Fuzzy logic control based maximum power point tracking technique in standalone photovoltaic system

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ABSTRACT

This study describes the development of a smart technique for tracking the highest power point on a standalone photovoltaic (SAPV) system when temperature and irradiance conditions are changing using fuzzy logic control (FLC). The PV systems comprises of a PV array, a boost converter, a controller for tracking the maximum power point, and an inverter to power the AC loads. The FLC-based maximum power point tracking (MPPT) is proposed because the technique is not complex and does not need a deep comprehension of the particular model of the system. Furthermore, the technique is efficient and fast response in tracking maximum power (MP) from the PV array. The technique overcame the limitation of the conventional MPPT technique that resulted in slow tracking of the MP and was not accurate on the optimal position of the PV array output power. The SAPV system is integrated with the sealed lead acid (SLA) battery bank as an alternative power source and makes up for power shortages by supplying energy to the load without interruption during power shortages. A system for managing the battery has been included in the system to preserve the battery's longevity by controlling the battery's charging process. The PV system is able to supply single-phase output AC voltage of 230 Vrms and has low total harmonic distortion (THD) that is suitable for home appliances. The achieved simulation results demonstrate the effectiveness of the suggested fuzzy logic controller in tracking the MPP.

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1. INTRODUCTION

Increases in industrial growth and human consumption have resulted in a substantial increase in energy usage. In recent years, increasing energy demands and increasing pollution have prompted researchers to focus their attention on renewable energy sources [1]. Solar power systems are among the renewable energy sources that are being researched the most owing to their accessibility [2]. The technique of tracking the highest power point, known as maximum power point tracking maximum power point tracking (MPPT), is a widely recognized algorithm for boosting energy conversion efficiency. It controls how much power the PV system produces by monitoring the highest power point during weather conditions that are unstable and severe [3]. The PV array's performance indicators are impacted by climatic changes and exhibit nonlinear behaviour [4]. The method suggested in this paper allows the PV system to operate effectively regardless of weather conditions by charging and discharging the battery. An advantage of photovoltaic systems is that they can be set up in remote locations when grid access is either scarce or highly expensive. In this situation, implementing a standalone PV system is more economical than the cost of getting energy from the local provider through power lines and cables to the residence in a grid-connected PV system. Battery is an essential component of any standalone PV system, although they can also be optional, depending on the design. Solar-generated electricity is stored in batteries for usage at night or in an emergency during the day.

Photovoltaic power systems are infrequently used due to their low efficiency and high cost per watt compared to fossil sources. Conventional control techniques that have been around for a long time do not perform well [5]. As a result, more efforts need to be made to improve photovoltaic systems' efficiency and reliability. In every applicable section, most of the results from artificial intelligence techniques outperformed conventional methods [6]. The drawbacks of the traditional approach include its inability to quickly adapt to sudden changes in solar temperature and irradiation intensity and its failure to always locate the maximum power point [7]. Reliability in finding the highest power point of any solar system is a major concern as it is the most cost-efficient method for enhancing its overall efficiency [8]. Despite their effectiveness, most conventional algorithms only work well in uniform irradiance circumstances when just a single peak power has to be recognised. When numerous peaks occur due to partial shading, they become ineffective because standard MPPT algorithms cannot differentiate between global MPP and local MPP peaks [8].

Because of the non-linear nature of PV systems, the output power fluctuates with changes in atmospheric conditions. A DC-DC converter is therefore the most suitable device for controlling the output waveforms of a PV source. The MPPT becomes less useful due to poor converter selection based on the load, which has an impact on converter efficiency [9]. The MPP will change as the irradiance and temperature parameters change during the day. Thus, the duty cycle must be tweaked to keep up with the new MPP [10]. One of the toughest challenges for these controllers is to adjust to shifting conditions of solar radiation intensity, shading, and ambient temperature. These conditions can cause significant changes in a PV array's current-voltage characteristics curves (I-V curves), which can change where the maximum power point is located [11]. The traditional boost converter that does not have a constraint condition for measuring the highest power point are rarely used due to its high cost and subpar performance [12]. Another aspect that needs to be considered in designing a standalone photovoltaic system is the type of battery used. The cost-benefit analysis of a standalone photovoltaic system using lead-acid batteries is more favourable than using lithium-ion batteries, despite the fact that lithium-ion batteries have several advantages over lead-acid batteries, including high energy density, low maintenance, eco-friendliness, and a longer lifespan. This is because lead-acid batteries have lower initial investment costs than lithium-ion batteries [13].

