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Photovoltaic Fuzzy - MPPT Based Smart Battery Charger for Low Power Applications

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Abstract: The advent of photovoltaic (PV) modules has revolutionized electricity generation, but their nonlinear characteristics impose constraints on achieving maximum energy output. To address this challenge, the utilization of Maximum Power Point Tracking (MPPT) techniques has become crucial to optimize power generation even in unfavorable conditions. Although MPPT-enabled battery chargers for high-power systems are readily available, there is an increasing need to develop chargers specifically designed for low-power applications. These chargers will ensure efficient power supply during emergencies, catering to the demands of various low-power scenarios. This research paper aims to create a self-contained solar PV charge controller that incorporates MPPT capabilities. The MATLAB/Simulink environment is used to simulate the circuitry, and the charge controller utilizes a buck converter setup. The goal is to accurately track and optimize the solar panel's maximum power output, which is achieved by implementing the Fuzzy MPPT technique. The effectiveness of the Fuzzy MPPT approach is compared to the Perturb and Observe (P&O) and Incremental Conductance (INC) MPPT strategies in a comparative analysis. Additionally, the battery charge controller (BCC) charges lead-acid and lithium-ion batteries in three stages. MPPT bulk charge, constant voltage (CV) absorption charge, and float charge are among the various stagesThe efficiency of the model is assessed based on its capacity to track MPPT, the effectiveness of battery charging, and the charge controller's overall performance. The results show that the Fuzzy MPPT technique demonstrates quick tracking of the PV panel's maximum power point, achieving this in less than 0.5 seconds even when subjected to variations in solar irradiation circumstances. It also accomplishes a remarkable maximum power tracking efficiency of 99.7%.

Keywords: *MPPT Technology, Converter Topology, Battery Charge Controller*

1. Introduction

Solar PV energy has drawn a lot of attention in the last ten years as a leading renewable energy source. One of the most rapidly expanding renewable energy strategies, it has seen extraordinary growth. The growing popularity of solar PV can be due to a number of factors, including its wide availability, environmental sustainability, and reducing costs. A clean and dependable source of energy, solar PV systems convert sunshine directly into electricity. With less greenhouse gas emissions and reliance on fossil fuels, this renewable energy technology has enormous promise for meeting the world's energy demands. As a result, solar PV energy has emerged as an important contributor in the global energy transition to a low-carbon and more sustainable future. The cumulative installed capacity of renewable energy sources increased significantly by 295 GW last year, according to the International Renewable Energy Agency (IRENA), reaching 3,372 GW globally [1]. The steady decline in solar module prices over the past 10 years is primarily responsible for the large increase in worldwide renewable capacity. The cost of solar PV energy has decreased, making it more accessible and desirable for mass use. Moreover, the wide acceptance of solar PV energy across diverse industries can be attributed to its convenient installation process, adaptable scalability to accommodate various energy demands, and minimal maintenance requirements. A notable advantage of solar PV technology lies in its operation without any moving components, which enhances its reliability and durability. The production of electricity in a PV system is reliant on the availability of sunlight, thereby limiting its utilization to daylight hours. However, to overcome this constraint and effectively utilize solar energy throughout the day, even in the absence of sunlight, the incorporation of battery energy storage is widely regarded as a viable and effective solution. Hence, the solar PV charge controller plays a pivotal role in facilitating the implementation of this solution. The primary components of a PV charge controller are the solar PV arrays and the controller itself. The charge controller using solar PV array finds extensive application in standalone system setups, such as street lighting [2], telecommunication base stations, rural electrification [3], and more. It serves as a vital component in managing and regulating the charging process of the batteries connected to the solar PV system, ensuring optimal performance and efficient utilization of

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solar energy. In a solar PV charge controller with MPPT, two crucial components are present: an MPPT tracker and a BCC. The tracker (MPPT) is responsible for monitoring and accurately tracking the maximum power output from the PV panel. This power is then directed to the BCC. To ensure safe and efficient charging of the battery, the charge controller employs a multi-stage charging strategy. This strategy helps to prevent the potential battery damage caused by excessive charge gassing and overheating. Numerous researchers are actively involved in exploring and discussing various MPPT techniques [4–7], modelling techniques, and Simulink-based implementations [8]. Their endeavours are directed towards enhancing the performance and efficiency of MPPT in solar PV systems.However, upon reviewing the MPPT techniques developed by researchers, it is apparent that there is a lack of evaluation regarding the tracking time and tracking efficiency of these techniques. Additionally, there is a dearth of discussion on the integration of MPPT with a BCC. Within the field, the existing literature predominantly focuses on multi-stage charging approaches [9], comparative analyses of different multi-stage chargers [10], and solar PV charge controllers [11] specifically in relation to the BCC side. However, these controllers operate without MPPT functionality, and there is a lack of performance analysis specifically related to charger efficiency.

In addition, there is literature works focused on the modelling of solar PV charge controllers with MPPT [12-13]. Nevertheless, the models discussed in these studies lack detailed modelling information and do not include a performance analysis with regard to efficiency.Furthermore, there is no comparison with commercial BCCs to validate the models. To summarize, the existing literature lacks comprehensive models and fails to provide performance analysis of MPPT and overall efficiency of charge controller, as well as benchmarking against commercial charge controllers with MPPT for model corroboration. The fundamental goal of this paper is to address the aforementioned gaps by offering a detailed framework of the solar PV Fuzzy MPPT BCC using Simulink. Additionally, the paper conducts a performance evaluation in the subsequent sections to assess the system's efficiency and effectiveness.

The paper's structure is as follows: Section 2 provides an extensive literature review on the topic, delving into its details. In Section 3, the complete model of the BCC is presented, encompassing an in-depth explanation of the functioning of the converter topology (DC-DC), MPPT controllers, and the Lead Acid/Lithium-Ion BCC. Section 4 focuses on showcasing the results obtained from the proposed controller and engaging in discussions based on these results. Overall, Section 5 serves as the paper's conclusion, summarizing the major findings and outlining potential future research directions.

2. Literature Survey

In this phase, a comprehensive literature review is carried out in order to investigate various MPPT techniques and charge controllers. Throughout the study, two crucial factors are given particular focus:

2.1 MPPT Techniques: The investigation looks into several MPPT methods and how well they function in various situations, such as changing weather, sun irradiance levels, along with partial shadowing. It seeks to provide light on the potency and applicability of these methods for maximizing solar energy conversion.

2.2 PV Solar Charge Controllers: The survey also covers several PV solar charge controller models and looks at current developments in this area. It attempts to compile data on the most recent improvements, characteristics, and capabilities of charge controllers employed by photovoltaic systems.

Ultimately, this literature review aims to examine and summarize the current research on MPPT approaches and charge controllers, illuminating their uses, constraints, and prospective areas for development.

