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FUZZY LOGIC AND PI CONTROLLER FOR PHOTOVOLTAIC PANEL BATTERY CHARGING SYSTEM

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ABSTRACT: Due to the nonlinear property of the PV panels, there are a few significant restrictions and limitations in the PV solar system. The PV panels always have to depend on environmental conditions such as temperature and solar radiation to generate efficient power. This paper proposed an optimum control system that can handle the uncertainties and nonlinearities of any system by using the Fuzzy Logic Control system (FLC). The proposed system utilized an FLC system for a DC-DC boost converter, tracking the PV panel's maximum power point (MPPT). A PI control system is also used to maintain the continuous power supply for an optimum battery charging system for the DC-DC Buck converter. The goal is to provide constant voltage and appropriate current for charging the battery. It will increase the system efficiency and reduce the losses. It would also increase the battery life cycle and help the battery to charge fast. There are several MPPT methods found in the literature. The FLC can make a precise decision by considering the environmental state of the system. It can get a response to nonlinear environmental conditions instantly. The proposed system yielded an expected accuracy of 92% to 96%, with a system efficiency of 76% to 83%. Besides, it does not require any knowledge about the system since it is a rule-based system. The entire system has been designed in MATLAB/Simulink. The simulation results have been analyzed under 9 environmental states in a 1.0 s period.

ABSTRAK: Berdasarkan struktur tak linear panel PV, terdapat beberapa faktor kekangan yang jelas dan had tertentu dalam sistem solar PV. Panel PV selalunya sering bergantung kepada kondisi persekitaran seperti suhu dan radiasi solar bagi menghasilkan tenaga optimum. Kajian ini mencadangkan sistem kawalan optimum yang dapat mengawal ketidaktentuan dan ketidak linearan apa-apa sistem menggunakan sistem Kawalan Logik Fuzi (FLC). Sistem yang dicadangkan ini menggunakan sistem FLC bagi penukaran penggalak DC-DC, mengesan titik tenaga maksimum panel PV (MPPT). Sistem Kawalan PI turut digunakan bagi menyediakan bekalan tenaga berterusan untuk sistem pengecas bateri optimum melalui penukaran Balik DC-DC. Matlamat adalah bagi menghasilkan voltan berterusan & arus mencukupi bagi mengecas bateri. Ia dapat meningkatkan kecekapan sistem dan mengurangkan pembaziran tenaga. Ia juga dapat meningkatkan kitaran hayat bateri dan membantu bateri mengecas dengan cepat. Terdapat beberapa kaedah MPPT dijumpai dalam kajian terdahulu. FLC dapat menghasilkan keputusan tepat dengan mengambil kira keadaan persekitaran pada sistem tersebut. Ia dapat memberi respon kepada keadaan persekitaran tak linear dengan serta merta. Sistem yang dicadangkan menghasilkan ketepatan yang dijangkakan sebanyak 92% hingga 96%, dengan kecekapan sistem sebanyak 76% hingga 83%. Selain itu, ia tidak memerlukan apa-apa pengetahuan tentang sistem tersebut kerana sistem ini berdasarkan aturan.

Keseluruhan sistem dibangunkan menggunakan MATLAB/Simulink. Dapatan simulasi dikaji menggunakan 9 tahap persekitaran dalam tempoh 1.0 s.

KEYWORDS: *FLC; MPPT; PI controller; PV panel; battery charging control*

1. INTRODUCTION

In recent decades, the world has been observing tremendous pressure from insufficient available energy resources and several environmental threats such as rising greenhouse gases. According to scientists and environmental researchers, future energy development is dependent on renewable energy since all the non-renewable energy sources like fossil fuels, coal, and natural gases are finite [1,2]. Renewable source Solar cells are also considered one of the possible alternatives to non-renewable energy sources. Considering the advantages of the photovoltaic system, it is gaining popularity day by day. However, the PV panel has some disadvantages, such as low power efficiency (9% - 17%) and high maintenance and installation costs [3, 4]. The power of the PV panels always depends on the environmental condition. The nonlinear change of the environmental condition causes the change in the current and voltage of the PV panel [3,4]. The main challenge is to drive the PV panels at Maximum Power Point (MPP) to make the system more efficient and affordable. The maximum power point tracking (MPPT) is a method or algorithm that extracts the highest power from the PV panel and delivers it to the load [5]. The entire PV system operates on the PV curves, which can be applied under all environmental conditions. It enables the process to provide maximum output power while maintaining maximum efficiency [2]. Many MPPT methods have been designed and applied in literature and journals. Some of the popular MPPT methods are the Constant Voltage (CV) method, the Perturb and Observe (P and O) method [6,7], VSINC method [8] MPPT method by DC-DC Boost converter [5]. This paper has analyzed and proposed an optimum fuzzy logic-based control system to track the MPP from the PV panel. Fuzzy logic is a part of artificial intelligence that can handle the nonlinear properties of any system. It shows better performance compared to the conventional control method. Moreover, it can be implemented on any microcontroller since the fuzzy logic algorithm is simple.

Although PV panel has considered one of the most effective renewable sources, it is unavailable, such nighttime. Due to the limitations of the PV panel and uncertainties of the environmental conditions, a battery storage system is attached for continuing supply to the load when there is no power supply from the PV panel [1]. Furthermore, a suitable charging control system is applied to improve the cost and system efficiency, which would increase the battery lifetime and its efficiency [8]. This paper describes the design of a PI control system as a battery charging controller to ensure that the PV panel will supply the constant current and constant voltage to the Battery under any environmental condition.

A similar study was conducted by Unal Yilmaz and friends in 2018, where they used FLC for MPP tracking and PI controller as a charge controller [4]. Although, the studies did not mention the state of charge (SOC) of the Battery with constant current and voltage supply. The proposed system has used different algorithms for FLC, and the system's efficiency is much higher than that studies. Besides, the proposed system has shown the results of the SOC of the Battery with constant current and constant voltage under variable environmental conditions.

2. CONTROLLER DESCRIPTION

2.1 Fuzzy Logic Controller for MPPT

Many MPPT methods have been designed in literature, such as Perturb and Observe (P&O) method and the Conductance and incremental MPPT method [6,7]. In this project, the fuzzy logic controller (FLC) has been chosen and applied to track the maximum power point from the PV panel over other methods. Figure 1 shows the basic functional block diagram of an FLC. The FLC offers much better performance in handling nonlinearity and uncertainties. The other MPPT method, like the P&O technique, faces disturbance in tracking MPP when the environmental condition changes nonlinearly and rapidly [7]. The FLC is a rule-based system requiring complex mathematical models like root locus and bode plots. Besides, the algorithm is straightforward and can be implemented in a microcontroller [9].

