PV cell, while I_{PV} stands for the PV cell's output current. I_{ph} represents the photocurrent, and I_O is the saturation current. $V_t = k\,T/q$ symbolizes the thermal voltage of the PV cell, where q represents the charge of an electron ($q = 1602 \times 10^{-19}$ C), k is the Boltzmann constant ($k = 1380 \times 10^{-23}$ J/K), and T represents the temperature of the p-n junction. The parameter a corresponds to the diode's ideality factor. Additionally, the parallel and series resistances of the PV cell are denoted as R_{pm} and R_{sm}, respectively.

The photocurrent is primarily influenced by the intensity of solar PV radiation and the temperature of the PV cells. This relationship can be represented as follows:

$$I_{ph} = \left(I_{sc} + k_i(T_c - T_{stc})\right)\left(\frac{G}{G_{stc}}\right) \qquad (2)$$

where the photocurrent generated under Standard Test Conditions (STC) is denoted as I_{ph}, with the temperature and irradiance at STC being T_{stc} (25°C) and G_{stc} (1000W/m²), respectively. The short-circuit current coefficient, abbreviated as k_i, is normally supplied by the cell producer.

On the other hand, the saturation current of the diode can be determined using the following equation:

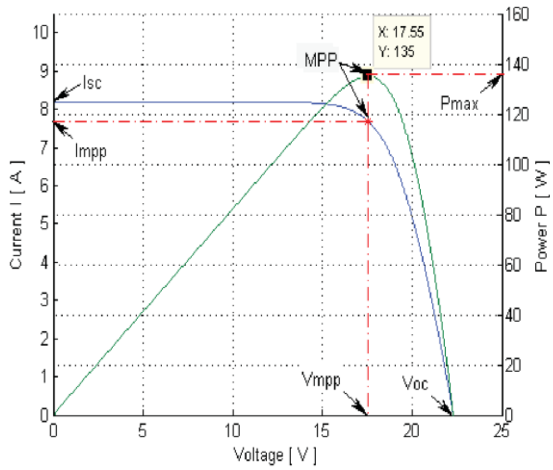
$$I_o = \frac{I_{ph}+k_i(T_c-T_{stc})}{\exp\left(\frac{V_{OC}+k_v(T_c-T_{stc})}{aV_t}\right)-1} \qquad (3)$$

Here, V_{OC} represents the open-circuit voltage at STC, and k_v is the open-circuit coefficient, both of which can be located in the datasheet. For the MATLAB/Simulink model in this study, the 1Soltech 1STH-215-P PV module is utilized. This module consists of multicrystal silicon solar cells arranged in two parallel strings with two series-connected modules per string. The nominal maximum power output of this module is 213.15W. Table I provides detailed specifications for the PV module.

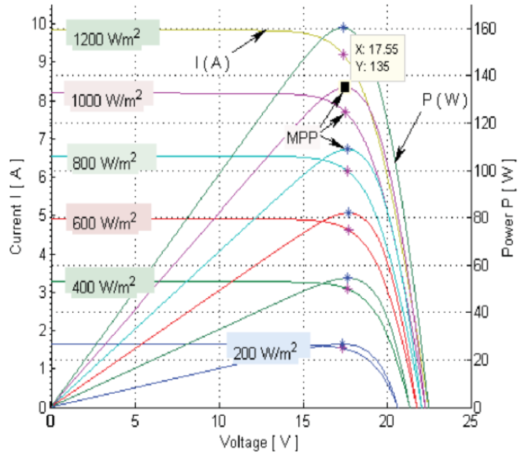
TABLE I
LIST OF 1SOLTECH 1STH-215-P PV MODULE SPECIFICATIONS

Electrical characteristics	Values
Open-circuit voltage (Voc)	36.3 V
Short-circuit current (Isc)	7.84 A
Optimum operating voltage (Vmpp)	29 V
Optimum operating current (Impp)	7.35 A
Maximum power at STC (Pmax)	213.15 W
Current temperature coefficient of Isc	0.102% /°C
Voltage temperature coefficient of Voc	-0.36099%/°C

Determining the power-voltage (P-V) and current-voltage (I-V) characteristic curves for the solar panel is the first step in obtaining the MPP of the PV panel [18]. The P-V and I-V characteristics of a photovoltaic module during STC are shown in Fig. 3(a), indicating for a temperature of 25°C and an irradiation of 1000 W/m². Within the P-V curve, there exists a distinct point where the solar module operates at its maximum efficiency, generating its highest output power (P_{max}) at a specific current (I_{mpp}) and voltage (V_{mpp}). However, an increase in irradiance leads to higher power and voltage levels for the PV panel, while elevated temperature adversely affects power and voltage, as demonstrated in Fig. 3 (b) and Fig. 3 (c).