2.1 MPPT Techniques

Solar PV is a highly acclaimed and impressive renewable energy source for power generation. However, its power-voltage (P-V) characteristic is nonlinear, presenting a notable challenge in attaining maximum power point (MPP) operation and extracting the utmost power output. The P-V characteristic curve of a PV array encompasses multiple power-voltage points, yet only one specific pair can yield the highest power output. Furthermore, the online nature of PV generation leads to frequent changes in the power-voltage characteristic due to environmental fluctuations. Hence, the primary objective is to effectively track the MPP region and rapidly converge to the true MPP in order to optimize power extraction [14]. The non-linear correlation between power output and PV input parameters often leads to suboptimal power extraction [15]. To overcome this limitation, significant research efforts have been directed towards MPPT techniques, which aim to enhance the solar power system’s efficiency (η) by ensuring that the operating point consistently aligns with the MPP [16]. Extensive research has been conducted by numerous scholars on different MPPT algorithms, which can be broadly categorized into two groups: traditional MPPT algorithms, and advanced MPPT algorithms. Traditional MPPT algorithms, such as hill climbing and P&O [43, 49, 50, 51], along INC [47, 51], have gained significant popularity and widespread usage. These algorithms are favored for their simplicity and straightforward implementation.However, they encounter several challenges such as difficulties in tracking the MPP under non-uniform solar irradiation conditions and the occurrence of output oscillations. Moreover, these techniques fail to accurately track the global MPP (GMPP) in scenarios involving partial shadow circumstances (PSC). In such instances, the power output of the solar power system demonstrates various peaks, including a GMPP and several local peaks, as illustrated in figure 1. Consequently, traditional MPPT techniques face difficulties in accurately identifying the true MPP amidst the multiple peaks, posing a significant challenge. When there are rapid fluctuations in solar irradiation, the P&O and INC algorithms with fixed step sizes may exhibit low response rates. To address this issue, modified versions of the INC [51] and P&O techniques [44, 50] have been proposed. These modified techniques aim to make accurate decisions and adjust effectively in the face of sudden changes in solar irradiance levels. appropriate modifications, these algorithms can enhance their responsiveness and adaptability, enabling them to respond more effectively to rapid changes in solar irradiation.

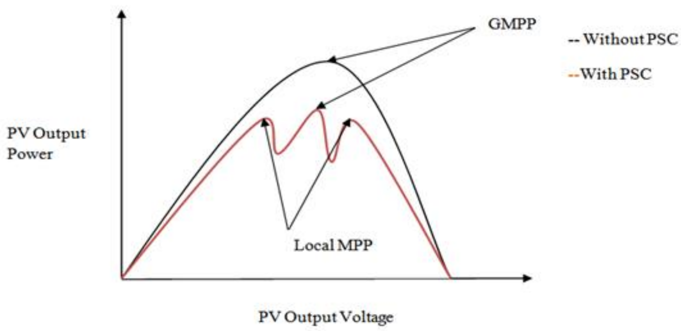


Fig 1. Effect of PSC on PV curve [42]

Advanced MPPT methods, like fuzzy logic controllers (FLC) [17-21], artificial neural networks (ANN) [22-23, 25-26], neural networks [24], evolutionary computation [31–33, 40], and genetic algorithms (GA)[27–29, 42], offer enhanced performance in both uniform solar irradiance and PSC. However, these techniques are more complex to implement and require precise parameter settings for optimal operation. Despite their effectiveness, the implementation and parameter tuning process can be challenging due to the intricate nature of these advanced techniques.

To maximize power output from PV modules under PSC, a novel optimization algorithm inspired by pigeons has been employed [30]. The fundamental goal of this MPPT algorithm is to achieve fast convergence of the operating point and minimize power losses in the system output. By leveraging the natural foraging behavior of pigeons, this technique demonstrates desired performance even under real-world conditions. Additionally, there are other MPPT techniques that utilize bird-inspired searching behaviors to track the GMPP under varying solar irradiance levels [34, 39]. Furthermore, a deterministic variant of the Cuckoo Search (CS) technique has been implemented to eliminate randomness in the voltage calculation equation, which is present in the conventional CS method [35]. In [45-47], several fast MPPT techniques are introduced, focusing on their performance evaluation in terms of tracking efficiency, tracking time, and steady-state oscillation error. The study reveals that the Kalman-based MPPT technique outperforms both the Self-tuned and Auto-tuned MPPT techniques in terms of overall performance.Furthermore,a hybrid approach is suggested to enhance the tracking performance of MPPT controllers when confronted with changing environmental circumstances [36-37, 42, 48].The hybrid approach combines multiple strategies or algorithms to achieve improved performance, presenting a promising solution for optimizing MPPT performance in dynamic environments. A hybrid strategy known as FLC-PO is created, integrating the benefits of both approaches while eradicating their downsides, to overcome the limits of the P&O-MPPT and Fuzzy Logic MPPT methodologies. This method uses the MATLAB Simulink environment to create a hybrid intelligent controller (PO-ANN and IC-ANN), with the goal of maximizing power extraction from solar PV modules [37]. To increase power extraction from solar PV modules, another method is suggested that makes use of a model based on the Adaptive Neuro-fuzzy Inference System (ANFIS) [38]. The Particle Swarm Optimization (PSO) modified P&O and an improved version of PSO are combined in a hybrid MPPT technique that is also suggested. This method is applied in situations that use software and DSpace. The results demonstrate significant improvements in speed and accuracy, allowing the suggested technique to successfully monitor the real

GMPP regardless of how complex the shading circumstances are [48].

Table 1 presents an comprehensive study of both traditional and complex MPPT algorithms, focusing on their performance under various conditions, such as sensing parameters, tracking time, steady-state oscillation error, hardware/software platform and tracking efficiency. The investigation shows that FLCs, hybrid techniques, and computational methodologies beat other approaches. These techniques can lessen steady-state oscillation errors and improve tracking performance. The findings suggest computational, FLC, and hybrid techniques as potential avenues for enhancing MPPT system performance.

Table 1. Comparative analysis of MPPT Techniques

Sr. No.	MPPT Algorithm	Sense parameter	Hardware/ Software platform	tracking time(s)	tracking efficiency (%)	Steady -state oscillat ion (%)	Implementation complexity
1	FLC [17]	Voltage and current	MATLAB/ Simulink and arduino	--	--	±4.0	Medium
2	FLC [18]	Voltage and current	DS1104 DSpace	0.43	98.5	±1.7	Medium
3	FLC [19]	Voltage and current	FPGA and MATLAB/ Simulink	0.3	98	±1.0	Medium
4	FLC [20]	Voltage and current	MATLAB/ Simulink	--	99	±0.06	Medium
5	FLC [21]	Voltage and current	PVPM 2540C, MATLAB/ Simulink	Less than 0.01	99.37	--	Medium
6	ANN [22]	Voltage and current	MATLAB/ Simulink and experiment	0.06	upto 99.68	--	Medium
7	Modelling of ANN [23]	Voltage and current	MATLAB Simulink	--	Above 90	--	Medium
8	Neural network [24]	Voltage and current	MATLAB/ Simulink	--	--	±0.1	Medium
9	ANN[25]	Voltage and current	MATLAB/ Simulink	0.2-0.4	Above 90	--	Medium
10	Feed forward ANN [26]	Temperatur e and irradiance	MATLAB/ Simulink	0.3	--	±0.7	Medium
11	GA [27]	Temperatur e and irradiance	MATLAB/ Simulink	--	--	--	High
12	GA [28]	Voltage and current	dSpace and Terra- SAS control soft- ware	--	--	--	High
13	GA [29]	Voltage and current	MATLAB/Simulink	--	--	--	High
14	Pigeon [30]	Voltage and current	MATLAB/ Simulink	±0.1	--	--	High
15	PSO [31]	Voltage and current	MATLAB/ Simulink	±1.0	--	--	Medium