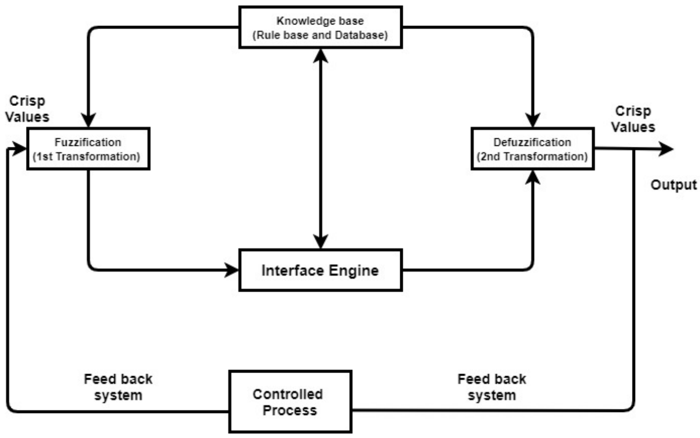

Fig. 1: Block diagram for FLC.

2.2 PI Controller for Constant Voltage Supply

Many research papers prove that the continuous charging and discharging process makes the battery life shorter and can be overcharged and insufficiently charged. Charging a battery up to 70% to 80% is not difficult. The challenging part would be charging the rest 30% to 20% [10]. A fast and efficient charging process requires a continuous power supply. It can be achieved using a specific control system such as fuzzy logic control or PI control strategy [1,3]. Figure 2 shows the basic function of a typical PI controller. This research proposes a PI controller to maintain the appropriate current and constant voltage supply to the Battery since it is simpler and easier to implement than the FLC battery charging method. It also shows precise and satisfactory results [4,8].

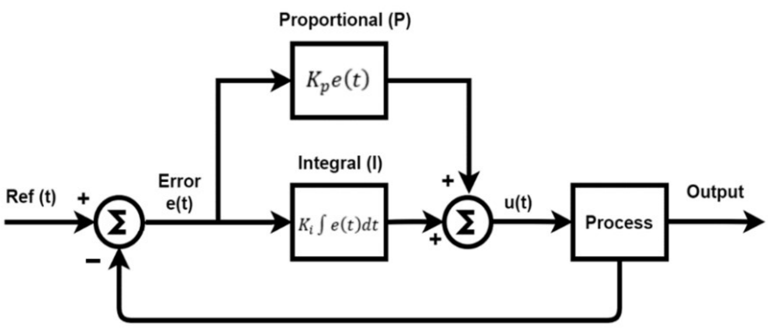

Fig. 2: PI controller block diagram.

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The PI has only two constant gains, which are Kp and Ki. Therefore, by considering the output, $u(t)$, the following equation of the PI controller is derived by [10].

$$u(t) = K_p\, \varepsilon(t) + \frac{1}{\tau}\int_0^t \varepsilon(t)dt \tag{1}$$

3. DESIGN AND IMPLEMENTATION

Figure 3 shows the proposed system block diagram for the PV panel's MPPT and battery charge control. The proposed system consists of a PV panel, a DC-DC boost converter with FLC for maximum power point tracking, and a DC-DC buck converter with a PI controller for the constant current and voltage supply load. A battery has been adopted as an energy storage system - finally, the current and the voltage flow through the FLC from the PV panels. The current and the voltage are used as the input for the FLC. The FLC converts the input and generates the output, the system's duty cycle. The FLC regulates the duty cycle of the PWM (Pulse Width Modulation) scheme, which is applied to switch to the DC-DC converter to control the converter's power.

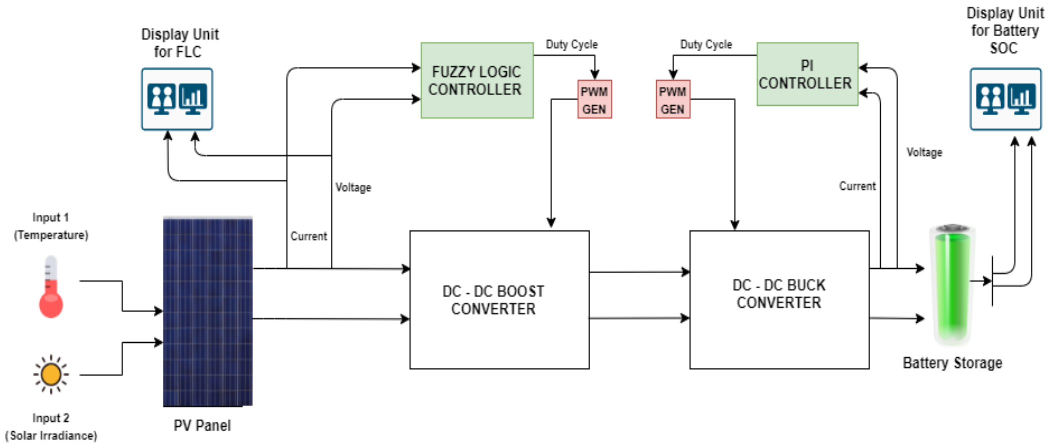


Fig. 3: Proposed system for MPPT and battery charge control of the PV panel.