(a)



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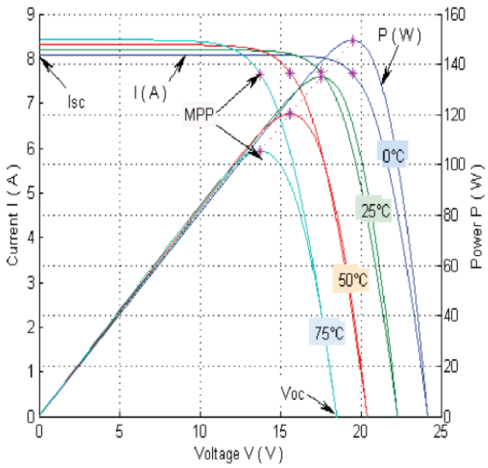


(c)

Fig. 3. P-V and I-V curve (a) During STC condition (b) Variable irradiance at a temperature of 25℃ (c)Variable temperature at irradiance of $1000W/m^2$[17]

B. Power Converter

A DC-to-DC converter is an equipment that transforms one type of DC power into another, with the benefit of controlling the output voltage despite the event of variations in the DC input voltage [19]. This converter is highly appropriate for application in PV systems, given the inherent variability and fluctuations in power output. One of the most crucial functions that DC-to-DC converters can perform is Maximum Power Point (MPP) tracking. To accomplish this, a DC-to-DC converter is positioned in between the PV generator and the load. The converter's pulse-width modulation (PWM) duty cycle is changed to ensure that the operating point coincides with the MPP. Fig. 4 illustrates the boost converter circuit, which comprises switches, inductors, capacitors and resistors. Typically, the semiconductor device used as the switch in DC-to-DC converters is the MOSFET transistor.

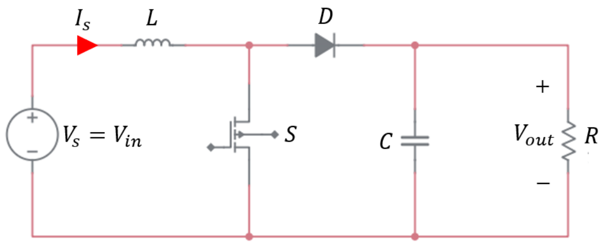


Fig. 4. The boost DC-to-DC converter circuit

V_s represents the source voltage, which also serves as the input voltage for this boost converter circuit, derived from the PV cell voltage. The MOSFET serves as a switch and can exist in both an on and off state. When 0 < t < DT, current flows through the MOSFET, turning it on, while the diode is reverse biased. The voltage across the inductor is expressed as:

$$V_L = V_{in} \tag{4}$$

Meanwhile, when DT < t < T, the MOSFET is in the off state, and the diode is in forward bias. In this state, the inductor functions as a power source, and the energy stored within it is discharged and transferred to the load resistance. The voltage across the inductor is stated as:

$$V_L = V_{in} - V_O \tag{5}$$

In both states of operation, when the system reaches a steady-state, the net change in inductor current becomes zero, hence

$$\Delta(i_L)ON + \Delta(i_L)OFF = 0$$

$$\frac{V_O}{V_{in}} = \frac{1}{1-D} \tag{6}$$

The parameters of both capacitor and inductor for a boost converter can be determined using the following equation, as shown below:

$$\Delta I_L = \frac{V_{in\_min} \cdot D}{fs \cdot L} \tag{7}$$

where V_{in_min} represents the minimum input voltage, fs is the switching frequency, D stands for the duty cycle, and L signifies the inductance.

$$L = \frac{V_{in} \cdot (V_{out} - V_{in})}{fs \cdot \Delta I_L \cdot V_{out}} \tag{8}$$

where V_{in} denotes the input voltage, V_{out} represents the output voltage, and ΔI_L stands for the estimated inductor ripple current.

$$C = \frac{I_{out} \cdot D}{fs \cdot \Delta V_{out}} \tag{9}$$

where C implies the capacitor, I_{out} signifies the output current and ΔV_{out} indicates the estimated output ripple voltage.

III. Fuzzy Logic Control (FLC) Algorithm

In the realm of renewable energy applications, fuzzy logic controllers find a diverse range of applications in system control. Fuzzy logic controllers have gained increasing popularity in recent years due to their user-friendliness, capability to handle imprecise inputs, adeptness in managing nonlinearities, and independence from the need for a specific mathematical model [20], [21]. In this study, a Fuzzy Logic Controller (FLC) serves as the controller tasked with determining the maximum power point achievable by PV modules under varying weather conditions. The FLC process comprises three key steps: fuzzification, fuzzy inference rules, and defuzzification. Fig. 5 illustrates these components, along with the fundamental design of a fuzzy logic system (FLS).

