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MPPT Charge Controller using Fuzzy Logic for Battery Integrated with Solar Photovoltaic System

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ABSTRACT

In comparison to other Renewable Energy (RE) resources, solar energy has become the most prominent and prospective source for generating electricity, substituting conventional sources. However, solar Photovoltaic (PV) energy production is dependent on solar irradiance and cell temperature. By implementing the Maximum Power Point Tracking (MPPT) algorithm, it is achievable to maximize the power from solar PV. In spite of this, there is still a slower convergence rate, a significant fluctuation around Maximum Power Point (MPP), and a drift issue caused by rapid irradiance variations in solar PV. In order to prevent oscillation and attain a steady state and continuous output of the PV module, a Fuzzy Logic (FL)-based MPPT has been designed in this work. With the buck converter as the DC-DC converter and the lead acid battery as the input, the Perturb & Observe (P&O) MPPT method is selected. The overall design will be developed using Matlab Simulink, and the efficiency of the FL-MPPT charge controller will be evaluated under constant and step irradiance. Additionally, the battery's State of Charge (SOC) will be monitored to prevent overcharging and discharge. In addition, the effectiveness of the controller will be evaluated with and without the MPPT method. On the basis of simulation results obtained from constant and step irradiance levels, the FL-MPPT charge controller with the P&O algorithm and the lead acid battery as the load was able to maintain maximum system efficiency while extending battery life. The FL-MPPT charge controller obtained about 96% efficiency for both irradiance profiles, whereas the system without the FL-MPPT algorithm only achieved 42% efficiency.

1. Introduction

Solar Photovoltaic (PV) has become the most common method for generating electricity in comparison to other Renewable Energy (RE) sources due to its ubiquity, environmental friendliness, vast availability, and sustainability [1,2]. However, the PV module's output characteristics are non-

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linear, and the quantity of power produced by the PV panel depends on solar radiation and cell temperature, causing output power to fluctuate [3]. Thus, the 15-20% efficiency of electricity generation from solar PV is quite poor [4]. As a result, the Maximum Power Point Tracking (MPPT) algorithm is commonly employed as a charge controller in PV systems in order to circumvent this issue and harvest the maximum power from PV modules.

The MPPT is an electronic DC-to-DC converter that optimizes the compatibility between photovoltaic panels, battery banks, and the utility grid [5]. Basically, the algorithm is fundamentally dependent on the movement of PV voltage or current to routinely deliver maximum power to the loads [6]. MPPT is considerably more advanced than Pulse Width Modulation (PWM) controllers, allowing the solar panel to function at the optimal voltage for maximum output power. A solar panel's operating point is rarely at its maximum power when it is directly connected to a load. So, depending on how the PV array is working, MPPT will employ a number of strategies to maximize output power. Among the MPPT techniques are Perturbation and Observation (P&O), Incremental Conductance (IC), Current Sweep, Constant Voltage, and Temperature approach [7]. However, P&O techniques are most frequently used because of their popularity and ease of use [8].

The P&O MPPT approach is the simplest, but it has a slower convergence rate, a significant variation around Maximum Power Point (MPP), and a drift issue owing to rapid irradiance fluctuations [9,10]. In order to overcome these shortcomings in tracking, Artificial Intelligence (AI)-based MPPT algorithms with increased speed, better performance and lower steady-state oscillation than standard MPPT approaches [11,12] were developed. Hence, in this work, a Fuzzy Logic (FL) based MPPT has been proposed to prevent oscillation and to achieve a steady state and continuous output of the PV module. Moreover, the Fuzzy Logic Controller (FLC), which has the advantages of tolerating nonlinearity, dealing with incorrect inputs, and not requiring a precise mathematical model, can provide superior control for this type of nonlinear application [13].

To maximize the efficiency of PV systems, several kinds of studies have been conducted over the years in regard to FL-based MPPT algorithms. In order to compare the results, Cherif *et al.,* [14] proposed an MPPT built on an FLC that uses a boost converter. Their research shows that the FLC controller works up to 98.9% better than the traditional P&O technique in terms of reaction time, performance speed, tracking accuracy, and efficiency. Similarly, a comparative analysis between two conventional algorithms, P&O and IC, and an intelligent algorithm FLC, under dynamic environmental conditions was conducted by Bhardwaj *et al.,* [15]. Based on their simulation for performance analysis, FLC showed a superior result in tracking MPP when compared with both conventional techniques P&O and IC. Meanwhile, Essakhi *et al.,* [16] reported on the analysis, modeling, and simulation of a PV system using an intelligent MPPT controller that is based on fuzzy logic. Additionally, they contrast the dynamic performances of the traditional controller based on the P&O algorithm with the fuzzy controller in terms of quickness and stability. Besides, Pandey *et al.,* [17] assessed the efficacy of FLC-based MPPT for PV systems utilizing transient experiments with real solar irradiation, such as rapid and abrupt irradiance scenarios. In addition, Bishla and Khosla [18] developed a Hybrid Leader Optimized (HLO) based MPPT controller along with the Enhanced Chimp Optimization Algorithm (ECOA) optimized Factional Order Proportional Resonant (FOPR) controller to improve the power tracking, battery scheduling, and power quality in PV integrated with electric vehicles charging. Meanwhile, Subramanian *et al.,* [19] proposed a FLC based MPPT controller to the PV panel and fuel cell systems via DC-DC boost converter to improve the system reliability and stability of the response of the system.