3.1 Design a Fuzzy Logic Controller

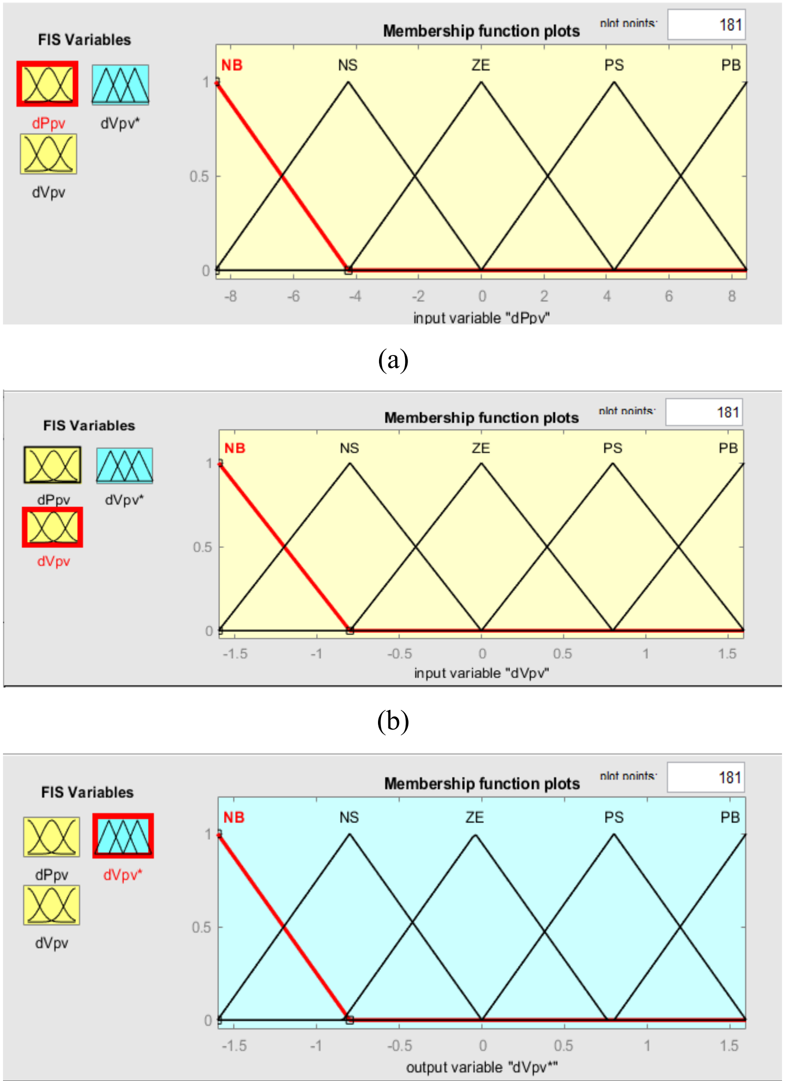
A proposed FLC has been designed based on Fig. 1, and four different logics have been developed using the membership function. Figure 3 shows the main operational steps of the FLC. To get the appropriate output results to track the Solar MPP, each logic of the FLC has to play a different role in the controller.

Step 1: Convert the crisp value into a fuzzy value (Fuzzification). The input (*E*) and Change of Error (*CE*) ranges are selected based on the proposed design. Then, each input (the crisp value) is converted into 5 Fuzziness values. The respected fuzziness values are Negative small (*NS*), Negative big (*NB*), Zero (*ZE*), Positive small (*PS*), and Positive big (*PB*). The input 2 for FLC is the change of PV voltage. The voltage deviation is used to develop the MPPT algorithm for FLC.

Step 2: Selection of membership function. A triangular membership function has been chosen for both inputs and output. The membership function is a graphical illustration to demonstrate the magnitude of input variables. There are five fuzziness values in both input and output, as shown in Fig. 4.

Step 3: Apply the rules. Since each input has 5 fuzzy values, so 5×5 matrix has been applied to generate the output. Therefore, 25 rules have been made to track the MPP of the PV panel. After defining the inputs and the output membership functions, the fuzzy logic rules are made based on Table 1. Where the delta P (ΔPpv) and delta-V (ΔVpv) are the inputs and the reference delta-V (ΔVpv*) is the output of the system.

Step 4: Defuzzification**:** At the final step, the fuzzy values are converted into crisp values to use as an output, a Duty cycle of the system. The FLC uses the rules-based system and generates the output accordingly whenever changes occur on the input side.



(a)

(b)

(c)

Fig. 4: Membership function, (a) input 1, (b) input 2 and (c) output.

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Table 1: Rules table of FLC for proposed algorithm

ΔVpv*[0/p]	Vpv [i/p]				
ΔPpv[i/p]	**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

3.2 Design of MPPT Algorithm by Using FLC

The FLC is considered one of the efficient control systems. Giving intellectual and intelligent output under nonlinear conditions makes the FLC unique from other controllers. The basic working strategies of the FLC to achieve the maximum power from the PV panel are, first, the FLC algorithm takes voltage and current from the PV panel as an input to the system. Then it uses to compute the power (P = IV) to find out the controller's inputs. Two inputs of the FLC are considered as the error and the change of error. Finally, the output of the FLC goes through the duty cycle of the PWM to maintain the DC-DC Boost converter [4,7].

$$Error(k) = \frac{P(k) - P(k-1)}{V(k) - V(k-1)} \tag{2}$$

$$Change_{Error(k)} = Error(k) - Error(k-1) \tag{3}$$

Where the *P(k)* and *V(k)* are considered as instant power and the voltage of the PV generator, *V(k-1)* and *P(k-1)* are the previous current and the previous power, respectively.

TFLC uses the inputs for the MPPT of the PV panel to gain the appropriate outcomes. The following steps should be applied to run the duty cycle of the boost converter. First, the input and the output variables should be specified in the system. Then, the membership function of the system would convert the crisp value into fuzziness and generate the degree of the trueness of the process. Finally, the rule-based system determines the output by observing the input, as illustrated in Fig. 1. The rules are applied to trace the change in power in terms of voltage (*dp/dv*) that would control by the duty cycle of the PWM to make an appropriate adjustment (increase/decrease) of voltage until the desired maximum power point is achieved [6,9,13]. The entire PV system operates on the P-V characteristic graph under variable conditions. The MPPT algorithm should be designed accordingly to track the maximum power. Figure 5 shows the power versus voltage characteristics of a solar panel and the MPPT algorithm techniques. The power curve Fig. 5 illustrates the maximum power point under the standard condition when the irradiance is 1000 W/m^{2,} and the temperature is 25 ^{o}C. The trained of the curve observed from the curve that, for tracking the MPP from the PV panel, 4 conditions must be as follows.

1. When the P(k) - P(k-1) > 0 and V(k) – V(k-1) > 0, the Voltage should be increased.
2. When the P(k) - P(k-1) > 0 and V(k) – V(k-1) < 0, the Voltage should be decreased.
3. When the P(k) - P(k-1) < 0 and V(k) – V(k-1) > 0, the Voltage should be decreased.
4. When the P(k) - P(k-1) < 0 and V(k) – V(k-1) < 0, the Voltage should be increased.

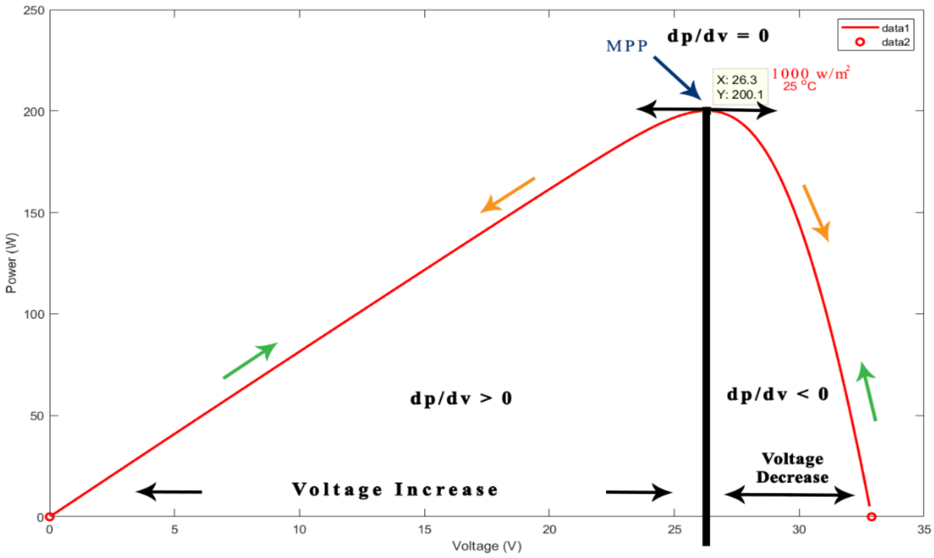

Fig. 5: Power vs voltage characteristic for MPPT algorithm.