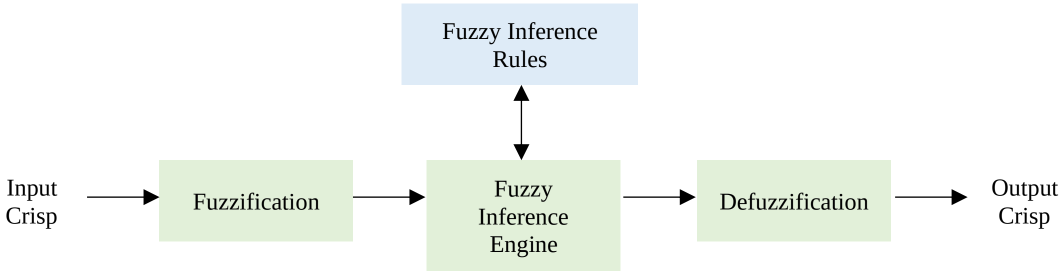


Fig. 5. The process of the FLC

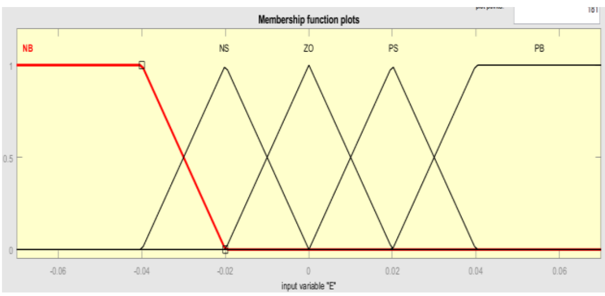
A. Fuzzification

Utilizing a membership function, the fuzzification process converts numerical input variables such as variations in voltage readings into language variables (occasionally referred to as fuzzy inputs). The PV module can be used to measure current (I) and voltage (V), and power (P) can be calculated using the formula $P = IV$. When two conditions are true for two input variables in the proposed controller, error $E(k)$ (which reflects the slope of the P-I characteristic) and rate of change of error, $CE(k)$, at sampling point k, then this step becomes operational. The following is how these variables, $E(k)$ and $CE(k)$, are expressed:

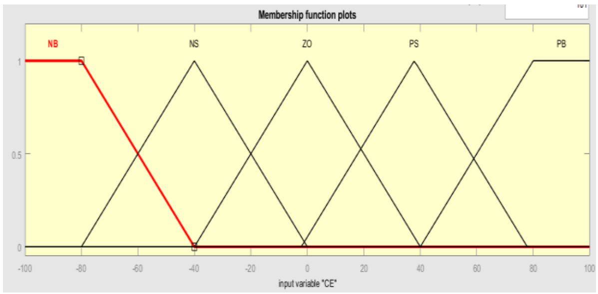
$$E(k) = \frac{P(k)-P(k-1)}{I(k)-I(k-1)} \quad (10)$$

$$CE(k) = E(k) - E(k-1) \quad (11)$$

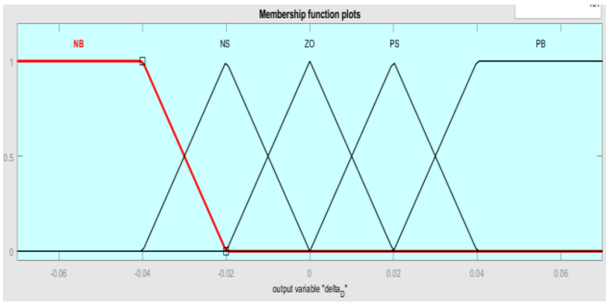
where the power and current drawn from the PV module are denoted by $P(k)$ and $I(k)$. As a result, the input $CE(k)$ represents the direction of the point's displacement, and the input $E(k)$ tells whether the operating point at instant k is on the left or right of the MPP on the P-I characteristic. The proposed controller's output is a change in the DC-to-DC converter's duty ratio, or ΔD. In order to move the operating point back to the ideal state, where the slope is zero, the control is therefore implemented by varying the duty ratio in line with the slope $E(k)$. E and CE serve as the input crisp, which is then transformed via fuzzy subset into fuzzy variables such as PB (positive large), PS (positive small), ZO (zero), NS (negative small), and NB (negative big). The membership function of five fundamental fuzzy rules for input and output variables is shown in Fig. 6.