Due to difference in temperature, solar irradiation, and load, a PV module's maximum power keeps changing. PV systems employ an MPPT to continuously collect the highest power that a solar panel can provide and then send it to the load in order to maximise efficiency. A controller and a converter are the fundamental components of a system for finding the highest power point. Using a tracking algorithm, the MPPT detects and maintains operations at the highest power point during changes in weather conditions. AI-based MPPT algorithms have faster speed, low steady-state oscillation and better performance compared to traditional MPPT methods [14]. Traditional MPPT methods also tend to be slow in responding to quick changes in temperature and solar radiation intensity and may not always be able to measure the highest power from the PV array.

This study aims to build and implement an MPPT using the FLC control technique for charging batteries. The objectives of this project are as: i) To create an MPPT method using fuzzy logic control that is highly accurate and efficient: ii) To develop a DC-DC boost converter that is combined with a sealed lead-acid battery which requires minimal maintenance and can provide AC power, as most household appliances operate on AC. The proposed PV system is basically shown in Figure 1.

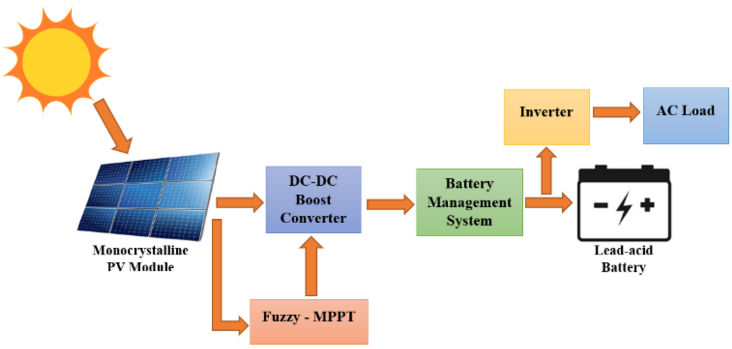


Figure 1. Proposed SAPV system

2. METHODOLOGY

This section discussed the overview of the system, MPPT technique, PV module, and balance of system (BOS) of the SAPV system. The BOS includes a boost converter and battery storage. This chapter will discuss about the overall flows and steps taken to complete the research. This study adopted a descriptive methods approach, which was based on prior research that had been reviewed.

2.1. Overview of the system

Figure 2 illustrates the steps taken to design the entire standalone photovoltaic system, as shown in Figure 1. The first step is determining the size of the PV system, and then selecting the suitable model of PV module. The Monocrystalline PV panel will collect solar irradiation intensity and cell temperature as inputs. The outputs of current and voltage from the PV module will then be input into the constructed DC-DC boost converter. Next, an algorithm using fuzzy logic control is developed to extract the highest power point and provide feedback to the boost converter. The energy is then stored in a sealed lead-acid battery which can be used during the night or during power outages. A system for managing the battery is implemented to control its charging and discharging to prolong its lifespan. Additionally, an inverter is installed to supply AC loads. Finally, the PV system is simulated in Simulink, and all related waveforms are recorded for further analysis.