The MPPT algorithm has been developed based on Eq. 2 and Eq. 3, and the above conditions. In addition, the MPPT algorithm flow chart has been designed to demonstrate the operations that have taken place inside the system, as shown in Fig. 6.

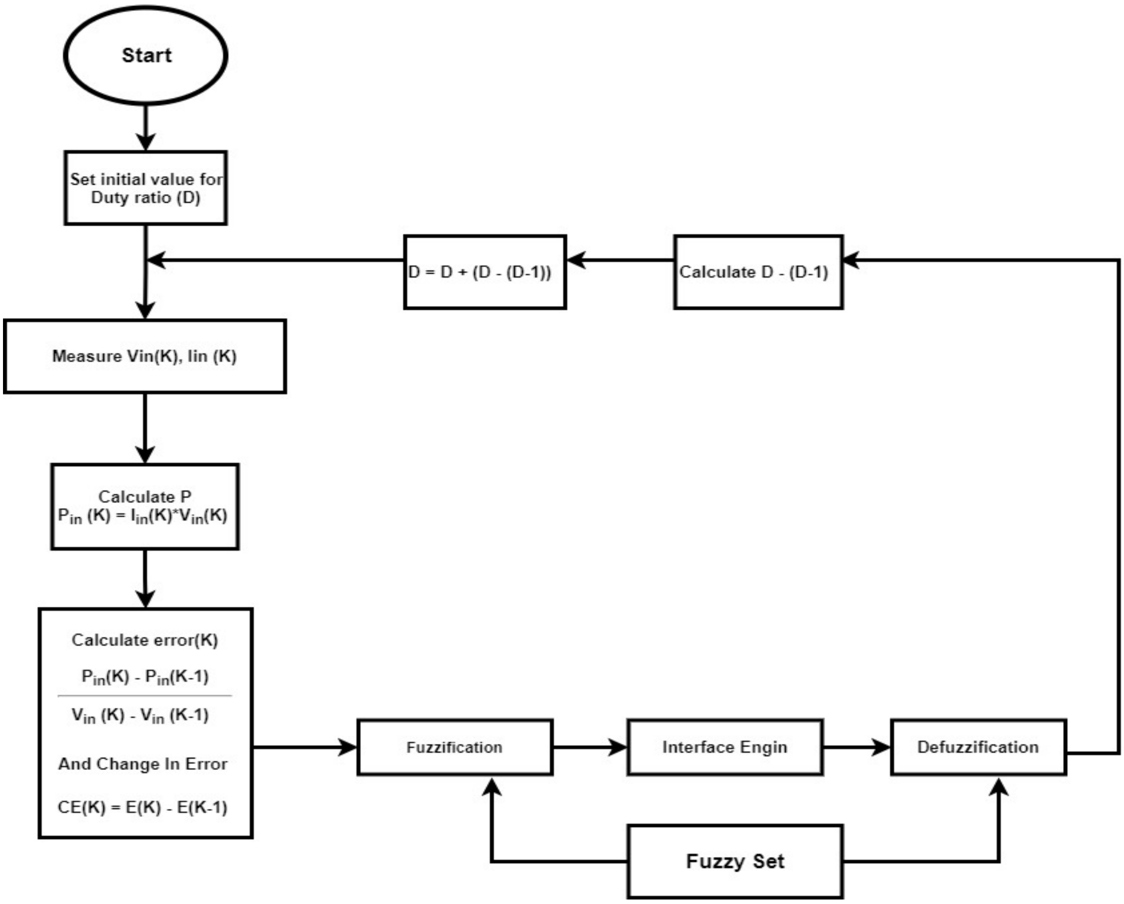

Fig. 6: The operational flow chart of the FLC.

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An MPPT algorithm has been developed based on the flow chart, and the system design has been built using the Simulink MATLAB function, as shown in Fig. 7. Table 2 shows the electrical parameters used for the proposed PV panel.

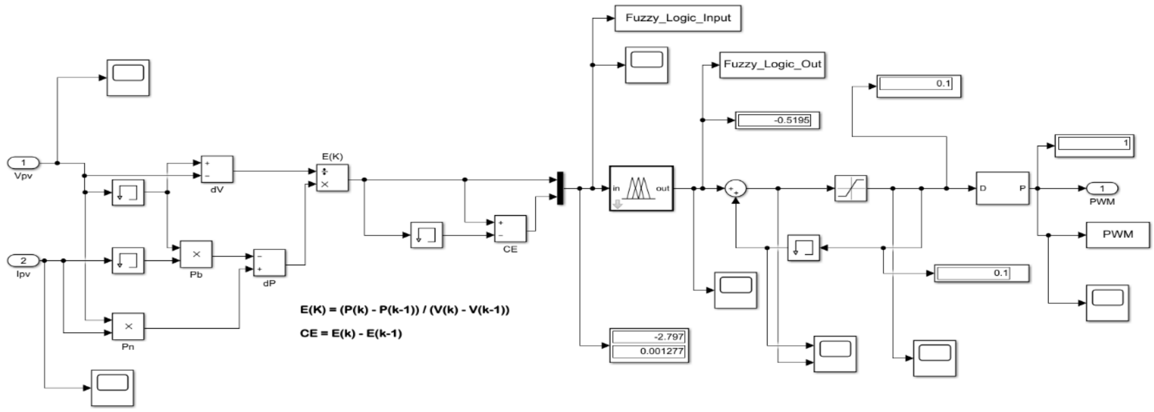

Fig. 7: The MPPT algorithm for the FLC.