The work of the PV system based on the FL MPPT technique and PI control as a charge controller was studied by Yilmaz *et al.,* [20] in their article. In their study, a boost converter-powered solar panel was subjected to varied temperature (25–60 °C) and irradiance (700–1000 W/m2) conditions while using the FL MPPT approach. Then a buck converter, acting as a charge controller, was subjected to the PI control. Overall, their system's FL MPPT technique raises its precision for identifying MPP from 94.8% to 99.4%. Similarly, an efficiency of more than 99.6% was achieved in simulations conducted by Al-Majidi *et al.,* [9] using a unique MPPT technique based on FL control and P&O algorithms. Their suggested approach combines the benefits of P&O-MPPT for handling moderate and quick fluctuations in solar radiation with FL-MPPT's quicker response time for complicated engineering challenges when membership functions are constrained. Moreover, Situmorang *et al.,* [21] construct and model a simple yet effective MPPT charge controller that combines simulation and hardware implementation. Meanwhile, Yaqin *et al.,* [5] demonstrated the design and modelling of MPPT based on FLC for PV systems using PSIM and Simulink software. Table 1 presents some of the existing methods that were discussed above.

Table 1
Comparative analysis of the literature study

Ref. No.	Proposed method	Advantages	Limitations
Al-Majidi *et al.,* [9]	MPPT technique based on FL control and P&O algorithm	Accurately tracks the MPP and avoids the drift problem, whilst achieving efficiencies of greater than 99.6%.	Time consuming and high complexity due to alteration of membership functions to achieve desired outcome.
Pandey *et al.,* [17]	Asymmetrical Interval Type-2 FL controller based MPPT approach	Faster response in terms of tracking time and improved efficiency.	The choice of membership function, fuzzy rules, and parameters.
Bishla and Khosla [18]	Hybrid Leader Optimized (HLO) based MPPT controller along with the Enhanced Chimp Optimization Algorithm (ECOA) optimized Factional Order Proportional Resonant (FOPR) controller	Higher convergence speed and tracking efficiency with wider bandwidth and transient response.	Battery lifetime need to consider for optimal scheduling of battery storage.
Subramanian *et al.,* [19]	Fuzzy logic MPPT method for a DC microgrid	Enhanced response time and accuracy of the proposed hybrid DC microgrid.	Control method for the DC microgrid using DC-DC converter.
Yilmaz *et al.,* [20]	Fuzzy logic MPPT with PI Controller	Charges the battery with the proper current and voltage, reducing losses and extending the battery's life cycle.	Difficulties of constructing FLC system and consideration on fuzzy parameters such as membership function.

Consequently, a P&O MPPT charge controller utilizing FL for battery integration with a solar PV system will be designed in this study. Prior to earlier research, this study aimed to develop a superior MPPT charge controller employing FLC with a 12 V battery output. Unlike previous studies, the battery State of Charge (SOC) can be monitored using FLC, extending the battery's lifespan in a manner similar to the PWM controller. This is due to the fact that the PWM controller is effective at extending battery life by permitting complete charging with minimal battery stress. While the MPPT controller is superior to the PWM controller in terms of solar power system output, it is inferior to PWM in terms of battery life extension [22]. Thus, by using the FL-MPPT to monitor the SOC, the battery lifetime can be prolonged in this work. In addition, the evaluation of controller performance with MPPT and without the MPPT technique will also be analyzed.

2. P&O MPPT Charge Controller Design using Fuzzy Logic

In this work, the solar PV array will be constructed with the MPPT technique using P&O as its algorithm, followed by the design of FLC, where the battery will be the controller output. The battery SOC will be monitored by FLC to prolong its lifetime. When the SOC is not between 20% to 80%, the FLC will detect the condition, thus maintaining the SOC limit by cutting off the charge when it reaches 80% and continuing to charge again when it is lower than 20%. Matlab Simulink will be used to construct the overall design, and the performance of the controller will be evaluated.

The overall block diagram for this study is depicted in Figure 1. In addition to being an input for the Fuzzy P&O MPPT algorithm, the PV module also powers the buck converter. Before supplying the PWM generator with power, the delta parameter will be modified to extract the MPP from the PV input power. Next, the PWM signal will be produced and sent to the buck converter to control the switching time. Finally, the output of the converter will charge the load, which in this case is a 12 V lead acid battery.