16	PSO [32]	Voltage and current	dSpace 1104 controller MATLAB Simulink	0.4	--	--	Medium
17	PSO [33]	Voltage and current	MC56F8245 micro-processor	±1.6	--	0.97	Medium
18	CS[61][34]	Voltage and current	Microchip DSP MATLAB/ Simulink	1.8-2.8	99	±0.050	Medium
19	GSA [63][35]	Irradiance and temperature	MATLAB/ Simulink	±0.04	-	±1.000	High
20	FLC with P&O [36]	Voltage and current	MATLAB Simulink	±1.000	99.6	±0.01	Medium
21	Hybrid intelligent controller [37]	Voltage and current	MATLAB Simulink	±0.400	>91	--	High
22	ANFIS [38]	Voltage and current	MATLAB/ Simulink	0.012	91	--	Medium
23	ACO [39]	Voltage and current	dSpace/ MAT-LAB/Simulink	0.38	--	--	Medium
24	DE [40]	Voltage and current	PIC18F4520 micro-controller	±2.00	99	--	High
25	Modified FPA [41]	Voltage and current	MATLAB/ Simulink	0.05	99.1	--	Medium
26	FLC [42]	Voltage and current	MATLAB/ Simulink	0.7	--	±3.0	Medium
27	ANN[42]	Voltage and current	MATLAB/ Simulink	0.25	--	< 1.0	Medium
28	SI [42]	Voltage and current	MATLAB/ Simulink	0.28	--	±1.7	Simple
29	Hybrid [42]	Voltage and current	MATLAB/ Simulink	0.23	--	±0.1	Medium
30	GA[42]	Temperature and irradiance	MATLAB/ Simulink	0.8	--	±10.0	High
31	P & O [43]	Voltage and current	MATLAB/ Simulink	1.6	96.5	4.2	Simple
32	Adaptive P& O [44]	Voltage and current	MATLAB/ Simulink	1.5	97.8	2.5248	Medium
33	Auto tuned MPPT [45]	Voltage and current	MATLAB/ Simulink	0.9	98.6	0.03	Medium
34	Self-tuned MPPT[46]	Voltage and current	MATLAB/ Simulink	0.6	99.3	0.012	Medium
35	Kalman filter based MPPT[47]	Voltage and current	MATLAB/ Simulink	--	99.25	--	Medium
36	INC[47]	Voltage and current	MATLAB/ Simulink	--	96.72	--	Simple

37	PO-PSO [48]	Voltage and current	dSpace and MATLAB Simulink	0.219	--	--	Medium
38	P & O[49]	Voltage and current	MATLAB/ Simulink/hardware	0.89	95	--	Simple
39	FLC[49]	Voltage and current	MATLAB/ Simulink/hardware	0.99	95.5	--	Medium
40	P & O [50]	Voltage and current	dSpace and MATLAB Simulink	0.5	--	--	Simple
41	MP & O [50]	Voltage and current	dSpace and MATLAB Simulink	0.4	--	--	Medium
42	SPP & O[50]	Voltage and current	dSpace and MATLAB Simulink	0.2	--	--	Medium
43	FLC [53]	Voltage and current	MATLAB Simulink	--	94.8	--	Medium
44	INC[51]	Voltage and current	MATLAB Simulink	--	96.3	--	Simple
45	MINC[51]	Voltage and current	MATLAB Simulink	--	97	--	same Medium
46	P & O [51]	Voltage and current	MATLAB Simulink	--	96.1	--	Simple

2.2 Recent advancements in solar charge controllers

The power flow from solar panels to batteries is managed by solar charge controllers (SCC), which are essential components of solar power systems. The batteries are safeguarded against overcharging, the charging process is optimized, and potential harm is avoided. Commonly used in these systems are different types of solar charge controllers.

1. PWM (Pulse Width Modulation) based Charge Controller: The most fundamental and popular sort of controllers are PWM ones. They operate by quickly turning on and off the solar panel's output, which controls the voltage delivered to the battery. These controllers are reasonably priced and appropriate for small to medium-sized solar projects.

2. MPPT based Charge Controller: PWM controllers are less sophisticated and effective than MPPT controllers. To extract more power and improve charging efficiency, they track the solar panels' MPP using sophisticated algorithms. Larger systems or installations with variable weather conditions are best suited for MPPT controllers.

Though there are various SCCs, it's crucial to consider factors like the system voltage, maximum current rating, efficiency, and specific requirements of a solar power setup when choosing a charge controller.

Effectively harnessing solar energy for battery charging presents a significant challenge due to the diverse requirements of different applications. The actual performance of batteries in solar PV systems often does not meet the specifications provided by manufacturers, as these specifications are typically derived from tests conducted under more ideal conditions. This discrepancy poses a considerable obstacle, as premature battery failure or capacity loss significantly impacts the overall cost of running such applications. To address these challenges, a BCC in PV systems serves the purpose of maintaining an optimal state-of-charge while preventing both overcharging and over-discharging of the battery. Additionally, maximizing the utilization of solar power and minimizing installation costs necessitates the operation of PV panels at their MPP under specific weather conditions. Hence, there is a need for charge controllers equipped with MPPT techniques to ensure efficient utilization of solar energy. Researchers from academic institutions and industry are persistently exploring and developing diverse types of SCCs, highlighting the ongoing research endeavors in this field. An example of a proposed charge controller is the one introduced by S. J. Chiang et al.[55], which incorporates a Proportional-Integral (PI) controller in combination with an incremental conductance MPPT algorithm. Their study focused on the implementation of MPPT techniques to extract maximum power from PV modules using a SEPIC converter. Similarly, Joydip Jana et al.[57] designed a SCC incorporating an MPPT controller. Their research emphasized the significant role of the MPPT controller in battery charging and presented an algorithm specifically developed for the battery's optimal functioning. These studies demonstrate the continuous advancements in SCC technologies and their application in maximizing solar energy utilization. Unal Yilmaz and their team [53] investigated the effectiveness of an advanced MPPT approach called FLC for solar energy systems. The choice of the FLC was motivated by its capacity to quickly adapt to fluctuations in weather conditions and its resilience in handling changes in circuit parameters. The preciseness of the FLC MPPT method implemented in their system demonstrated a significant improvement, increasing from 94.8% to 99.4% in tracking the MPP. When it comes to the charging of battery, the CC and CV methods are widely utilized as two traditional approaches. To achieve fast charging with minimal losses, the study employed a PI controller in conjunction with a buck converter. This combination proved to be effective in providing a constant current and voltage source for efficient battery charging. The fundamental objective of this study is to ensure that PV panels operate at their MPP even in a variety of environmental circumstances in order to improve their performance. This approach aims to enhance system efficiency, reduce costs, and provide the necessary current and voltage levels for efficient battery charging. By charging the battery quickly and minimizing losses, the study also aims to prolong the battery's lifespan . M. Lokesh Reddy et al.[11] carried out a comparative analysis that specifically examined various charge controller techniques for PV systems, excluding the inclusion of MPPT methods. The primary objective of the study was to determine the most appropriate charge controller method to optimize the efficiency of PV systems effectively. Table 2 presents a comparative analysis of SCCs based on several parameters, including the type of converter used, MPPT controller, charging technique, charge controller efficiency, and charging time. The results from the table indicate that SCCs equipped with MPPT controllers demonstrate superior performance. Both traditional MPPT algorithms, like P&O and INC, as well as advanced techniques like FLC, are utilized in these SCCs. various researchers have developed SCCs with both MPPT and traditional controllers, focusing primarily on the battery charging process. However, there is still ample research opportunity for SCCs concerning charging time, charging efficiency, and MPPT tracking efficiency specifically related to battery charging.