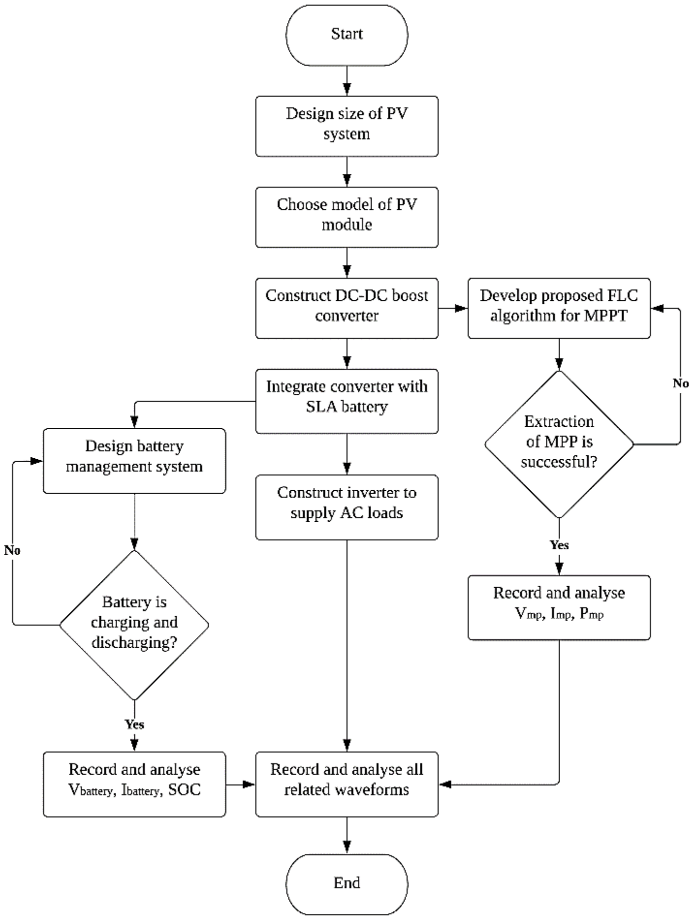


Figure 2. Overview of the system

2.2. Overall system design

Figure 3 illustrates the PV system model constructed in MATLAB/Simulink. It comprises of a PV array, a boost converter, an MPPT which are connected with a battery and inverter to provide power to AC loads. The battery management system is integrated with the battery to regulate charging and discharging. The simulation used the Yingli energy YL265C-30b PV module and Table 1 contains its parameters.

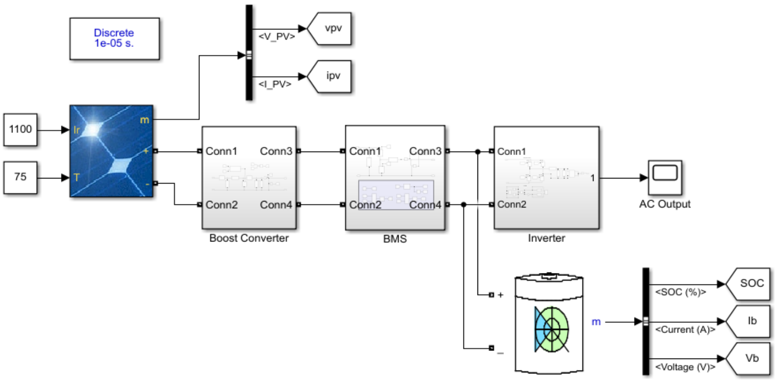


Figure 3. Designed PV system in MATLAB/Simulink

2.3. PV module

The PV module is made up of multiple PV cells arranged in parallel and series to achieve the required output parameters. The type of PV module used in this study is Monocrystalline, which has the highest efficiency rate. Table 1 displays the parameters of the selected PV module under standard test conditions (STC).

Table 1. PV Module's specifications

Electrical parameters at standard test condition (STC)			
Module name		PANDA 265	
Module type		YL265C-30b	
Power output	P_{max}	W	265
Module efficiency	η_m	%	16.2
Open circuit voltage	V_{oc}	V	39.0
Short circuit current	I_{sc}	A	8.93
Voltage at max power	V_{mp}	V	31.0
Current at max power	I_{mp}	A	8.55

2.4. DC-DC boost converter

The primary role of a switching mode in DC-DC converter in a PV system is to act as a middleman in power processing, adjusting voltage and current levels to take the highest power from the PV array [15]. Under most conditions of solar light intensity and temperature in a PV system with batteries, a commercial PV module's peak output is set higher than the voltage used to charge batteries [16]. In most cases, a buck converter can perform at the MPP, but it is unable to do so when the highest power point is below the voltage of battery charging due to poor solar irradiation intensity and high temperature. While the extra boost capability might improve overall efficiency [17]. Therefore, a boost converter is preferred due to its ability to track the highest power point despite load variations and weather conditions. The converter has the advantage of regulating the PV output voltage over a wide range of load voltages. By controlling the duty cycle, the operation point is adjusted to match the MPP to extract the maximum available power [18]. Figure 4 illustrates the design of the boost converter for the PV system in MATLAB/Simulink.

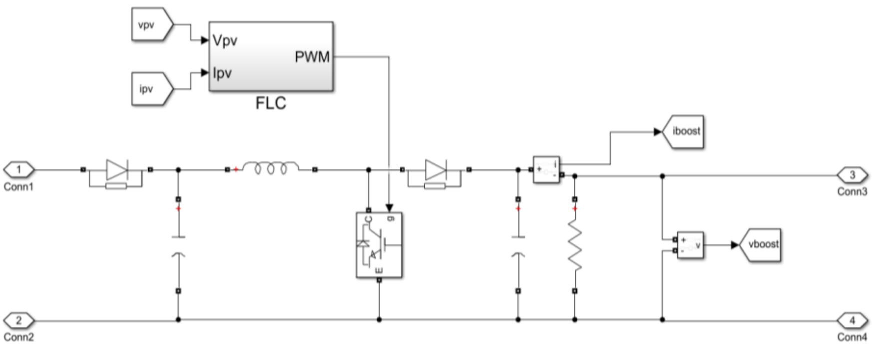


Figure 4. Boost converter circuit in Simulink

– Operation modes

The function of the boost converter may be classified into two modes, which are referred to as Mode 1 and Mode 2. When the transistor is turned on, the first mode, Mode 1, is initiated, as shown in Figure 5(a). The input current increases as it passes through the inductor and the transistor. Mode 2 initiates when the transistor is turned off, as shown in Figure 5(b). The input current flows through the load, capacitor, and diode before leaving the circuit. The current in the inductor decreases until the start of the next cycle. The load then receives the energy from the inductor.