(a)



(b)



(c)

Fig. 6. Membership function for (a) Input E (b) Input CE (c) Output ΔD

B. Fuzzy Inference Rules

Fuzzy rules play a vital role in the inference process by converting the fuzzy input obtained during the fuzzification step into fuzzy output during defuzzification. To evaluate the rules effectively, the crisp input values must first undergo fuzzification, determining the associated linguistic values (essential for establishing whether the rules are activated or 'fired') and quantifying the extent to which each component of the antecedent has been satisfied for each rule. The fuzzy inference rules are presented in Table II, encompassing fuzzy sets related to error $E(k)$, change of error $CE(k)$, and change in duty ratio ΔD.

TABLE II
THE FUZZY INFERENCE RULES

E	CE				
	NB	NS	ZO	PS	PB
NB	ZO	ZO	NB	NB	NB
NS	ZO	ZO	NS	NS	NS
ZO	NS	ZO	ZO	ZO	PS
PS	PS	PS	PS	ZO	ZO
PB	PB	PB	PB	ZO	ZO

If E is PS AND CE is NB, THEN ΔD is PS

Based on the information presented in Table II, the fuzzy rules can also be categorized in a 3D-dimensional format, as depicted in Fig. 7. Additionally, the rule viewer within the MATLAB interface for fuzzy logic is illustrated in Fig. 8. These rules play a critical role in the regulation of the DC-to-DC boost converter to ensure that the PV module's MPP is reached. The fundamental concept behind these rules is to align the operating point with the MPP. In practical terms, if the operating point deviates significantly from the MPP, the duty ratio is adjusted to mitigate the variations in the PV module's output. Table II is a visual representation of a control rule.: IF E is PS AND CE is NB THEN ΔD is PS. This rule implies that if the operating point is situated far from the MPP on the left-hand side, and there is a small change in the slope of the P-I characteristic in the opposite direction, then the duty ratio is incrementally adjusted. Typically, fuzzy control employs one of the following inference techniques: Max-Min, Max-Prod, or Sum-Prod. In this study, the Mamdani inference approach, which utilizes the Max-Min fuzzy combination, is employed.

In this work, the designed FLC has been finely tuned to produce optimal power generation decisions at the Maximum Power Point (MPP). The following is an explanation of how the FLC can be well-tuned. Design 'rule base' and 'membership functions'. Both the 'rule base' and 'membership functions' are employed in inference to determine the required fuzzy output values based on the given fuzzy inputs. This is a critical step in handling the FLC, and well-defined rules and membership functions are the keys to the overall system's effectiveness. The 'rule base' and 'membership functions' heavily rely on the designer's knowledge of the system. The first step is to define a rule base that is appropriate for the MPP control problem. The rule base is a collection of 'IF...THEN' rules that define how the system should respond to changes in the input. Mapping Input-Output. An FLC designer must understand how each input influences the desired output (MPP). This involves measuring and understanding the relationship between the inputs and the PV system's output. Ensure that the fuzzy mapping or model accurately reflects this relationship.