Table 2: Electrical characteristic for the proposed PV panel

Parameter	Value
Maximum Power (Pmax)	200 W (+10%/-5%)
Maximum Power Voltage (Vmpp)	26.3 V
Maximum Power Current (Impp)	7.61 A
Open Circuit Voltage (Voc)	32.9 V
Short Circuit Current (Isc)	8.21 A
Temperature Coefficient of Voc	-1.23$\times 10^{-1}$ V/C
Temperature Coefficient of Isc	3.18$\times 10^{-3}$ A/C

3.3 Operation of DC-DC Boost Converter

According to the proposed design, a DC-DC Boost converter is used. The efficiency of the maximum power point tracking system depends on the MPPT control algorithm and the MPPT circuit. Usually, the boost converter is connected to the MPPT circuit and the PV panel [7]. It maintains less energy loss when the energy is transferred between two circuits. It also boosts the DC voltage level. In the MPPT algorithm, the FLC is used to switch off the boost converter to control the duty cycle of PWM. The DC-DC boost converter circuit is a switch-based power supply circuit that steps up the system's voltage. It is made of MOSFET, Diode, output capacitor, and an inductor. The MOSFET, the switch of the circuit, played a significant role here since the duty cycle of the PMW generator is connected to MOSFET's gate. It switches ON and OFF the circuits very fast [4].

To find the inductor voltage of the system,

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

To operate the system at the steady-state condition, the current shift on the inductor must be zero during the switching period.

$$\frac{V_{out}}{V_{in}} = \frac{1}{1 - D} \tag{5}$$

By using the following equations, the inductor and the capacitor of the boost converter can be found.

$$\Delta I_L = \frac{V_{in\_min} D}{f_s L} \tag{6}$$

where, f_s= switch frequency, L= inductance, D = Duty cycle, V_{in_min}= minimum input voltage. V_{out} = output voltage, V_{in}= input voltage, ΔI_L= estimated inductor ripple current. C = capacitance, I_{out} = output current, ΔV_{out}= estimated output ripple voltage

$$C = \frac{I_{out} . D}{f_s . \Delta V_{out}} \tag{7}$$

3.4 Design and Operation of DC-DC Buck Converter

The Buck converter with the PI control system to achieve the appropriate current and constant voltage has. The goal of using the DC-DC buck converter in the circuit is to step down the voltage and make it appropriate for battery charging. It is also a switch-mode power supply system regulated by a PWM generator like the DC-DC Boost converter. The converter can be used fort he wireless charging system [14]. The DC-DC buck converter circuit reduces the input voltage by stepping up the current. That is another advantage of the buck converter. The PWM generator is connected to the MOSFET's gate to operate the circuit switch. The inductor voltage of the converter can be calculated by the equation [4].

$$V_L = V_{in} - V_{out} \tag{8}$$

$$V_{out} = D\, V_{in} \tag{9}$$

Overall, when the switch is ON, the inductor gets current from the source. When the switch is OFF, the inductor receives current from the capacitor, so the total current becomes more significant than the input source current. The Inductor current of the converter is as follows,

$$\Delta I_L = \frac{V_{out}(V_{out} - V_{in})}{f_s\, L\, V_{in}} \tag{10}$$

The capacitor of the converter [4],

$$\Delta V_{rpl} = \frac{D\, I_L}{8\, f_s\, C} \tag{11}$$

where, V_{rpl} = ripple voltage.

3.5 PI Controller for Constant Voltage Supply

The PI controller is used in this project as a negative feedback system, as shown in Fig. 8 and Fig. 9. A reference voltage has been set that indicates what the system would do. The PI controller compares these two signals and passes the zero-error signal. PI controller has proportional gain (*Kp*) that can calculate the present error, and it is helpful to reduce set up time and integral gain (*Ki*) that can calculate the past error. Furthermore, it is instrumental in lowering the steady-state error [4].

To obtain the constant voltage method, the PI control system is used to control the output voltage of the buck converter. The reference voltage = 26.567 V since this is the fully charged voltage for a 24 V DC lead-acid battery (open-circuit voltage of the battery when

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the SOC = 100%). That indicates that when the voltage level reaches that point, the battery stops charging.

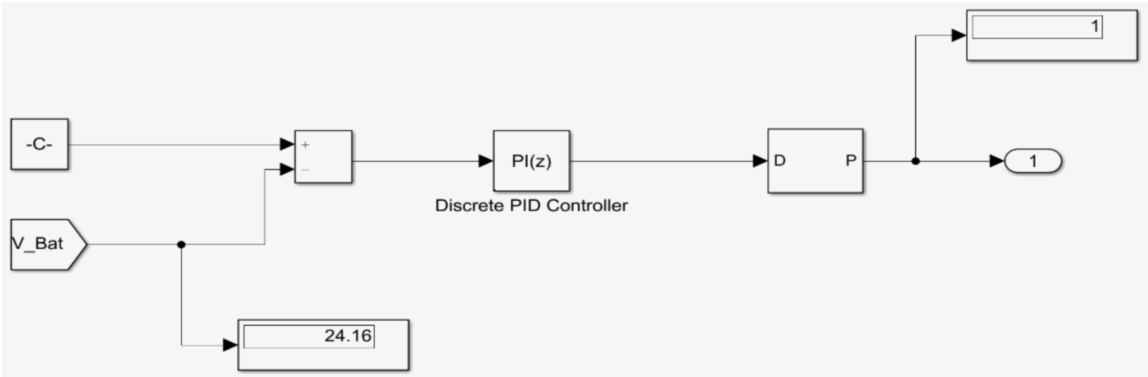

Fig. 8: PI controller for constant voltage supply.

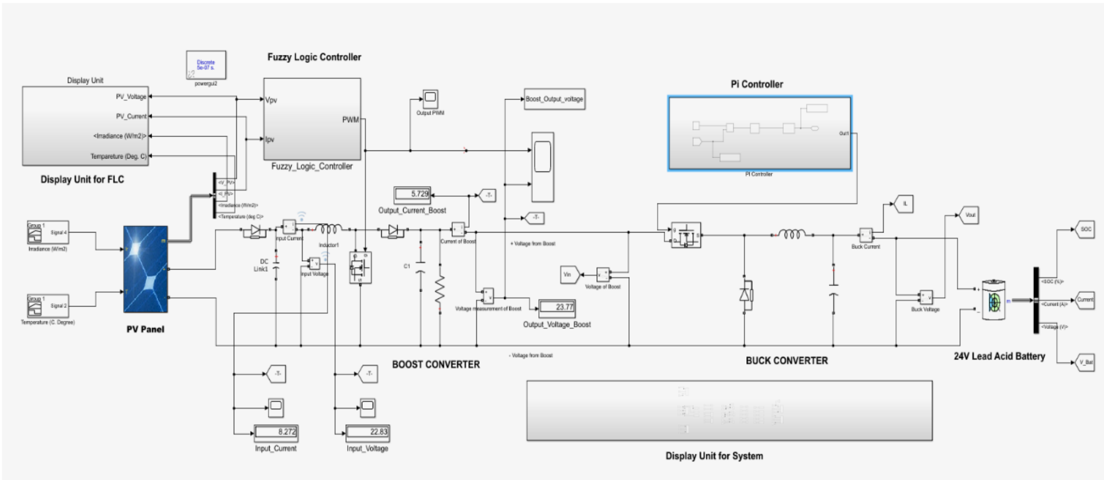

Fig. 9: Simulink model of the proposed system.