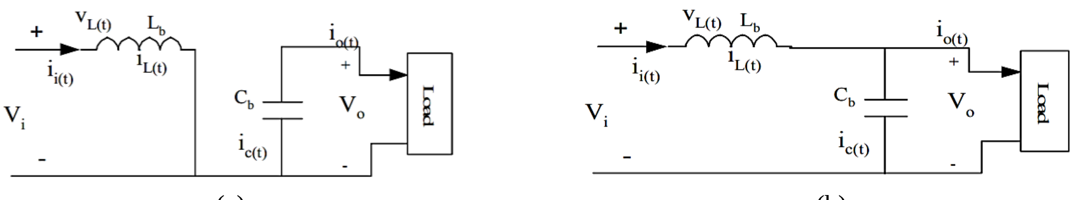


Figure 5. Circuit for boost converter (a) Mode 1 and (b) Mode 2 [19]

2.5. Fuzzy logic control

FLC is a fuzzy logic control system that converts analogue inputs to continuous digital values of 0 and 1. It was created to overcome the drawbacks of traditional MPPT approaches, such as oscillation around MPP, high settling time, and steady-state error (SSE). It is simple to develop since it does not need the knowledge of a precise MPPT model. FLC is a novel technique for controlling the tracking of the highest power point [20]. Most fuzzy logic-based MPPT controllers have three main components: fuzzification, inference engine, and defuzzification [21], as illustrated in Figure 6.

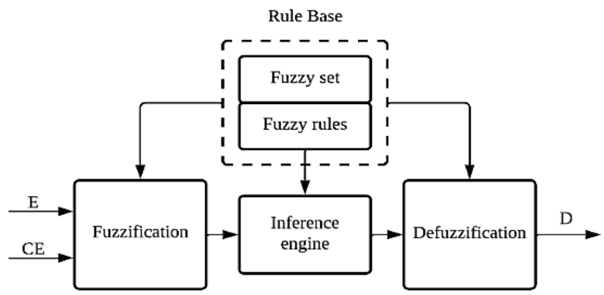


Figure 6. Operation of FLC

2.5.1. Fuzzification

Voltage and current may be multiplied to determine the PV's output power as illustrated in (1). The inputs for fuzzification are the error, E, and the change of error, CE. The E represents the slope of the P-V characteristic and can be calculated as shown in (2). As illustrated in (3), CE is the difference between the present error, E(n), and the prior error, E(n-1).

$$P_{pv}(n) = \mathrm{V}_{pv}(n) \times I_{pv}(n) \tag{1}$$

$$E(n) = \frac{P_{pv}(n)-P_{pv}(n-1)}{V_{pv}(n)-V_{pv}(n-1)} \tag{2}$$

$$CE(n) = E(n) - E(n-1) \tag{3}$$

Where $P_{pv}(n)$ and $V_{pv}(n)$ refer to the PV's power and voltage respectively. As a result, the input E(n) indicates whether the operating point at time n is on the left or right of the P-V characteristic plot [22], and the input CE(n) describes the direction of the displacement of this point. The controller's desired output is the duty ratio (D) of the DC-DC converter. To bring the operating point back to the ideal position, where the slope is zero [23], the control is achieved by adjusting this duty in accordance with slope E(n). Figure 7 illustrates the circuit that implemented all in (1), (2), and (3) in Simulink.