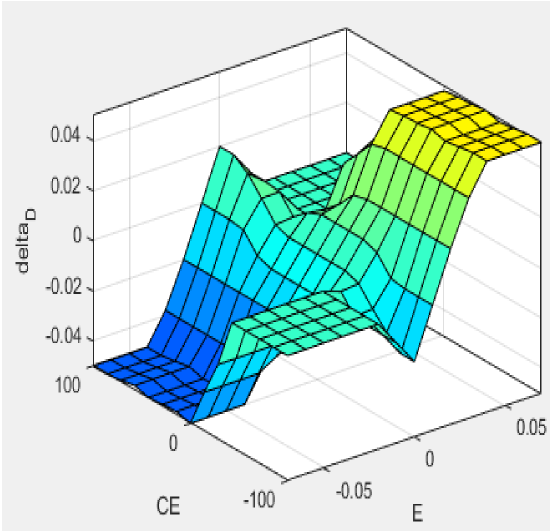


Fig. 7. 3D dimensions of fuzzy rule

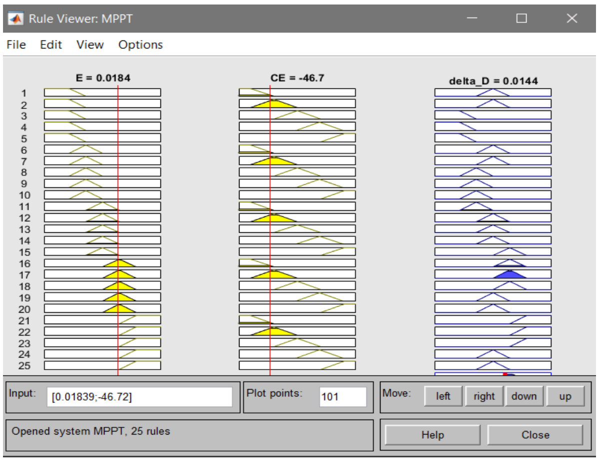


Fig. 8. Rule viewer in MATLAB windows of fuzzy logic

C. Defuzzification

Defuzzification is defined as the process of transforming a fuzzy set into a crisp output. In mathematical terms, defuzzification is often referred to as 'rounding it off.' The most commonly used method for defuzzification is the Center of Area method (COA), which is also commonly known as the centroid method. This approach calculates the center of the area under the fuzzy set and provides the corresponding crisp value.

The entire area of the membership function distribution utilized to represent the collective control action is partitioned into multiple sub-areas. Each sub-area's area and centroid are computed, and the sum of all these sub-areas is aggregated to determine the defuzzified value for a fuzzy set. In the case of discrete membership functions, the defuzzified value denoted as x using the centroid method is expressed as:

$$x = \frac{\sum_{i=1}^{k} x_i \mu(x_i)}{\sum_{i=1}^{k} \mu(x_i)} \tag{12}$$

Here, x_i represents the sample element, and $\mu(x_i)$ corresponds to the membership function for the k-th fuzzy set.

IV. Simulation Results and Discussion

The proposed fuzzy logic controller is implemented and simulated in MATLAB using the fuzzy logic toolbox, which corresponds to the designed fuzzy rule set. Fig. 9 illustrates the Simulink configuration of the PV system, employing the 1Soltech 1STH-215-P as the PV module model. The PV array, with a capacity of 213.15W, comprises two series modules and two parallel strings. This simulation encompasses the PV generator, DC-to-DC boost converter, MPPT controller, and the load. Fig. 10 depicts the fuzzy subsystem with two inputs and one output, serving as the MPPT controller. The fuzzy controller employed is the Mamdani fuzzy controller [22], and the defuzzification method used is the centroid method. The parameters of the DC-to-DC boost converter utilized in the simulation studies are outlined in Table III.