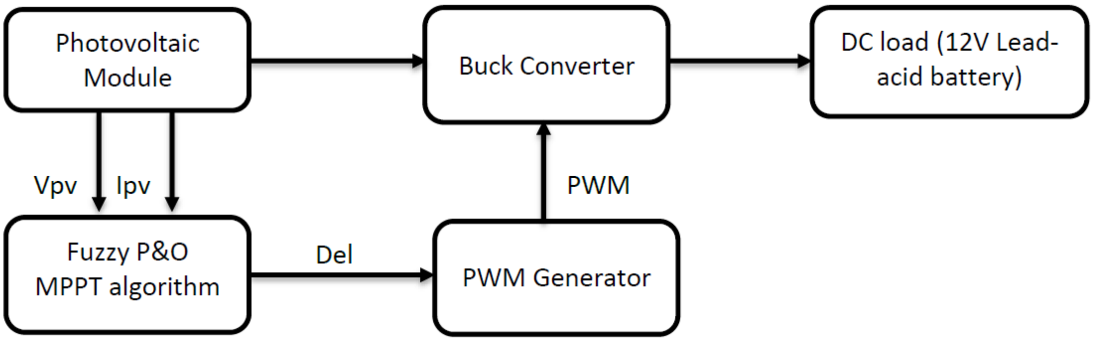

Fig. 1. Overall block diagram

The Matlab Sim Power System block set was used to create the PV module that was used in this work. Table 2 displays the characteristics of the PV module utilised in this design, where the module has a maximum output voltage of 30.7 V and a maximum output power of 250 W. This PV module can power a lead acid battery with a nominal voltage of 12 V since it uses a buck converter to scale down the voltage. The buck converter consists of a power switch MOSFET, power diode, capacitor and an inductor at the output. Using the operating voltage of the PV panel as V_{ip} and the output voltage of the PV panel as V_{op} with ripple current, ΔI assumed to be 10% of output current, it is projected that the switching frequency in the design will be 5 kHz. The formula for calculating the inductance is described as Eq. (1).

$$\text{Inductance, L} = \frac{V_{op}(V_{ip}-V_{op})}{f_{sw}*\Delta I*V_{ip}} \tag{1}$$

where V_{op} is the output voltage, V_{ip} is the input voltage, f_{sw} is the switching frequency and ΔI is the ripple current.

Table 2
Specifications of 1Soltech 1STH-250-WH PV Module

Parameter	Value
Maximum power, Pmax	250.205 W
Open Circuit Voltage, Voc	37.30 V
Open Circuit Current, Isc	8.66 A
Voltage at MPP, Vmp	30.70 V
Current at MPP, Imp	8.15 A

In addition, an input capacitor will be placed across the ends of the PV panel. It will be a series connection between a capacitor and a resistor which are assumed to be 1000 µF and 1 mΩ respectively, with the purpose of maintaining the voltage through the diode in steady state condition. The ripple voltage of the buck controller's capacitor, ΔV, is anticipated to be 1% of the PV panel's output voltage. The formula for calculating capacitance is hence Eq. (2).

$$\text{Capacitance, C} = \frac{\Delta I}{8 * f_{sw} * \Delta V} \quad (2)$$

where the ΔI is the ripple current, f_{sw} is the switching frequency and ΔV is the ripple voltage. By using Eq. (1) and Eq. (2) and the PV module's parameter, Table 3 summarizes the buck converter's components.

Table 3
Buck converter parameter selection

Parameter	Value
Switching frequency	5 kHz
Input resistor	1 mΩ
Input capacitor	1000 µF
Output capacitor	379.979 µF
Inductor	776.942 µH

Due to its capacity to handle nonlinearity in the system, the FL-MPPT is chosen as the algorithm for tracking the MPP in the PV system in this study. This MPPT method expands the selection of variable duty cycle step size, thereby enhancing the performance of the PV system. Using the slope value of the Power-Voltage (P-V) characteristic, this method attempts to calculate the variable step for a PV module. The duty cycle is then set to the appropriate value [23]. The three functional elements of an FLC are fuzzification, rule inference, and defuzzification [24]. The input variables of the FLC are error (e) and change in error (ce), while the output variable is duty cycle change. Design considerations and effectiveness of the fuzzy MPPT algorithm are determined by the input and output variables employed. In general, the duty ratio command is the output variable of the FL-MPPT algorithm, which modifies the operating point of the PV module to optimize power production. The most frequently utilized input variables for FL-MPPT are the slope and variations of the P-V curve of the PV module. Since the slope disappears at the MPP, both inputs may be computed as in Eq. (3) and Eq. (4) respectively [24,25].

$$\mathrm{e(k)} = \frac{P_{pv}(k) - P_{pv}(k-1)}{V_{pv}(k) - V_{pv}(k-1)} \quad (3)$$

$$\mathrm{ce} = \mathrm{e(k)} - \mathrm{e(k-1)} \quad (4)$$

where, the power and voltage in the P-V curve are represented as P_{pv} and V_{pv}, respectively. Eq. (3) uses the difference between P_{pv} to the previous value of P_{pv} and divides it by the difference of V_{pv} to the previous value of V_{pv}. In short, the equation is ΔP/ΔV. For Eq. (4), the difference of error to the previous value of error is computed.