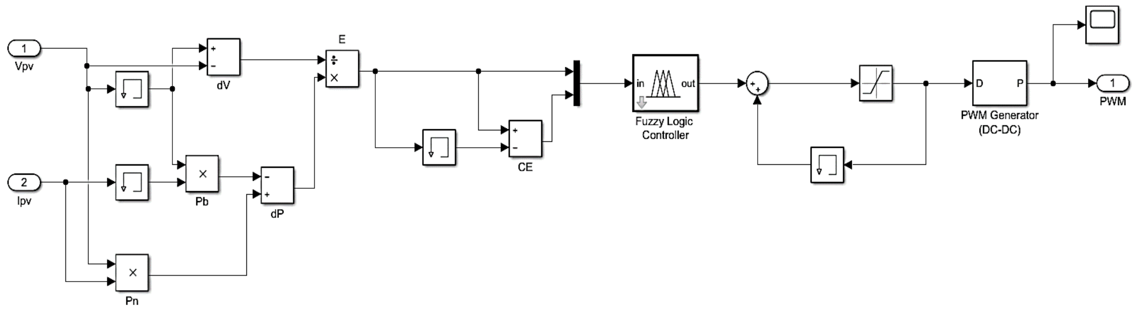


Figure 7. Equation for FLC in Simulink

2.5.2. Inference engine

By applying the rules to the fuzzy inputs generated by fuzzification, the inference engine creates the fuzzy outputs [24]. The crisp input values must be translated into fuzzy values to obtain the corresponding linguistic values. The FLC's rule table is shown in Table 2, where each entry in the matrix represents a fuzzy set of error (E), change of error (CE), and duty ratio (D) for the converter. The variables of the membership function are expressed in different fuzzy levels: VL (very low), L (low), Z (zero), H (high), and VH (very high). Figures 8 (a) and (b) show the membership function plots of the inputs, E and CE, while Figure 8(c) shows the membership function plots of the output, D, where those plots were decided by trial and error using tools in MATLAB/Simulink.

Table 2. Fuzzy rules for inference engine

E / CE	VL	L	Z	H	VH
VL	VH	H	VL	L	L
L	H	H	VL	L	L
Z	L	L	L	VH	VH
H	L	VH	H	VL	VH
VH	VL	VL	VH	H	VH

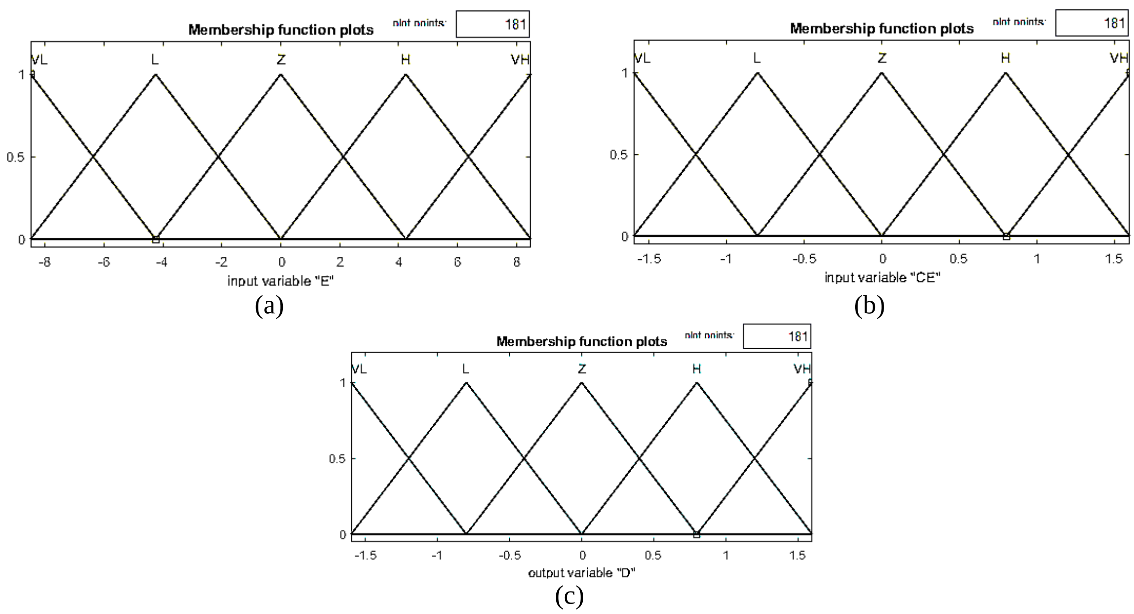


Figure 8. Membership function: (a) input 'E', (b) input 'CE' and (c) output 'D'

2.5.3. Defuzzification

Defuzzification is the process of converting a fuzzy quantity into a precise amount [25]. The defuzzification process takes place by extracting a duty cycle from the output of an aggregated fuzzy set. After that, the boost converter, which will raise the voltage based on the circumstances, will be run on the duty cycle.

2.6. SLA battery

Lead-acid batteries are used in the system because they are the most economical and readily available. Using three stages—constant-current charge, topping charge, and float charge the constant current constant voltage (CCCV) technique is used to charge lead-acid batteries. About half of the overall charging time is spent during the constant-current charge, which applies the bulk of the charge. Saturation is ensured at a reduced charging current due to the topping charge. Lastly, the float charge covers for self-discharge loss.