4. RESULTS AND ANALYSIS

The proposed design was simulated under nine different states of the environmental condition. The results were compared to determine the accuracy and efficiency of the system, as shown in Fig. 10.

Fig. 10: Inputs of the system.
Irradiance 1000 W/m^2, AM 1.5 spectrum, module temperature 25 ^{o}C.

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The MPPT may depend on the characteristic of the PV panel.

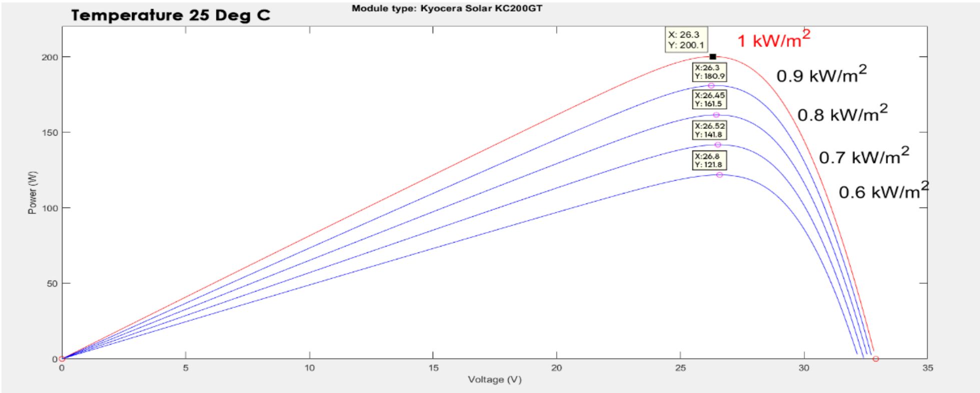

Fig. 11: P-V characteristic curve under variable solar irradiance.

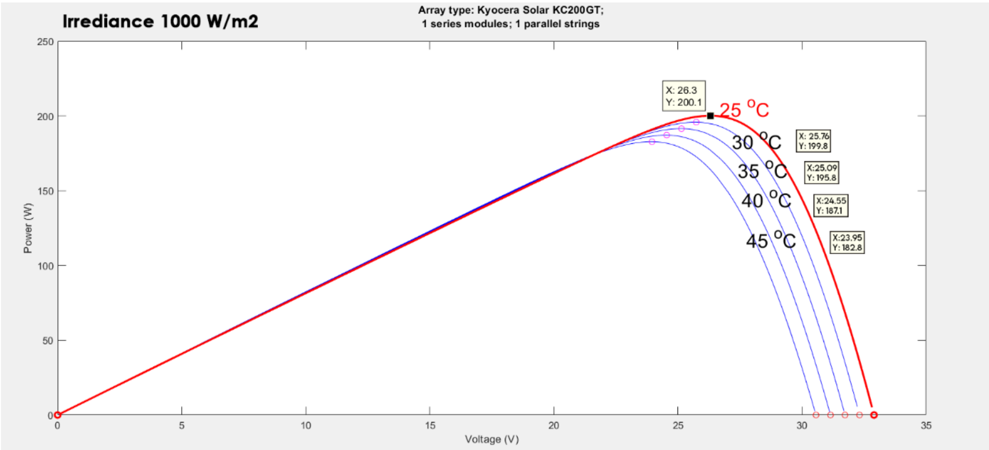

Fig. 12: P-V characteristic curve under variable temperature.

The P-V characteristics curves have been shown in Fig. 11 and Fig. 12 according to nine different states. The simulation results for maximum power point tracking using the FLC algorithm as shown in Fig. 13. The graphs have illustrated the power comparison between PV, DC-DC Boost converter and DC-DC Buck converter circuits. Figures 14, 15 and 16 show the power compensation graphical result of the simulation.

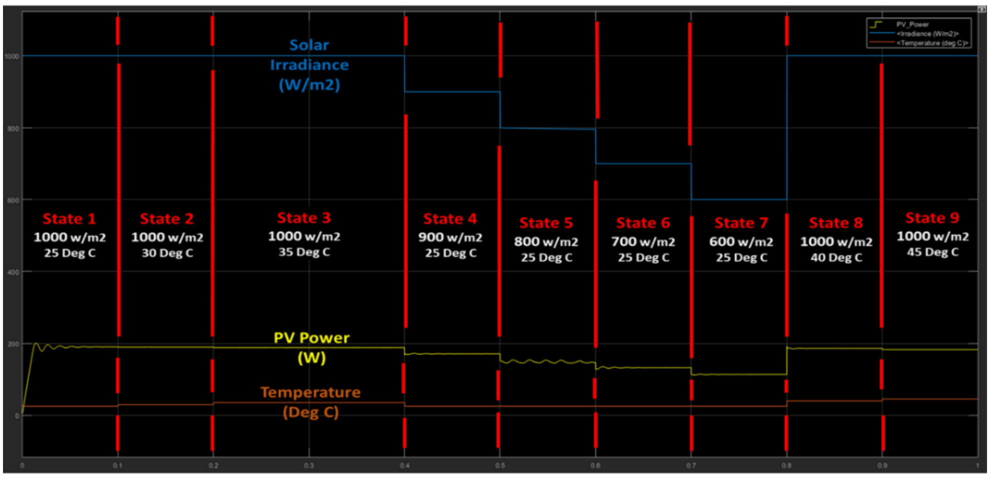

Fig. 13: PV power graph in terms of variable inputs.

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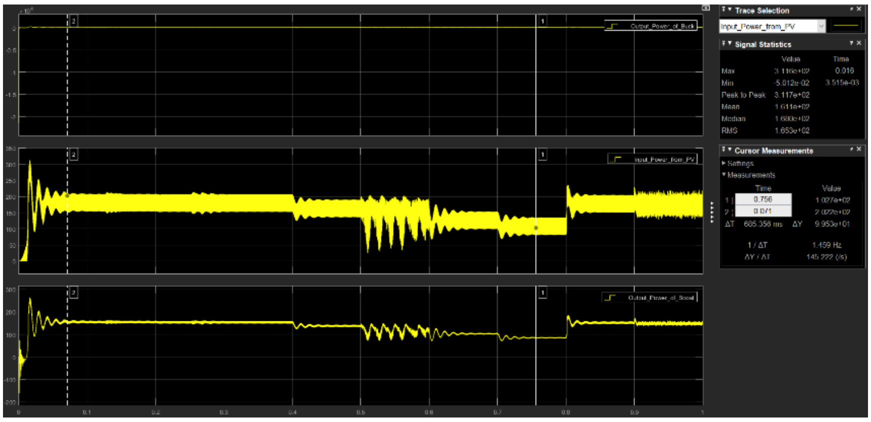

Fig. 14: PV power graph.