TABLE III
PARAMETERS OF THE BOOST DC-DC CONVERTER

Parameters	Values
Inductor, L	2 mH
Capacitor, C	100 µF
Resistor, R	20 Ω

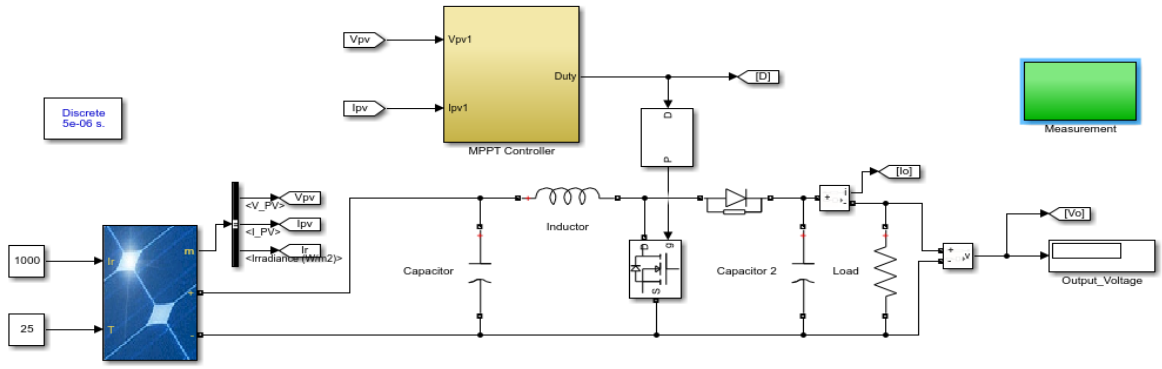


Fig. 9. Simulink based on MPPT fuzzy logic controller

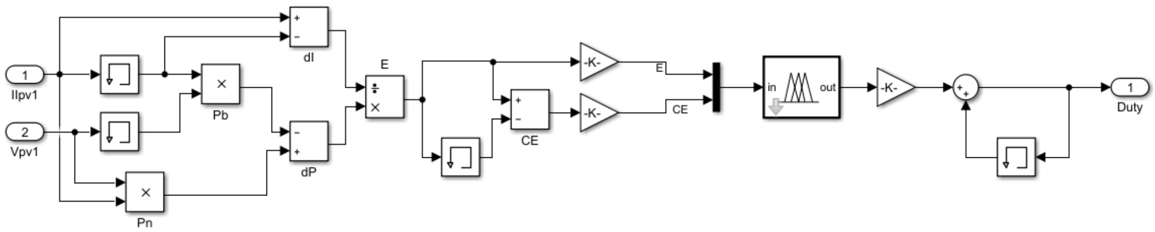


Fig. 10. Fuzzy logic toolbox subsystem of PV MPPT

To validate the efficient operation of the proposed fuzzy logic controller, a simulation study was conducted under two scenarios. In the first case, the simulation was conducted under Standard Test Conditions (STC). In the second case study, the simulation entailed adjusting