However, there is a limitation to simulating in MATLAB/Simulink, which is the run time takes too much time. The end result did not show the full stages of charging the SLA battery. The obtained result only shows the first stage of the charging state, which is the bulk stage. In this study, the PV system will be in operation for 6 hours during daylight hours. After calculations, the battery's ideal nominal voltage is 48V, and its recommended capacity is 60Ah.

2.7. Battery management system (BMS)

The fundamental goal of a battery management system (BMS) is to use the battery's energy as efficiently as possible in order to minimise the danger of battery deterioration. In order to prevent overcharging and maintain a long battery life, this is accomplished by watching over and managing the battery's charging and draining operation. Additionally, the BMS keeps track of the battery's discharge and stops it when the battery is empty to prevent harm. The BMS monitors the battery's state of charge (SoC) and utilises this value to regulate the battery's charging and discharging in order to handle the battery properly and safeguard it from abuse. Figure 9 shows the BMS circuit in Simulink.

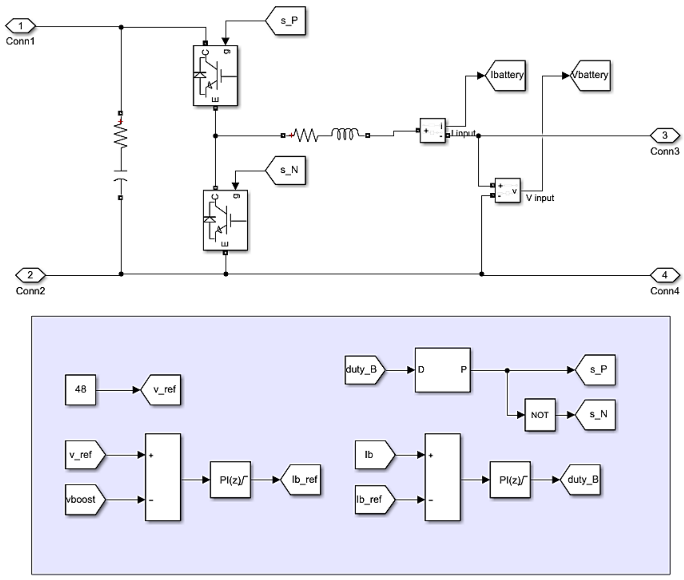


Figure 9. Battery controller circuit in MATLAB/Simulink

2.8. Single-phase inverter

DC-AC inverter is being implemented in this project to convert the DC voltage to AC because most home appliances need AC to operate. Figure 10 shows the simulation circuit for the single-phase inverter in MATLAB/Simulink. The inverter's main components are IGBT, capacitor, diode, inductor, and resistor. By using this component, the circuit can be combined to form an electrical circuit in four distinct ways, which are the RL circuit, the RC circuit, the RLC circuit, and the LC circuit. Each circuit has its own specific purpose. For the schematic diagram shown in Figure 10, an RLC circuit is used. The RLC circuit act as the output filter for the output waveform generated.