Table 2. Comparative analysis of SCCs used for PV system

Sr.No.	Ref. No.	Solar Charge controller with /without MPPT	MPPT algorithm used/controller	Converter used	Hardware/ Soft-ware Platform	Charging Technique	Charge Controller Efficiency (%)	Charging Time (Hr)
1	[52]	Both	P & O	Asynchronous Buck Converter	Arduino microcontroller, MATLAB Simulink	Constant Current Constant Voltage	78	--
2	[53]	With MPPT	Fuzzy logic controller/PI control	Boost /Buck Converter	MATLAB/ Simulink	Constant Current Constant Voltage	--	--
3	[54]	Without MPPT	Series/Shunt Charge Controller	--	MATLAB/ SIMULINK.	--	--	--

4	[55]	with MPPT	Incremental Conductance / PI charge Controller	SEPIC Converter	80 W prototype MATLAB/ SIMULINK.	1.Constant Current 2.Constant Voltage 3.float charging	--	--
5	[56]	with MPPT	P & O	Buck Converter	2KW prototype MATLAB Simulink	--	--	--
6	[11]	without MPPT	Series/Shunt Charge Controller	--	MATLAB Simulink	--	--	--
7	[57]	with MPPT	P & O	Buck Converter	FPGA controller with MATLAB Simulink	1. Constant Current 2. Topping Charging 3.float charging	--	--

The outcome of the literature survey is that there is need to develop MPPT by considering various factors such as the effect of temperature, PSC, changing weather conditions. The performance of MPPT technique is evaluated by complexity of the algorithm, convergence time of tracking the operating speed, power loss, tracking efficiency, dynamic response and extraction of maximum power from PV module in the real time condition. Many MPPT techniques are developed by various researchers. But most of the researches are focusing on the tracking time of the MPPT and measuring the maximum power produced by PV module. But all the parameters related to MPPT are not covered by the most of the researchers. There are almost 20 MPPT techniques are reviewed from various published scopus indexed papers, IEEE transaction papers and SCI journal papers. It has been   from this literature survey that the advanced techniques are giving better performance in-terms of tracking time, oscillation steady state error and other parameters. The suggested approach in this study is to employ the FLC based MPPT technique to accurately track the operating point at the MPP, especially when faced with rapid variations in the solar insolation level. How effectively the proposed MPPT technique is effectively responded at varying environmental conditions and effective use of the solar energy obtained from the sun.

The summarization of literature survey related to SCC about PV systems is that different types of SCCs are developed by researchers and industry persons. But they are having some limitations. Their research is not considered   few parameters such as charging time, charge controller efficiency and the convergence time of MPPT controller. There is a need to develop SCC for solar PV applications by considering the proper utilization of solar energy. Here Fuzzy MPPT based SCC is proposed by considering three stage charge technique to charge lead acid as well as lithium ion battery . The performance of SCC is evaluated in-terms of charging time and charge controller efficiency in the MATAB Simulink environment by comparing P & O MPPT based SCC and INC MPPT based SCC.

3. Methodology

The solar PV MPPT BCC framework created using the MATLAB/Simulink platform is illustrated in figure 2, offering a comprehensive view of the system. The model technique encompasses key components such as a solar PV array, DC-DC converter, battery, and a block of charge controller with MPPT. The MPPT charge controller block integrates three distinct techniques: P&O, INC, and Fuzzy MPPT. Moreover, the model includes a three-stage charge controller tailored specifically for lead-acid and lithium-ion batteries, as illustrated in Figures 3, 4, and 5 respectively. In the

MPPT charge controller block, there is an integration of an MPPT tracker and a three-stage charger that is specifically designed for lead-acid or lithium-ion batteries. The main role of this block is to produce a PWM control signal that effectively regulates the DC-DC converter's switching device. This particular design is extensively used in commercial solar PV MPPT BCCs, where the P&O or INC MPPT techniques are commonly implemented. The developed model has the capability to charge a battery of 48V rated voltage using a PV array of 2kW power ratings as the power source. Extensive testing and simulation of the model were conducted within the Simulink environment to analyze its performance. In the subsequent sections, a comprehensive description of the circuitry framework as well as the charge controller with MPPT block is provided, offering a detailed explanation of their respective functionalities.

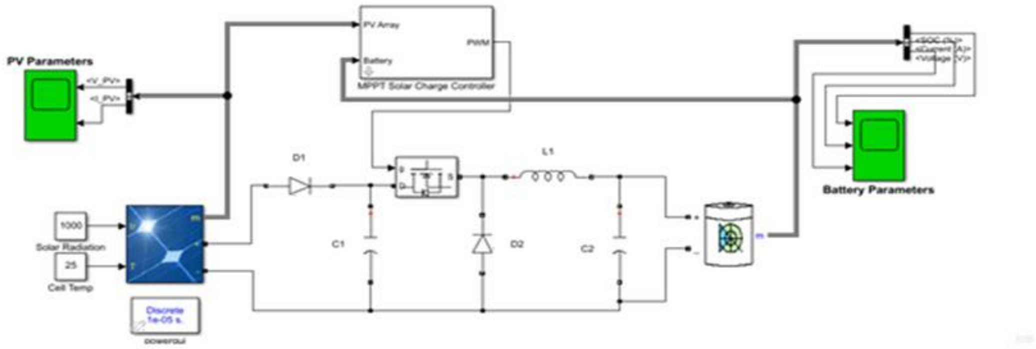


Fig 2. MATLAB implementation of a solar charge controller with lead/li-ion battery