the irradiance and temperature parameters within the PV system to provide additional confirmation of the effectiveness of the proposed FL-based MPPT. The signal was partitioned into four distinct states, as listed below. Fig. 11 and Fig. 12 depict the fluctuations in the irradiance and temperature signals, respectively.

State 1: 1000W/m² and 25°C
State 2: 700W/m² and 25°C
State 3: 1000W/m² and 40°C
State 4: 700W/m² and 40°C

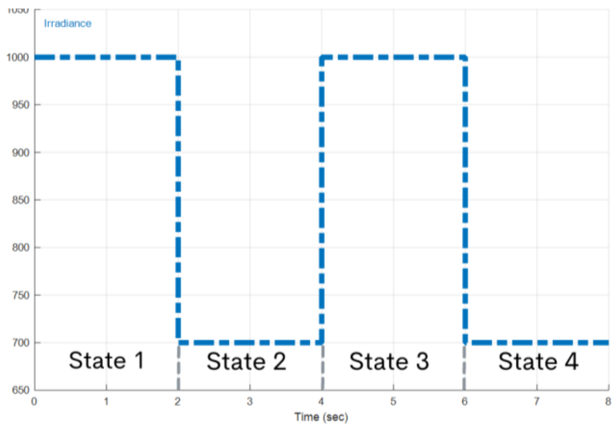


Fig. 11. Variable solar irradiance

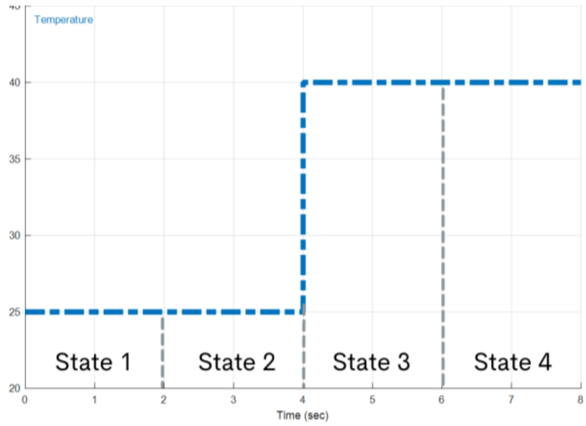
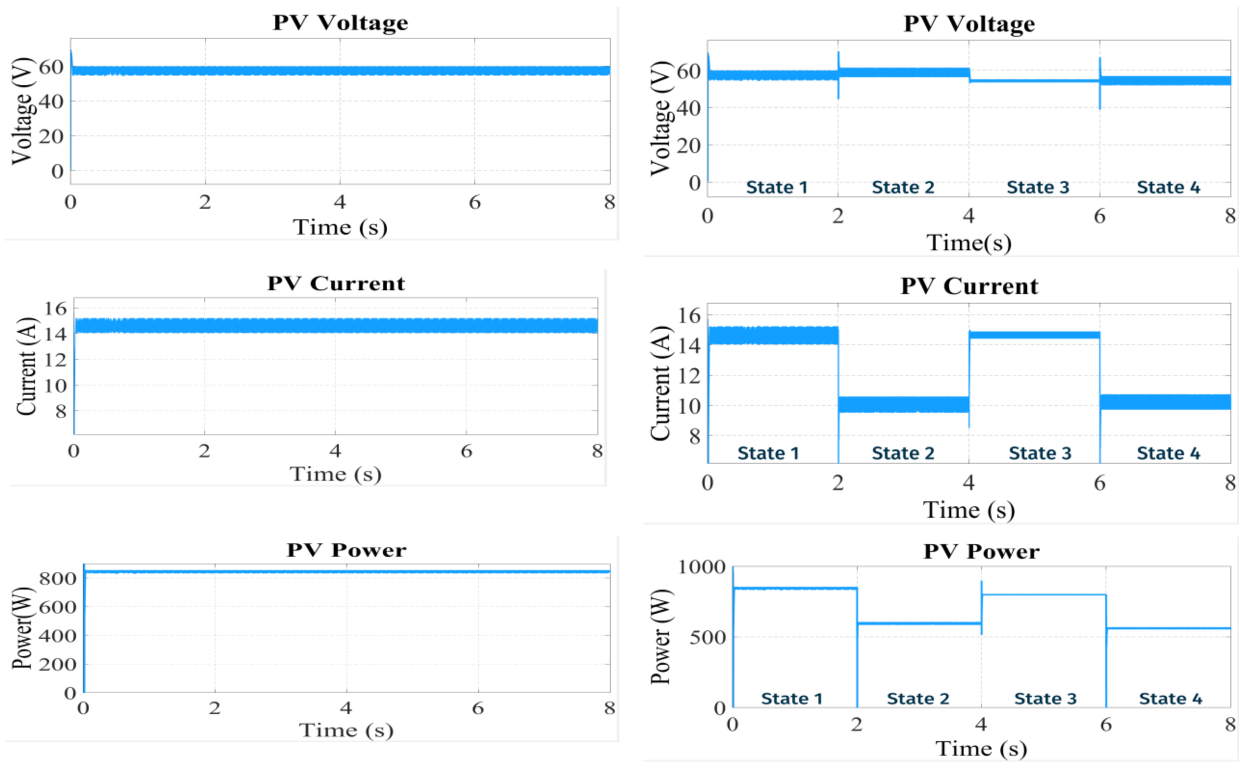