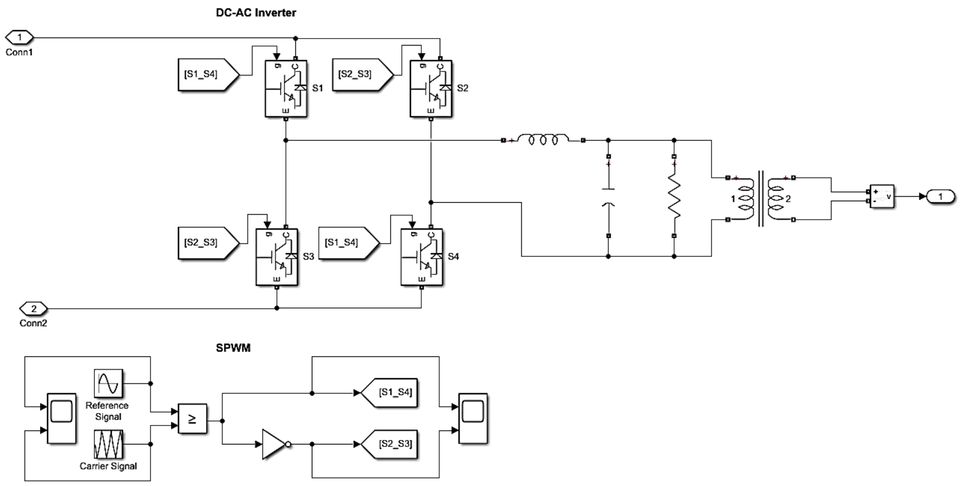
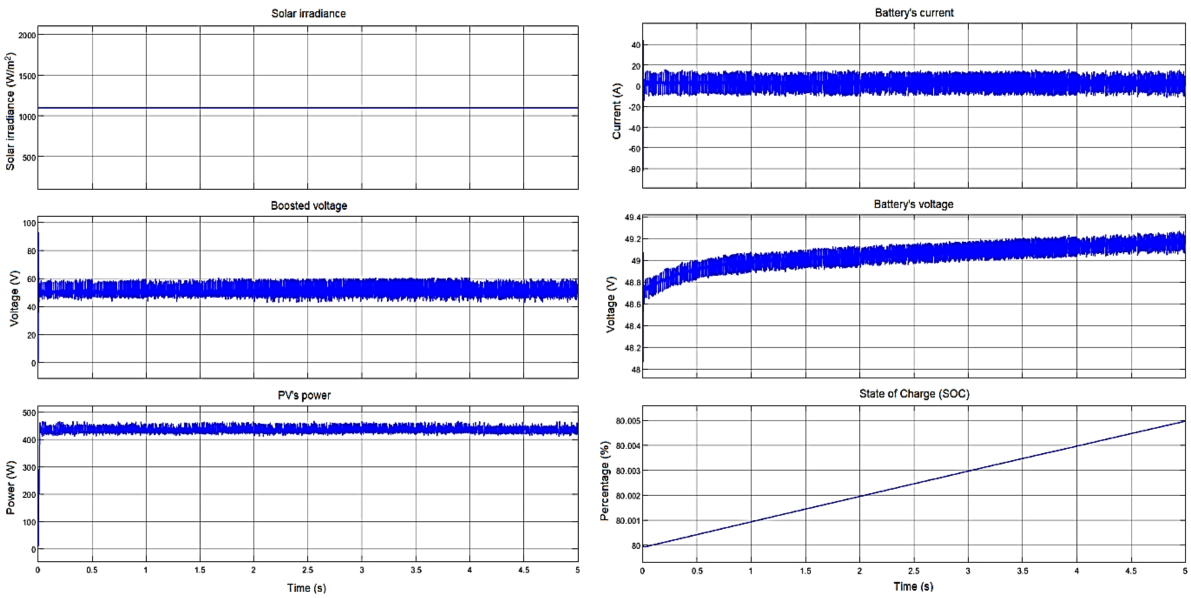


Figure 10. Single phase inverter in MATLAB/Simulink

Pulse width modulation (PWM) is a widely used technique to produce a true sine wave. In this case, the best method is sinusoidal pulse width modulation (SPWM). PWM involves creating digital waveforms where it is possible to modify the duty cycle so that the overall voltage waveform resembles a pure sine wave. To create the SPWM signal, the low power sine wave (reference signal) is compared to the high frequency triangular wave (carrier signal). Control switches can be used to control the SPWM signal.

3. RESULTS AND DISCUSSION

The PV array is made up of 2 modules linked in series, producing an output power of 450W at a constant irradiance of G=1100 W/m^2 and cell temperature of T=75 °C, as illustrated in Figure 11(a). The DC input voltage from PV is increased using the boost converter and converted to the 48V battery voltage level using the BMS. The FLC is implemented using Simulink's fuzzy logic toolbox. Figure 11(b) shows the condition where the battery is charging, and SOC is increasing, indicating that the battery is in the bulk charging stage. At this stage, the current of the battery stays constant while the voltage increases.