The fuzzification procedure converts the input variables e and ce and the output variable d into linguistic variables by assigning membership function values to them. In this work, the variables are denoted as FSS representing Fixed Step Size, VSS for Varying Step Size while ΔP/ΔV is the product of PV module power divided by voltage. The variables are then transformed by the fuzzification procedure into the linguistic variables PVS (positive very small), PS (positive small), PM (positive medium), PH (positive high), and PVH (positive very high). PS, PM, and PH use triangle membership functions, while the other variables use trapezoidal. Hence, there is only one dominant fuzzy subset for every input condition. From this membership function, the fuzzy truth table was designed for the FL-MPPT algorithm.

The flowchart of FL-MPPT based on the P&O algorithm is presented in Figure 2. As inputs, the P&O algorithm uses the current and voltage of the PV panel to calculate the power (P). Fuzzy accepts ΔV/ΔP as input and uses the fuzzy truth table to generate Delta as output. If there is no difference between P and P (old), the system has already attained its maximum power point. Nonetheless, if it is not equal to zero, the system will re-evaluate whether it is greater than zero or less than zero. Next, if P is greater than zero, the system will proceed to check as depicted in Figure 2.

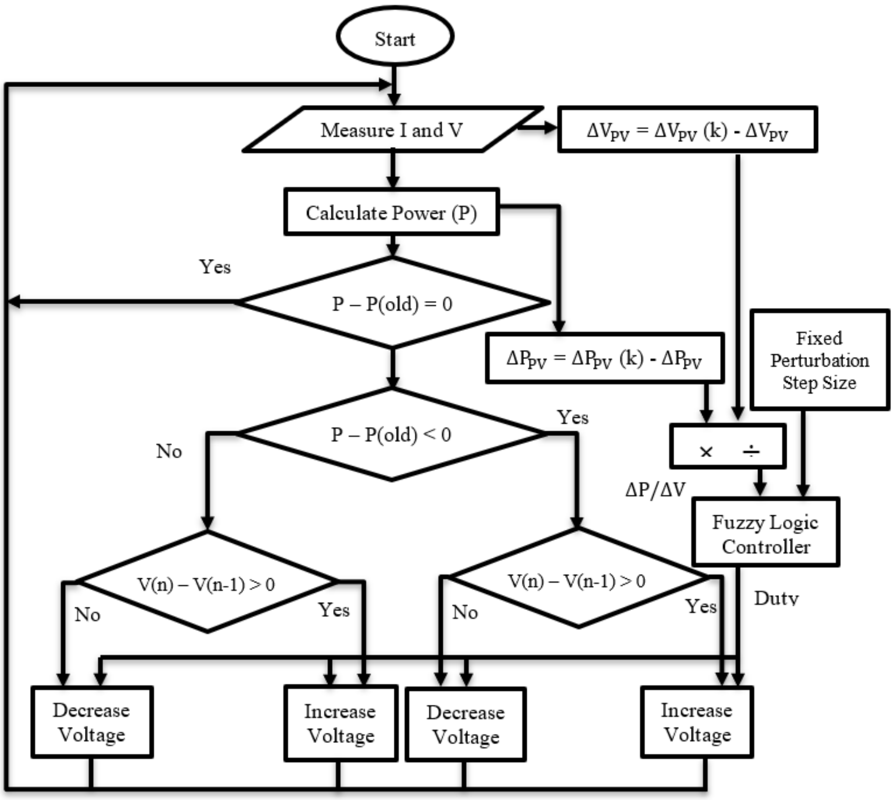

Fig. 2. Flowchart of fuzzy P&O algorithm

Figure 3 presents the total Simulink model of the P&O MPPT charge controller using FLC for battery integration with a solar PV system. The discrete time was set at 1 µs and the parameters of the buck converter were as specified in Table 3. The battery used in this work is a lead acid battery with a 12 V nominal voltage and a 100 Ah rated capacity. The PV module output voltage and output current are the inputs of the P&O FL-MPPT subsystem. While the output is a duty ratio coupled to the buck converter's MOSFET. In this work, the SOC of the battery is measured, and charging or discharging the battery is determined based on the SOC value. In addition, breakers are placed between the buck converter and the battery in order to connect and disconnect the battery from the load subsystem. Scopes have been incorporated into the design to continuously measure the voltage, current, and SOC of the battery.