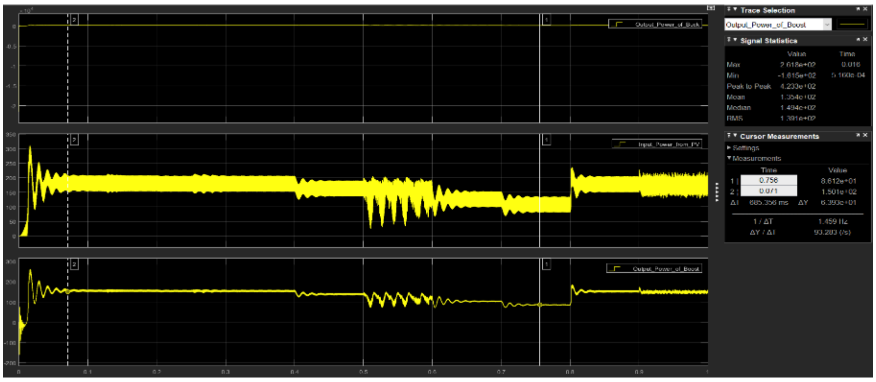

Fig. 15: DC-DC Boost power graph.

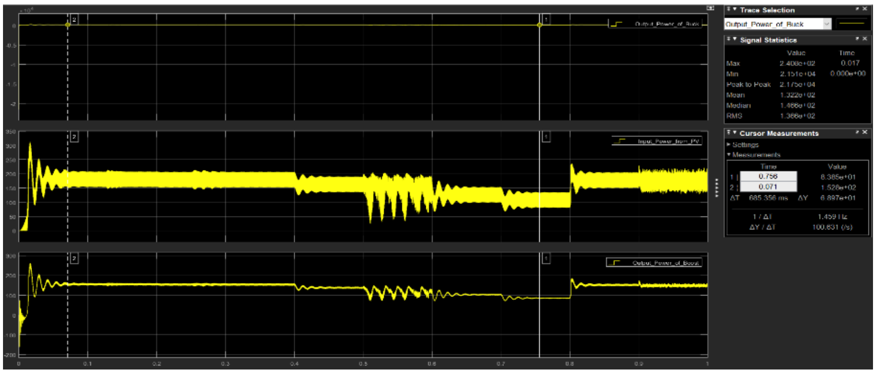

Fig. 16: DC-DC Buck power graph.

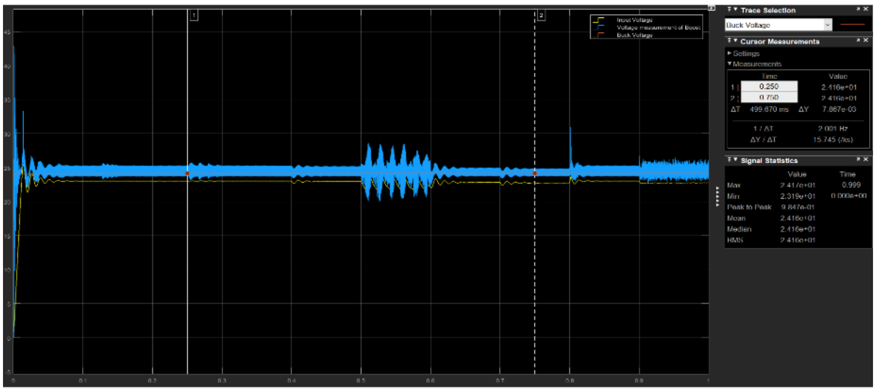

Fig. 17: Voltage comparison graph.

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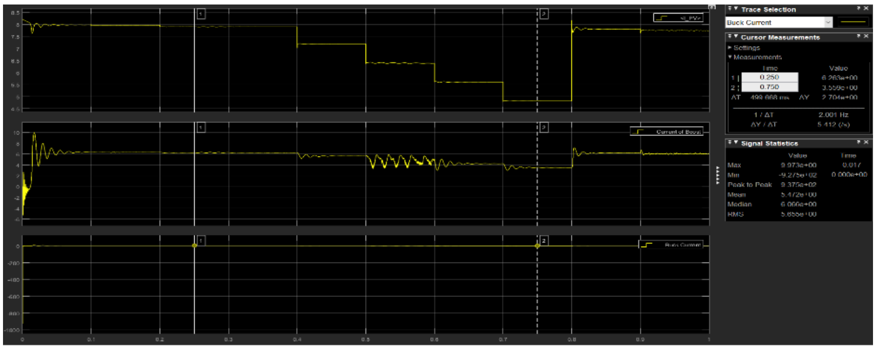


Fig. 18: Current comparison graph.

Figures 17 and 18 show the voltage and current comparison of the systems, respectively. The graphs showed the difference between the input and output voltage of the Boost converter. The yellow line represents the input voltage supplied by the PV panel, and the blue line represents the output voltage, which is used as an input voltage for the DC-DC Buck converter. It is observed that the FLC can track every change in the input signal and produce the output appropriately. The response observation has been done to predict how fast the fuzzy logic controller tracks the MPPT to sudden changes in the input signal. According to the above observation, the FLC takes around 0.004 seconds only to track MPP from the PV panel. Table 3 illustrates the simulation results and the system accuracy and efficiency of the proposed system.

Table 3: The MPPT summary of the results

Environmental State	P(mpp) (W)	P(pv) (W)	Accuracy (%)	P(buck) (W)	Efficiency (%)
State 1: (1000 W/m^2, 25 ^{o}C)	200.1	191.4	95.7	154.4	80.7
State 2: (1000 W/m^2, 30 ^{o}C)	199.3	192.6	96.6	152.5	79.2
State 3: (1000 W/m^2, 35 ^{o}C)	195.0	184.0	94.4	152.1	82.7
State 4: (900 W/m^2, 25 ^{o}C)	180.9	166.6	92.1	136.7	82.1
State 5: (800 W/m^2, 25 ^{o}C)	161.5	148.5	92.0	123.2	83.0
State 6: (700 W/m^2, 25 ^{o}C)	141.8	134.3	94.7	102.2	76.1
State 7: (600 W/m^2, 25 ^{o}C)	121.8	114.8	94.3	84.6	73.6
State 8: (1000 W/m^2, 40 ^{o}C)	187.1	179.8	96.1	154.8	83.0
State 9: (1000 W/m^2, 45 ^{o}C)	182.8	175.9	96.2	150.7	82.6

A constant power supply is essential to charge the Battery efficiently. It would reduce the losses and prolong the battery life. The DC-DC Buck converter with PI controller is used after the DC-DC Boost converter in the circuit to supply the Battery's appropriate current and constant voltage. The simulation results for SOC and constant voltage as shown in Fig. 19.