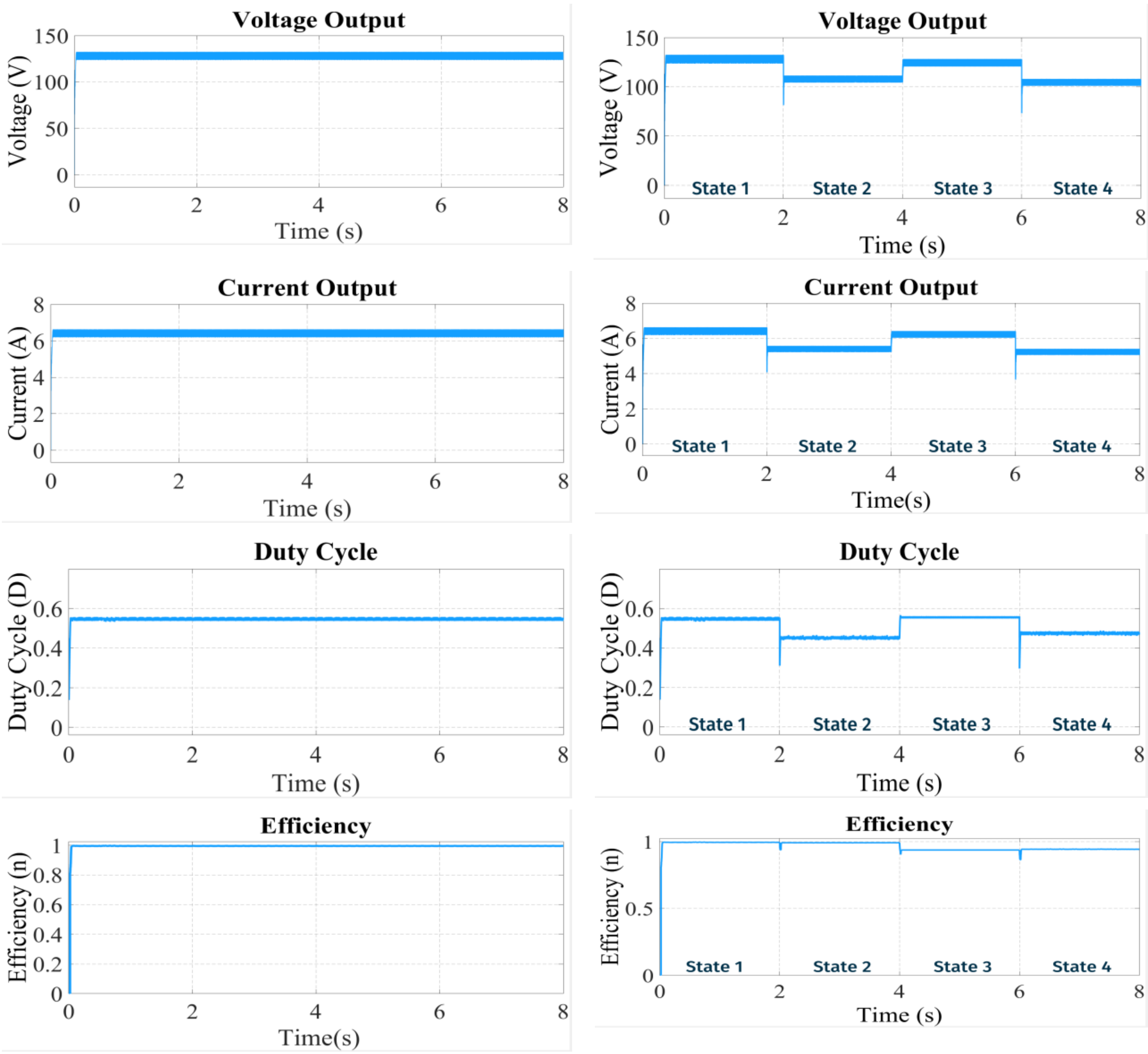
Fig. 12. Variable temperature

In the first scenario, the simulation was carried out under standard test conditions (STC). As shown in Fig. 13 (a), it is evident that the PV voltage, current, and power exhibit their optimal values when compared to the other conditions. In this STC scenario, both irradiance and temperature play crucial roles in achieving the highest MPP value, which is 850.3W. Additionally, it is noteworthy that under STC conditions, the converter operates with a duty cycle of 0.58, resulting in an impressive efficiency of 99.24%.

In the second scenario, Fig. 13 (b) illustrates the voltage output of 131.9V and the PV current of 14.39A when the system is in state 1. Transitioning to the second state with an irradiance of 700W/m² and a temperature of 25°C, the lower irradiance leads to a significant decrease in PV power and PV current, resulting in values of 598.7W and 9.938A, respectively. However, the PV voltage exhibits a marginal increase, reaching 60.25V. Moving on to state 3, with an irradiance of 1000W/m² and a temperature of 40°C, the irradiance increases back to the STC level, but temperature variations persist. As a result of these changes, the PV current and PV power remain relatively unaffected, while the PV voltage is impacted by the temperature increase, resulting in a value of 54.76V.

However, as the irradiance returns to standard conditions, the PV power increases compared to state 2, reaching a value of 799W. Finally, in state 4, the irradiance is 700W/m², and the temperature is 40°C. This state experiences reductions in both irradiance and temperature. From this state, it is noticeable that both PV voltage and output voltage have significantly decreased, with values of 52.48V and 107.6V, respectively. These changes result in a decrease in PV power, down to 561.2W. The duty cycle of the converter is 0.58 in states 1 and 3, and 0.48 in states 2 and 4. Furthermore, it is worth noting that in state 2, with an irradiance of 700W/m² and a temperature of 25°C, the proposed FL-based MPPT achieves an efficiency of 99.24%. In state 3, with an irradiance of 1000W/m² and a temperature of 40°C, the proposed method exhibits an efficiency of 93.76%.





(a) (b)

Fig. 13. Simulation result (a) STC condition (b) Varied of solar irradiance and temperature

V. Conclusion

In summary, the Maximum Power Point (MPP) of the PV generator is subjected to variations in solar irradiance and cell temperature. The objective of this research is to develop a Maximum Power Point Tracking (MPPT) controller based on fuzzy logic (FL) capable of identifying the MPP and optimizing the PV generator's operation at that voltage level. To evaluate the tracking performance of the FL-based PV system, a simulation study is conducted using the MATLAB/Simulink software. In the first case study, the simulation is conducted under standard test conditions (STC) to assess the performance of the proposed FL-based PV generator. The results indicate that the FL-based MPPT demonstrates rapid response times, effectively maintaining the output power at the MPP. In the second case study, to further validate the efficiency of the proposed method, additional simulations are conducted under four distinct scenarios, each characterized by varying solar irradiance and temperature conditions. The findings reveal that the designed PV system consistently achieves an efficiency of over 93% in all scenarios. This confirms that the proposed FL-based MPPT is proficient in tracking the MPP effectively, regardless of changes in weather conditions.

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Conflict of Interest

The authors declare no conflict of interest in the publication process of the research article.

Author Contributions

N. A. Yusri conceptualized the research, designed the experimental cases, conducted the analysis, and wrote the original draft. S. N. H. Mohd Tarmizi reviewed the literature, addressed current issues, and compiled relevant references. M. I. Zakaria provided full supervision throughout the research, continually reviewed the process until finalizing results, and edited the paper. S. F. Mohd was responsible for proofreading, grammar checking, and assisting in the preparation of figures. A. R. A. A Emhemed focused on proofreading and editing the manuscript for clarity and coherence.

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