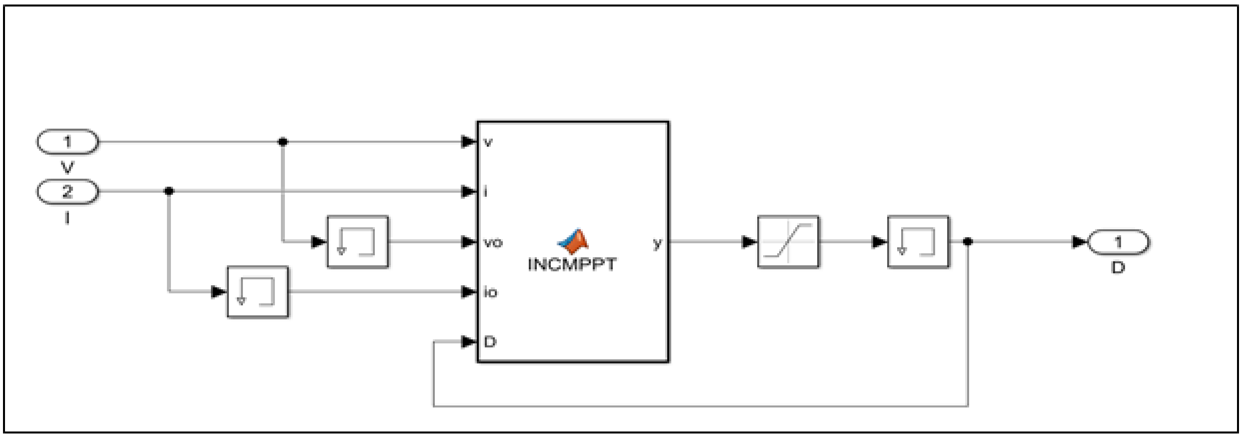


Fig 3. MATLAB implementation of PV battery Charger with INC MPPT

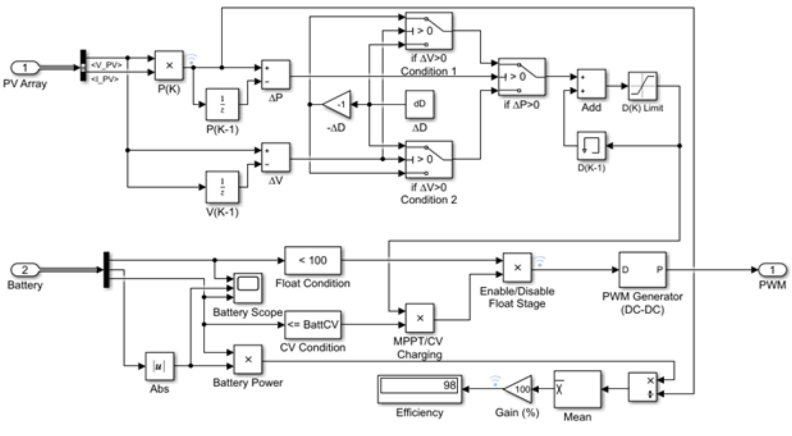


Fig 4. MATLAB implementation of PV battery Charger with P&O MPPT

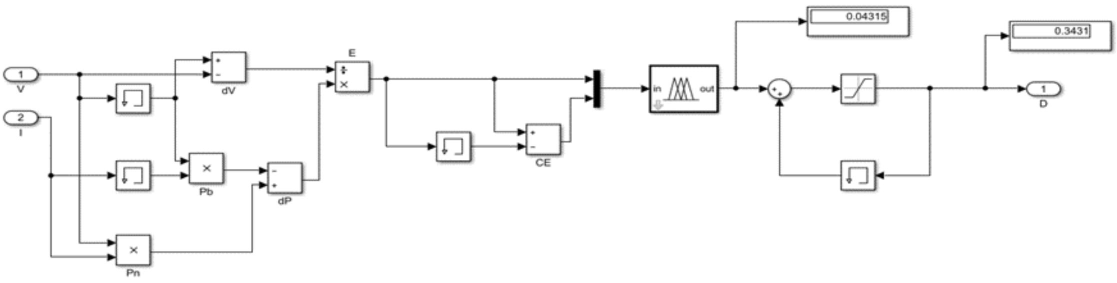


Fig 5. MATLAB implementation of PV battery Charger with FLC MPPT

3.1 Converter Topology (DC-DC)

The primary role of a converter topology (DC-DC) is to modify the voltage of a DC input source, either by increasing or decreasing it, to attain a desired DC output voltage.The buck topology is extensively utilized in solar PV charge controllers. Its primary purpose is to efficiently reduce a higher DC voltage to a lower DC voltage, making it well-suited for voltage conversion in this specific application. In solar PV systems, sunlight is converted into electricity by the PV array, resulting in a higher DC voltage. However, for effective battery charging, a lower DC voltage is required. This is where the buck converter plays a critical role by stepping down the PV array voltage to an appropriate level for battery charging. By employing a buck converter topology , the solar PV BCCs can effectively control the power flow from the PV array to the battery. This ensures that the battery receives the necessary voltage for charging while simultaneously maximizing energy conversion efficiency [58-60]. The primary role of a buck converter topology is to regulate voltage by lowering the input voltage generated by the PV array. To enable efficient battery charging, it employs a dual approach of decreasing the input voltage while simultaneously boosting the output current that enters the battery. The circuit of the converter topology comprises crucial components, including a switching device (MOSFET), a inductor (device of high power rating), a Schottky diode, and capacitors for both the input and output stages. The arrangement of these elements is depicted in Figure 1. To avoid the backflow of current from the battery to the PV array during nighttime, a reverse blocking diode (D1) is employed. Its purpose is to ensure that the current only moves from the PV array to the battery and not in the reverse direction. The buck converter circuit consists of a MOSFET (with a Ron value of 0.02 Ω) functioning as a switch. The MOSFET is controlled by a pulse generator operating at a frequency of 1000 Hz. Additionally, a Schottky diode (D2) with a forward voltage of 0.5 V is included in the circuit. Equation (1) can be used to calculate the buck converter's output voltage (Vout) by taking the product of the duty cycle and the input voltage (Vin). The PWM signal's duty cycle ,denoted as D, plays a crucial role in this relationship. Modifying the duty cycle allows the converter's (buck) output voltage to be controlled and kept within a specific range.

$$.D = \frac{V_{out}}{V_{in}} \quad (1)$$

In addition to adjusting the output voltage, the duty cycle of the buck converter has a significant impact on the impedance that the PV array observes. MPPT can operate effectively when the effective input resistance is optimized through duty cycle control. The effective input resistance can be calculated using Equation (2) while also accounting for the load resistance (or battery resistance) and the duty cycle. In order to achieve the best MPPT performance, the right conditions must be determined using this equation.

$$R_{in} = \frac{R_{load}}{D} \quad (2)$$

Equation (3) can be used to determine the peak-to-peak ripple current in the buck converter's inductor under steady-state conditions. This measurement of the ripple current is given an important in the buck converter's design and analysis, and its overall performance is affected.

$$\Delta I_L = \frac{V_{in} D(1-D)}{f_{sw} L} \quad (3)$$

Where,

Vin=input voltage,

D= duty cycle

fsw=switching frequency

L = inductor.