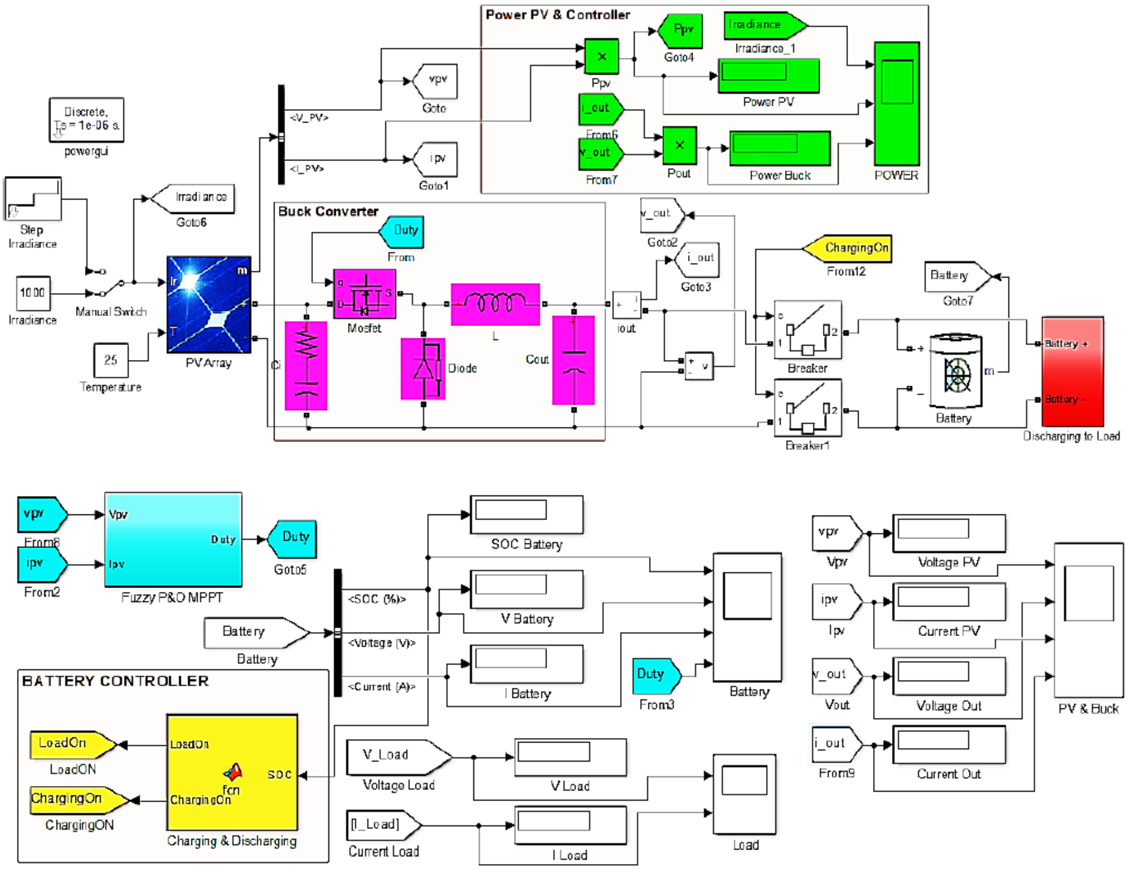

Fig. 3. Overall Simulink model

3. Results and Discussion

The performance of the devised FL-MPPT charge controller under constant and step irradiance was simulated and evaluated. In order to evaluate the effectiveness of the system's tracking algorithm, the irradiance of PV modules is simulated using two irradiance profiles. The first profile consists of 1000 W/m^2 of constant irradiance. While, gradually increasing the irradiance from 400 W/m^2 to 1000 W/m^2 will be the second profile. These two profiles are applied to two distinct systems, the first with the FL-MPPT tracking algorithm and the second without the FL-MPPT tracking algorithm. The performance will be verified by comparing the MPP recorded by the system to the MPP from the PV panel data sheet at each irradiance level, as shown in Table 4. Lastly, there will be an evaluation of the switching between charging and discharging of the battery, as well as the condition of SOC to be true when less than 20%, the battery will start charging and if it is more than 80%, the battery will stop charging.

Table 4
MPP at each irradiance level

Irradiance W/m²	MPP (W)
400	98.97
600	149.60
800	199.90
1000	250.20

Figure 4 presents the simulation results with and without the FL-MPPT algorithm for a constant irradiance profile. There are five types of results for each algorithm, which are the solar PV irradiance, buck converter output power and the battery's SOC, voltage and current versus time. Referring to Figure 4, the design with the FL-MPPT algorithm produces the maximum output power of 235 W, besides being able to maintain the output voltage level by adjusting the duty cycle to match the MPP. This can be seen as the battery's voltage and current are in a steady state. Furthermore, the negative value in the battery current indicates that the battery was charging, where an increase in the SOC can be seen. In contrast, the system without the FL-MPPT algorithm can only produce the maximum power of 104 W, which is less than the P_{max} value of 250.2 W for 1000 W/m², referring to Table 4. Therefore, the system cannot achieve the maximum power for the given irradiance level. In addition, the battery charges more slowly, and the battery voltage continues to rise without stabilizing, compared to a system designed with FL-MPPT. Based on the results shown in Figure 4 for a constant irradiance profile, the developed FL-MPPT charge controller achieved efficiency of around 96%, while the system without the FL-MPPT algorithm only managed to achieve 42% efficiency.