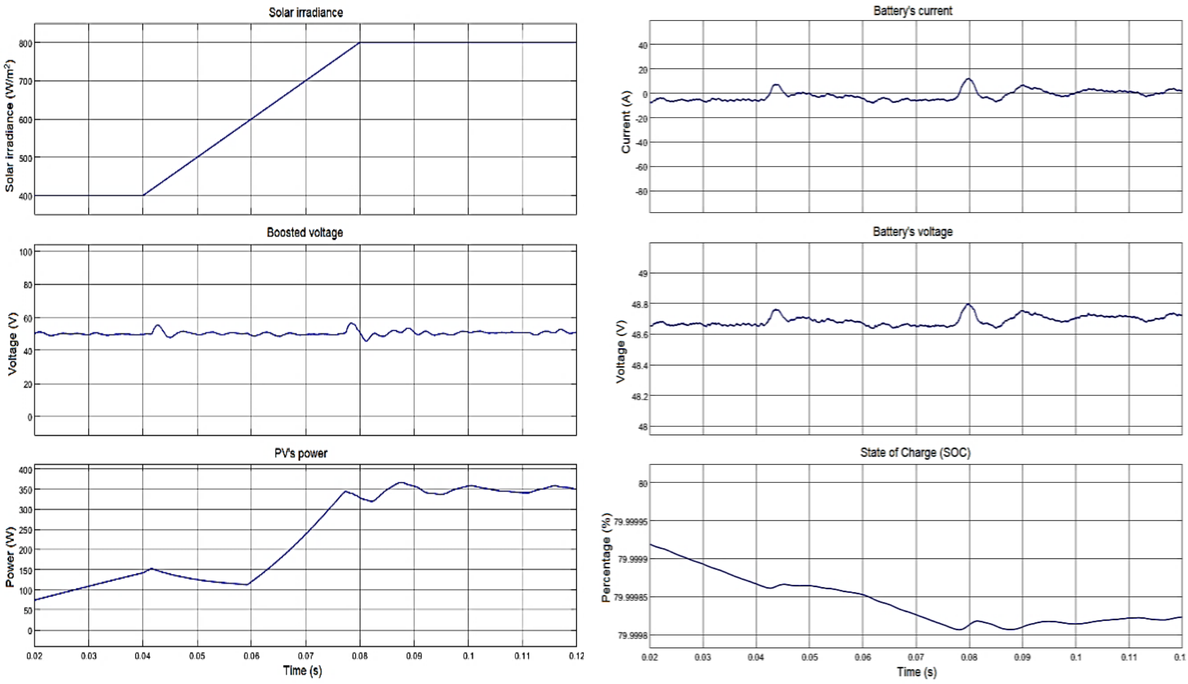


(a) (b)

Figure 11. Output waveform of (a) irradiance, boosted voltage, power of PV and (b) battery’s current and voltage, and SOC during fixed condition

The PV system is simulated under the dynamic condition to replicate the real environment of Malaysia's climate that varies in temperature and irradiation intensity. In the simulation work, the temperature and irradiation intensity increase linearly from solar irradiance, G=400 W/m^2 with temperature, T=40 °C to G=800 W/m^2 with temperature, T=50 °C, as shown in Figure 12(a). Figure 12(b) illustrates the battery's charging and discharging process during dynamic conditions. The increasing SOC indicates that the battery is charging, while the decreasing SOC indicates that the battery is discharging. During time t=0.02 sec., the battery is discharging, while at t=0.08 sec., the battery starts charging.

Figure 13 shows the total harmonic distortion (THD) of the output sine wave voltage, which is 0.35% indicating that it has a low and acceptable value of THD, which complies with IEEE 519 harmonics standard. The output waveform that has been converted by the inverter is 325.6 V peak voltage, equal to 230.2 V RMS voltage, which is suitable for most home appliances.



(a) (b)

Figure 12. Output waveform of (a) irradiance, boosted voltage, power of PV and (b) battery’s current and voltage, and SOC during dynamic condition

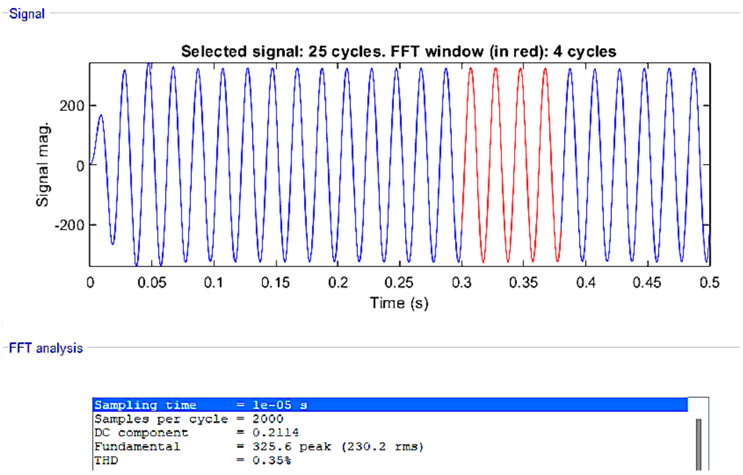


Figure 13. AC voltage THD analysis

4. CONCLUSION

This study presents the design of a FLC-based MPPT that can operate effectively in changing weather conditions under Malaysia's climate. An efficient standalone photovoltaic (SAPV) system for remote areas has been developed. The MPPT control algorithm is used to operate the PV module at its highest operating point, allowing the highest amount of energy produced to be stored in the sealed lead acid (SLA) battery connected across the boost converter's output terminal. The MPPT strategy used is fuzzy logic-based MPPT which is designed to function in various weather conditions under Malaysia's climate. Simulation findings indicate that the FLC-based MPPT delivers superior MPP tracking and has a faster convergence speed. In conclusion, there is a recommendation for future improvement by increasing the number of variables for the fuzzy rules to improve the accuracy of the fuzzy logic control (FLC).

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