Equation (4) gives an approach to calculate the peak-to-peak ripple voltage across the output capacitor of the buck converter under steady-state conditions. Important factors are taken into account by the equation, such as the output capacitor's value (C), the duty cycle (D), the fsw, and the input voltage (Vin) generated by the PV array. Its calculation heavily relies on these variables. It is possible to determine the ripple voltage magnitude precisely using this equation, which is a crucial step in evaluating the buck converter's performance and design.

$$\Delta V_c = \frac{V_{in}\, D(1-D)}{8Lf_{sw}^2 C} \quad (4)$$

In a specific scenario with 10 mH of an inductor's value and 1000 uF of a capacitor's value , assuming a switching frequency (fsw) of 1000 Hz, an 120 V of input voltage (Vin) , and 0.4 of a duty cycle (D) , the computed results indicate that the ripple current in the inductor (ΔIL) is approximately 0.288 mA, while the ripple voltage across the output capacitor (ΔVc) is approximately 2.3 nV. These values are relatively small, implying that the ripple components can be regarded as almost negligible, resembling a nearly flat DC signal.

3.2 MPPT Techniques

3.2.1. P&O Technique

The technique is widely used in charge controllers and grid-connected inverters for small and medium-sized commercial solar PV systems because it is efficient at maximizing power output from the PV array and is simple to implement. By adjusting the duty cycle of the buck converter in the BCC, the MPPT technique ensures optimal power delivery. The flowchart of the P&O MPPT technique, depicted in Figure 6, illustrates its operational steps. This technique utilizes a trial and error approach to track the MPP by continuously monitoring power variations. It dynamically adjusts the PV panel's voltage (operating) by modifying the switching device's duty cycle of the converter, thereby modifying the buck converter's effective input resistance. The technique iteratively assesses if the MPP has been achieved and repeats this process indefinitely to maintain optimal power tracking.

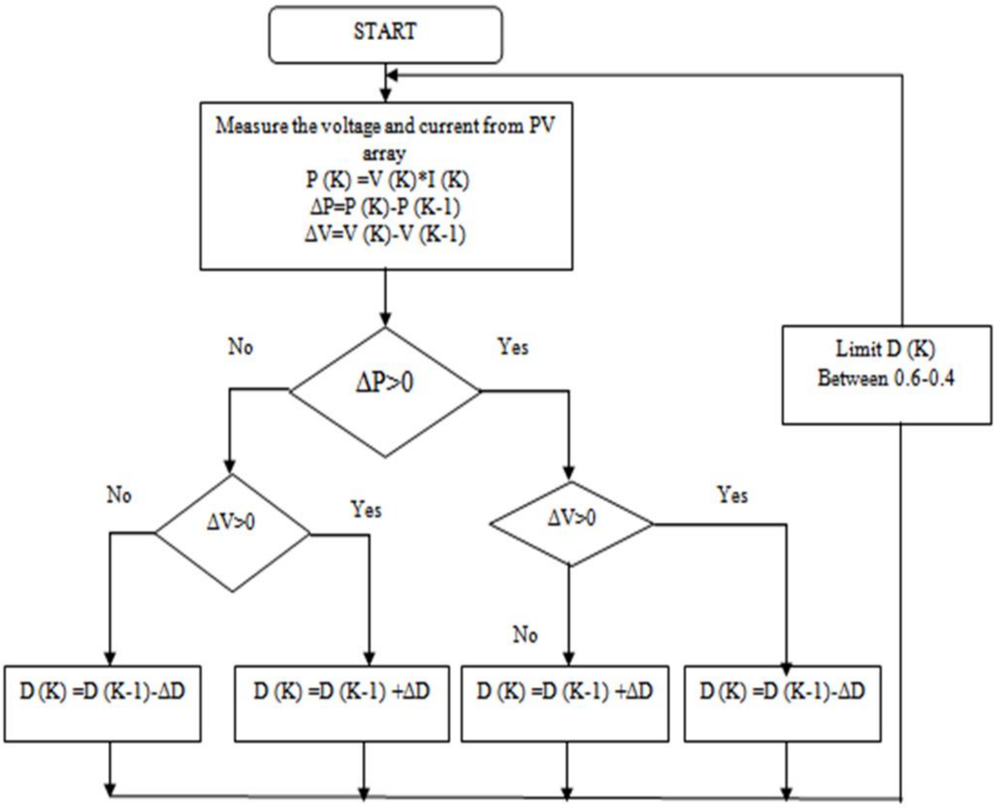


Fig 6. Flowchart of P & O Technique

Figure 2 showcases the utilization of Simulink for implementing the P&O MPPT technique. The implementation solely relies on Simulink blocks. Each block is properly labelled to denote its assigned function, aligning with the instructions provided in the accompanying flowchart.To execute the P&O technique, voltage and current readings are obtained from the PV array. The unit delay block is utilized to perform the operation on the previous sample (K-1). The condition switch block is responsible for handling the P & O technique's three if-else conditions. By utilizing the ΔD block, users have the ability to determine the perturbation step size for the converter's duty cycle. To facilitate the decrement as well as increment operations on the duty cycle, a combination of an adder and a memory block is employed. This integration forms a feedback loop denoted as D(K-1). The purpose of this arrangement is to store and utilize the previous duty cycle value (D(K-1)) in the current calculation. The duty cycle is kept within the range of 0.4 to 0.6 by using the duty cycle limit block. The duty cycle value cannot drop below 0.4 or rise over 0.6 thanks to the control mechanism provided by this block. The output of the duty cycle is linked to the BCC segment. The BCC module is also linked to the PV power output in order to calculate conversion efficiency.

Due to its noteworthy benefits, such as improved performance in rapidly fluctuating irradiation circumstances and better efficiency, this strategy is typically preferred over the P&O method. With this method, the best operating point for maximum power is determined by comparing the conductance and incremental conductance of the solar module in real-time.

3.2.2. INC Technique

The MPP is reached, as shown in Figure 7, when the sloping aspect of the P-V curve reaches zero. The following equations can be used to represent this specific strategy mathematically:

$$\left.\begin{array}{ll} \frac{dP}{dV} = 0, & \text{at MPP} \\ \frac{dP}{dV} => 0, & \text{Left of MPP} \\ \frac{dP}{dV} =< 0, & \text{Right of MPP} \end{array}\right\} \quad (5)$$

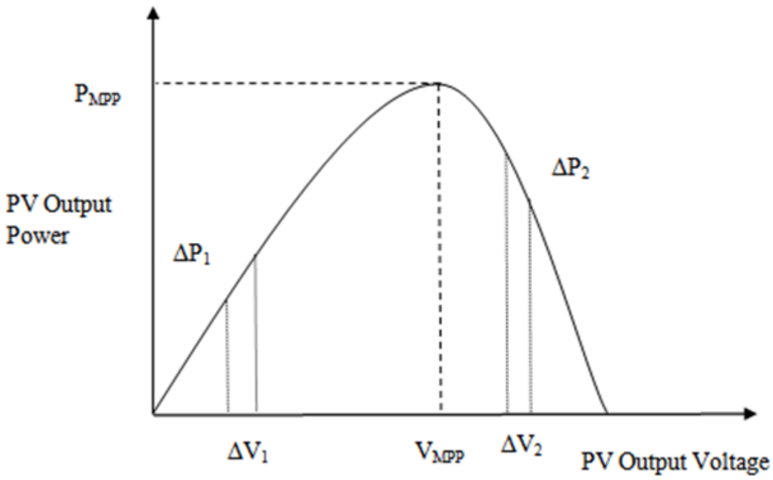


Fig 7. Operating curve of a PV array

Fig. 8 utilizes a flowchart to depict the complete INC process. Instead of using power and voltage as in P&O, it utilizes the difference of voltage and current over time as the input.