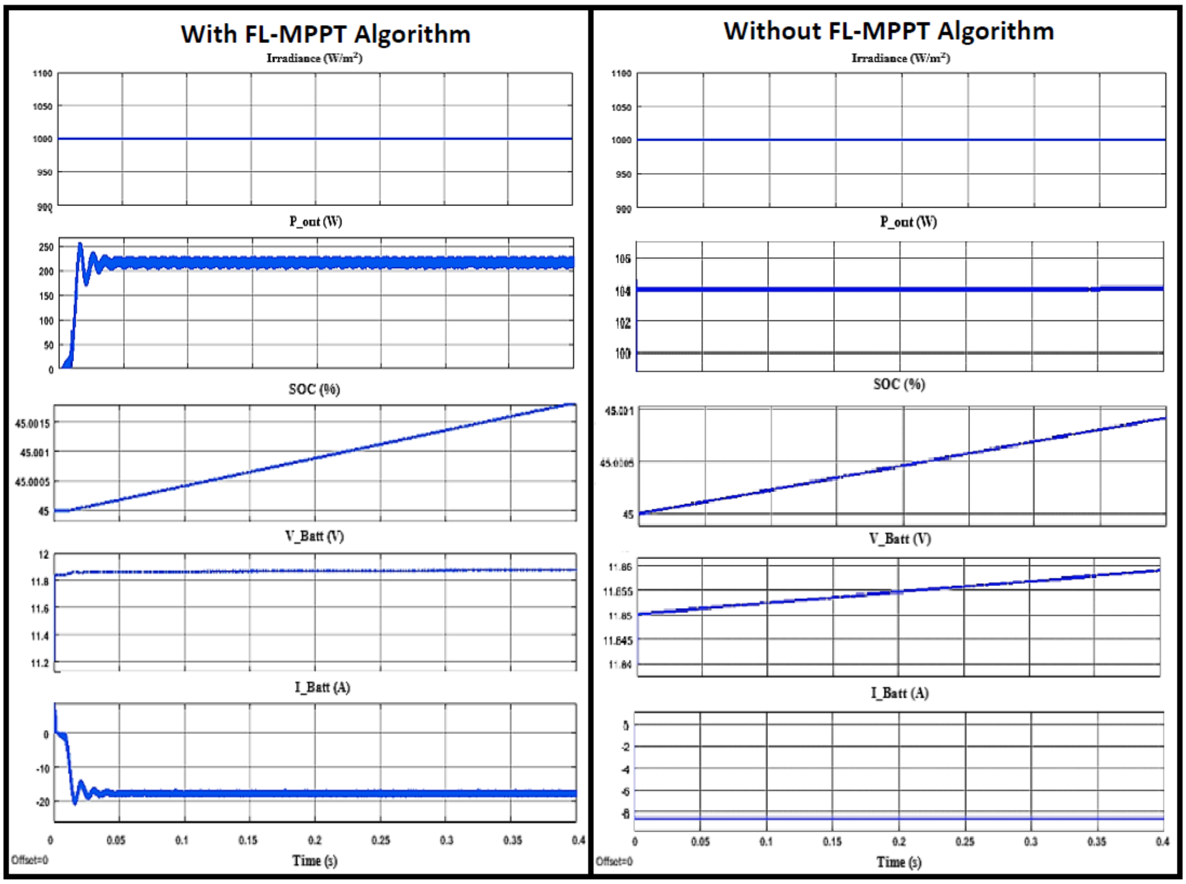

Fig. 4. Simulation results with constant irradiance for FL-MPPT and without FL-MPPT algorithm

Next, the designed FL-MPPT charge controller was simulated with step irradiance changes and the results were compared with the system without the FL-MPPT algorithm. Figure 5 depicts simulation results demonstrating that the system was able to increase output power as irradiance increased. The system with the FL-MPPT algorithm achieved maximum power at each irradiance step value when compared with the value given in Table 4. Thus, the FL-MPPT controller achieves an efficiency of around 96%. However, at 400 W/m² irradiance, the system requires time to maintain a constant level until it reaches 800 W/m², the point where the system begins to balance. The battery voltage increases slightly with each irradiance step and the battery current varied as well in the early stage, causing the SOC to rise more slowly compared to the first profile of constant irradiance of 1000 W/m². Meanwhile, without FL-MPPT, the system is unable to achieve the maximum power at each level of irradiance, which contributes to an efficiency of only 42%.