Figure 20 (a) and (b) show graphical results of how the power and current of a solar panel vary with the variation of environmental parameters, respectively. The graphs shown in Fig. 20(c) are the SOC of the battery in a period of 0.1 s. At time t = 0.250 s, SOC = 45.0001% (assume that the Battery was initially charged 45%), and at time t = 0.750 s, SOC = 45.0004%. These indicate that the Battery charges linearly despite many changes in the environmental conditions.

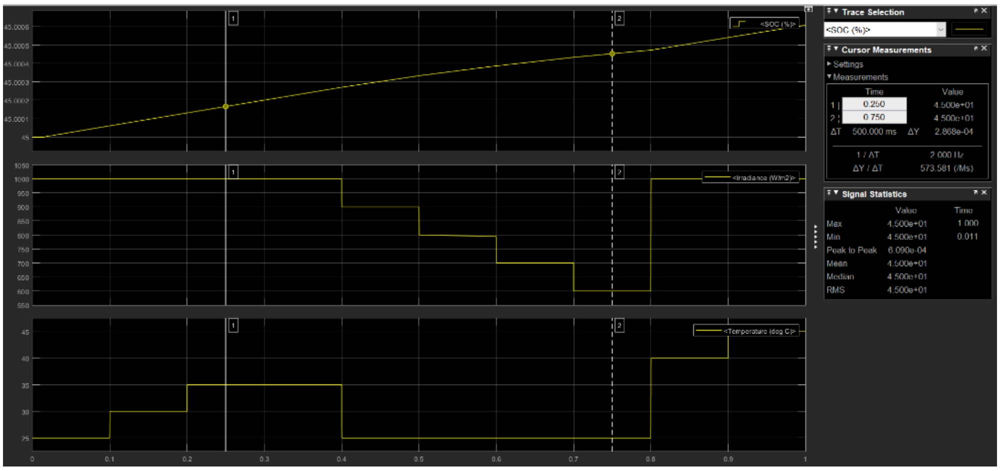
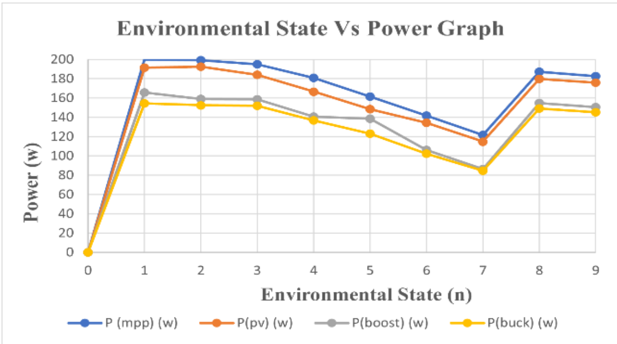
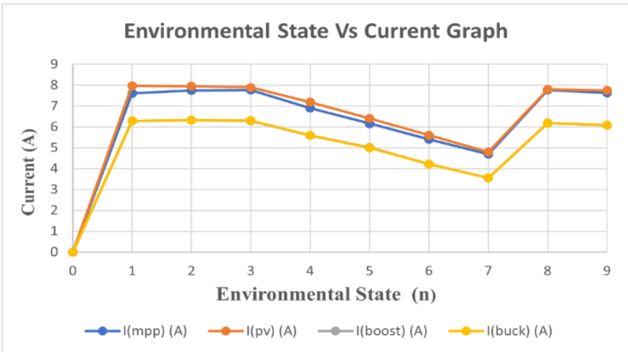


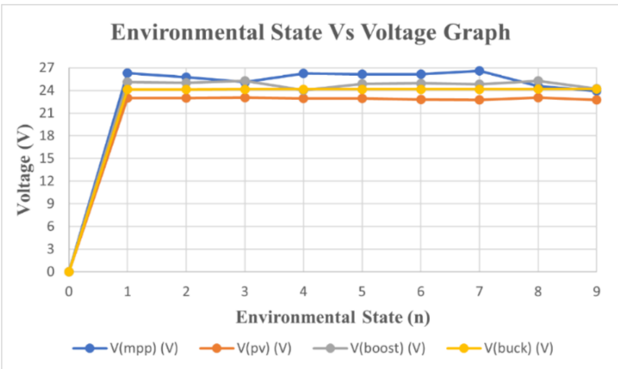
Fig. 19: State of charge (SOC) in terms of different environmental conditions.



(a)



(b)



(c)

Fig. 20: Variation of electrical parameters with environmental state, (a) power, (b) current, and (c) voltage.

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The input and output power, current, and voltage comparison in Fig. 19 have been illustrated under nine variable environmental states. It is observed from Fig. 20(c) that the DC-DC Buck converter voltage is nearly constant and consistent compared to the input voltage (Vpv) from the PV panel and the DC-DC Boost converter voltage (V_{boost}). Since the feedback reference voltage has been set, $V = 26.567$V (fully charged voltage of the Battery) in the PI controller, the output voltage of the buck converter would be settled after reaching that voltage.

Table 4 shows the lead-acid battery's specifications used in the simulation. The Battery's normal operating voltage is 24 V, and the voltage is 26.567 V when it is fully charged, which has been used as a reference voltage for the PI controller.

Table 4: Battery characteristics (from battery datasheet)

Parameter	Value
Voltage Per Unit (V)	24
Maximum Capacity (Ah)	250
Cut-off Voltage (V)	18.3
Internal resistance (Ohms)	0.0010
Operating Temperature Range	-20 to +55 ^{o}C
Fully charged Voltage (V)	26.5671

5. CONCLUSION

In this research, the usefulness of the fuzzy logic control system for the PV panel has been discussed and verified. From Table 3 and Fig. 19, it is justified that the proposed fuzzy logic controller effectively handles the nonlinearity and uncertainty of the environmental conditions. This paper also showed a system accuracy of around 92% to 97%. The efficiency with about 73% to 83%, whereas the literature, shows efficiency of around 55% [4,5,7]. According to the literature, charging a battery with a constant voltage and suitable current supply increases the battery life. The proposed system has been used a PI controller to maintain a constant voltage and an appropriate current supply, which can increase the battery life. The Simulink / MATLAB data of the simulation results can be used to conduct the research for hardware implementation by imploring the FLC algorithm in a microcontroller.

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