3.2.3. Fuzzy MPPT Controller

This is a robust MPPT algorithm specifically designed for Solar PV systems. It offers significant advantages over traditional MPPT techniques like P&O and INC. These advantages include the ability to minimize output ripples, handle nonlinearity, accommodate implicit inputs, and eliminate the requirement for an exact mathematical model. Furthermore, in comparison to the Fuzzy MPPT approach, it simplifies implementation and reduces computing complexity. The flowchart illustrating the Fuzzy MPPT technique can be found in figure 9.

Despite the challenges associated with constructing the FLC- based MPPT method, it offers the advantage of effectively identifying the MPP of PV panels. Unlike other MPPT techniques, the FLC MPPT method does not require prior knowledge about the system's model. The FLC takes two inputs: the system error (E) and the error's rate of change (CE). These inputs are utilized to assess the current state of the system. By considering both the error and its rate of change, the FLC can make informed decisions and carry out appropriate control actions based on the system's dynamics.The equations provided below clarify the definitions of E and CE.

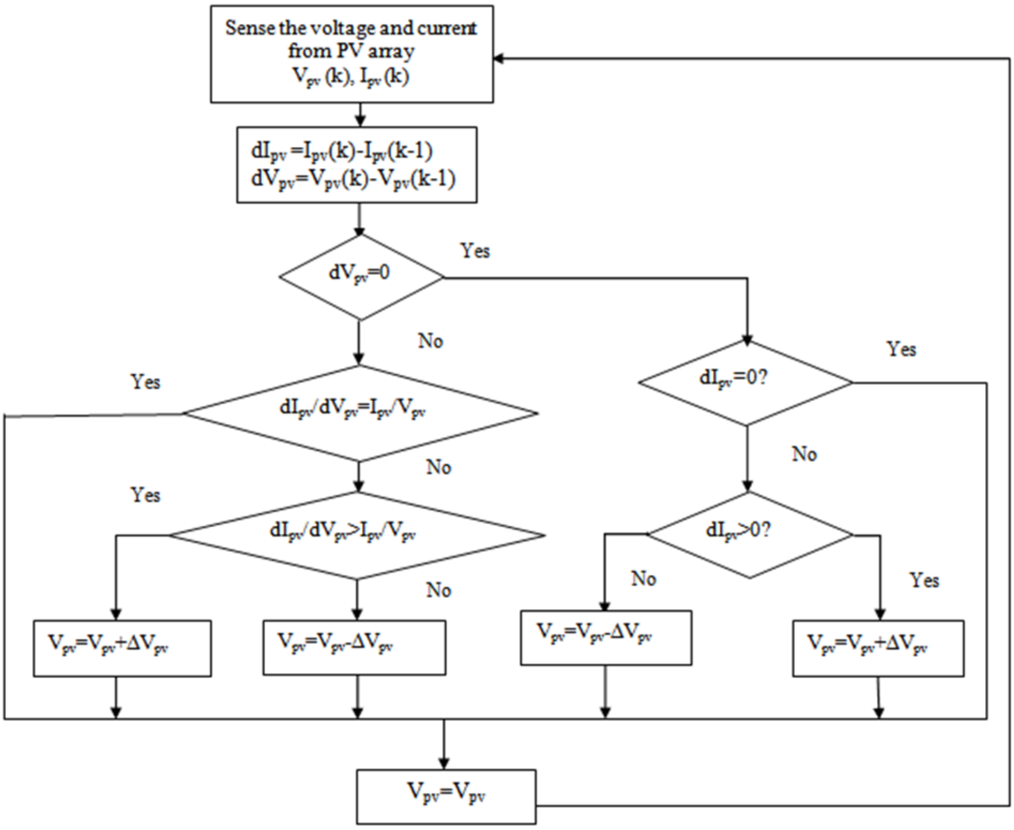


Fig 8. Flowchart of INC

3.2.3. Fuzzy MPPT Controller

This trustworthy MPPT algorithm was developed especially for solar photovoltaic installations. It offers several benefits over traditional MPPT techniques like P&O and INC. These advantages include handling nonlinearity, accommodating implicit inputs, reducing output ripples, and doing away with the requirement for an exact mathematical model. Comparatively to the Fuzzy MPPT approach, it reduces processing complexity and simplifies implementation. The flowchart illustrating the fuzzy MPPT strategy is shown in Figure 9.

The FLC-based MPPT approach has the advantage of accurately determining the MPP of PV panels notwithstanding the difficulties involved in its construction. The FLC MPPT approach does not require prior knowledge of the system's model, in contrast to other MPPT techniques. The system error (E) and the error rate of change (CE) are the two inputs that the FLC requires. To evaluate the system's current condition, these inputs are used. The FLC can make educated decisions and execute suitable control actions depending on the dynamics of the system by taking into account both the error and its rate of change. The definitions of E and CE are made clearer by the equations that follow.

$$\backslash E(k) = \frac{\Delta P}{\Delta V} = \frac{P(k)-P(k-1)}{V(k)-V(k-1)} \quad (6)$$

$$CE(k) = E(k) - E(k-1) \quad (7)$$

Where,

P(k) , V(k) = PV panel ‘s current power output, and voltage ,

P(k-1) ,V(k-1) = PV panel's prior power and voltage

The voltage needs to be modified in accordance with variations in power and voltage in order to achieve the MPP. Increasing the voltage will assist in reaching the MPP when there is a positive change in both power and voltage. Conversely, if the power changes positively but the voltage changes negatively, lowering the voltage is required to reach the MPP. Decreased voltage is the proper strategy for obtaining the MPP when there is a negative change in power but a positive change in voltage. Lastly, if both the change in power and voltage are negative, increasing the voltage is the appropriate action to reach the MPP.