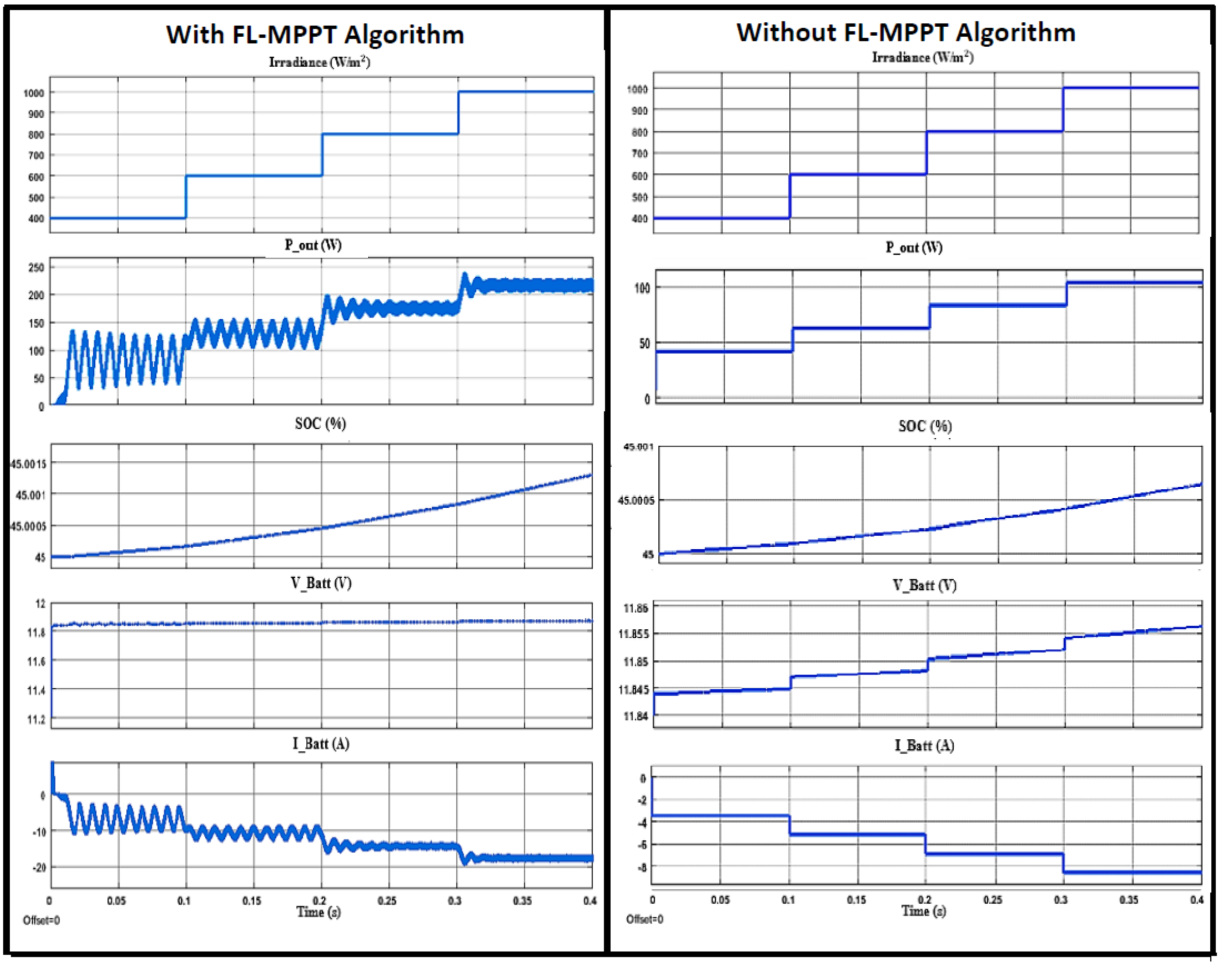

Fig. 5. Simulation results with step irradiance for FL-MPPT and without FL-MPPT algorithm

Figure 6 presents the simulation result for the evaluation of battery SOC at constant irradiance. From the figure, it can be seen that for a minimum SOC 20% simulation, the converter output is zero in discharge mode, but when the battery SOC reaches 20%, the system switches to charge mode, thus, the value begins to rise. Initially, the battery's SOC decreases slowly, but when it reaches 20%, the SOC begins to increase again, indicating that the battery is charging. Similarly, the battery voltage also decreases during discharge mode and starts to rise slowly during charging mode. At the same time, the current value remains constant at a positive value, indicating that the battery is in discharge mode, and when the system switches to charge mode, the current changes to a negative value. Hence, these results prove that the designed charge controller switching mode is functional.

Meanwhile, the evaluation of maximum SOC 80% results depicts that the power at the converter is zero and the battery's SOC, voltage and current are steadily decreasing, indicating that the battery is in discharging mode. As a result, this verifies that when the SOC condition is over 80%, the battery stops charging. Thus, with the designed FL-MPPT charge control algorithm, the battery can be prevented from being overcharged and overdischarged.

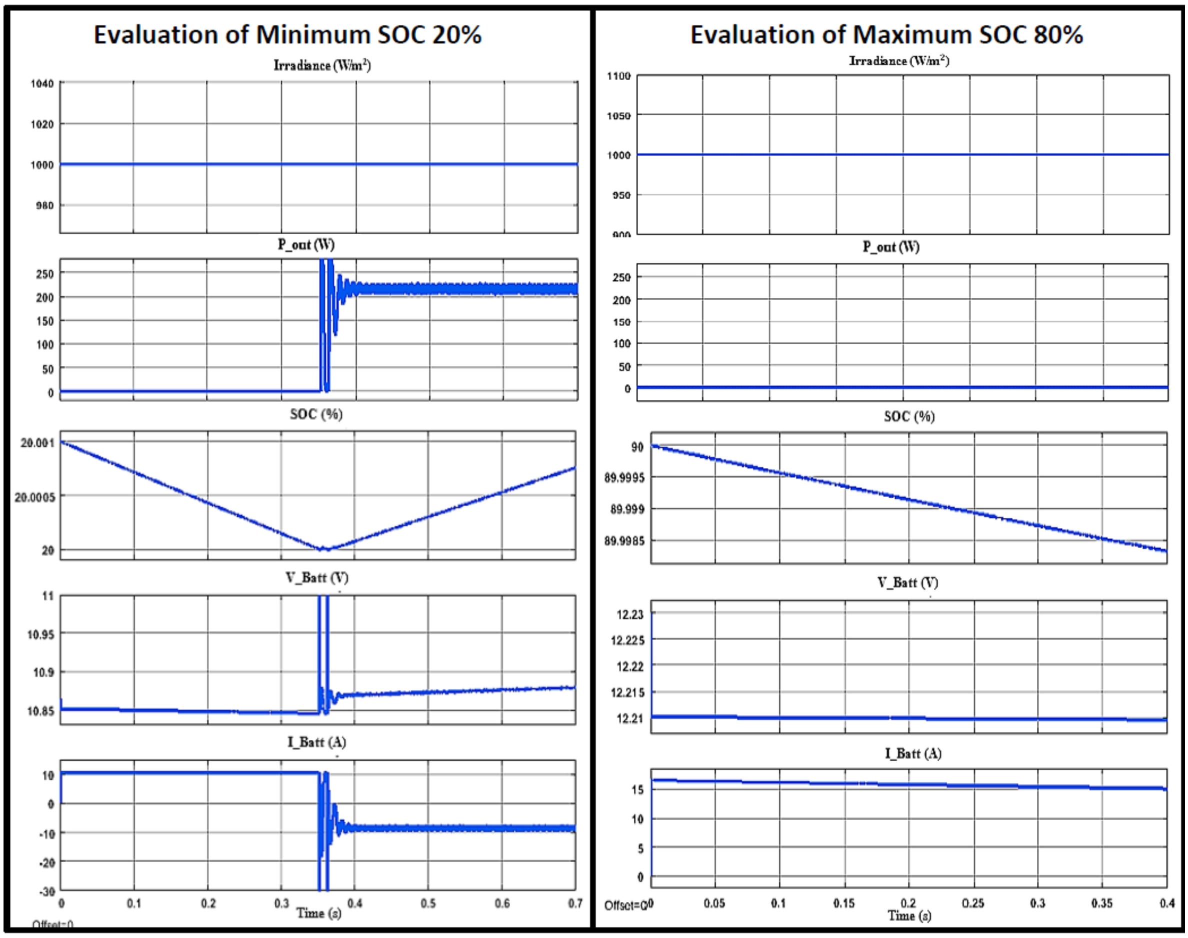

Fig. 6. Simulation results with constant irradiance for evaluation of battery SOC

Based on simulation results obtained from constant and step irradiance levels, the designed FL-MPPT charge controller with the P&O algorithm and the lead acid battery as the load was able to maintain the system's maximum efficiency while extending the battery's life. The FL-MPPT charge controller achieved 96% efficiency when compared to the system without the FL-MPPT algorithm, which only achieved 42% efficiency, as summarized in Table 5.

Table 5
Summary of simulation results

Irradiance Profile	With FL-MPPT		Without FL-MPPT	
	Maximum output power (W)	Efficiency (%)	Maximum output power (W)	Efficiency (%)
Constant 1000 W/m^2	235 W	96%	104 W	42%
Step from 400 W/m^2 to 1000 W/m^2	90 – 235 W	96%	45 – 104 W	42%

4. Conclusions

In conclusion, a P&O MPPT charge controller using FL for battery integrated with solar PV system was successfully designed and developed in this work. Based on the simulation results, the designed charge controller manages to produce maximum power relative to the value given from the PV panel data sheet at each irradiance level. Thus, the controller was able to achieve 96% efficiency for the overall solar PV system, compared to only 42% efficiency achieved by the system without the FL-MPPT algorithm. In addition, charging with the FL-MPPT algorithm at constant and step irradiance is much faster than charging without the FL-MPPT algorithm.

Besides that, the results of the battery SOC evaluation clearly demonstrate the success of extending battery lifetime through SOC regulation. When the battery SOC is less than 20%, the battery will stop discharging and start to charge, whereas this process would stop if the SOC reached more than 80%. This can prevent the battery from being overcharged or overdischarged. Overall, the system was able to provide constant power to the output, in this case the battery, by modulating the PV panel irradiance input. Nevertheless, it is suggested to add a second stage DC-DC converter with a Proportional Integral (PI) controller for further performance improvement.

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