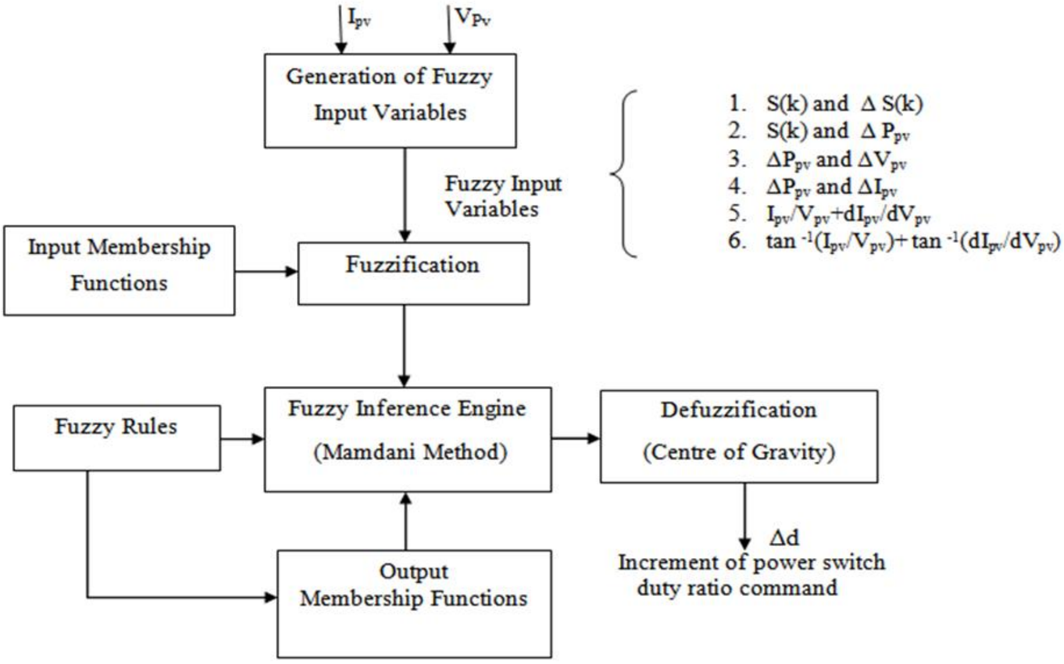
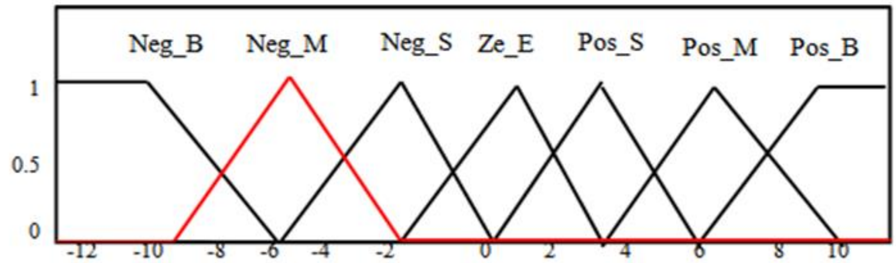


Fig 9. Flowchart of Fuzzy MPPT Algorithm

The subsequent task involves the creation of a rule table and membership functions for Fuzzy Logic in order to develop the Fuzzy MPPT technique. Table 3 presents the rule table, while Fig. 10 (a, b, c) provides a visual representation of the corresponding membership functions. To carry out this task, the Fuzzy Logic Designer App in Matlab/Simulink is employed as a tool.

Table 3. Rule table

E/CE	Pos_B	Pos_M	Pos_S	Ze_E	Neg_S	Neg_M	Neg_B
Pos_B	Ze_E	Ze_E	Ze_E	Neg_B	Neg_B	Neg_B	Neg_B
Pos_M	Pos_S	Ze_E	Ze_E	Neg_S	Neg_S	Neg_M	Neg_S
Pos_S	Ze_E	Ze_E	Ze_E	Neg_S	Neg_S	Neg_S	Neg_S
Ze_E	Neg_S	Neg_S	Ze_E	Ze_E	Ze_E	Pos_S	Pos_S
Neg_S	Pos_M	Pos_S	Pos_S	Neg_S	Ze_E	Pos_S	Ze_E
Neg_M	Pos_M	Pos_S	Pos_M	Pos_S	Ze_E	Ze_E	Neg_S
Neg_B	Pos_B	Pos_M	Pos_S	Pos_B	Ze_E	Ze_E	Ze_E



(a)

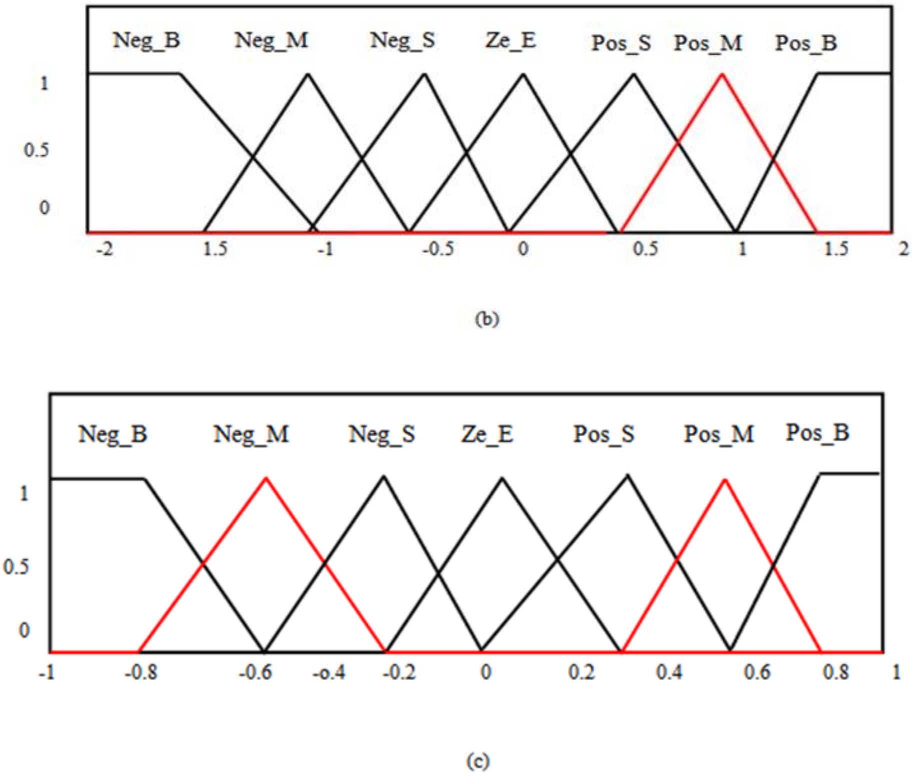


Fig 10. (a) Input: Error, (b) Input: Change of error (c) Output: Duty Cycle

3.3 Lead Acid/ Lithium-Ion Battery Charger Controller

In order to achieve efficient charging for a lead-acid battery, a dedicated BCC was developed using a three-stage charging method. This method involves three distinct stages: CC charging, CV charging, and finally the float charging. Each stage serves a specific purpose and contributes to the overall charging process.During the initial stage, referred to as CC charging or bulk charging, the battery is charged at its rated capacity. In this particular case, the charge current is adjusted to match the MPPT level, ensuring an optimized charging process. Following the initial bulk charging stage, the second stage is known as absorption charging or CV charging. During this stage, the battery undergoes charging at a predetermined fixed voltage, while the functionality of MPPT is disabled.The main goal of this stage is to guarantee that the battery reaches its maximum charge capacity. Following that, the third stage, known as float charging, is utilized to sustain the State of Charge (SoC) of the battery at 100% after it has reached full charge.This preventive measure is implemented to avoid gassing reactions and overheating, which can occur when the battery experiences uncontrolled excessive charging beyond 100%. For a visual representation of the BCC process, refer to Fig. 11 in the form of a flow chart.

The BCC monitors both the battery's SoC as well as battery's voltage. During the first condition, if the SoC is below 100%, the BCC transitions into either the CC or CV charging stage. Conversely, if the battery's SoC reaches 100% or more, the charger enters into the final floating stage, where the converter's duty cycle is set to zero. Based on the battery's voltage level, the second condition determines whether the charger should operate in the MPPT bulk charging stage or transition to the CV absorption charging stage.

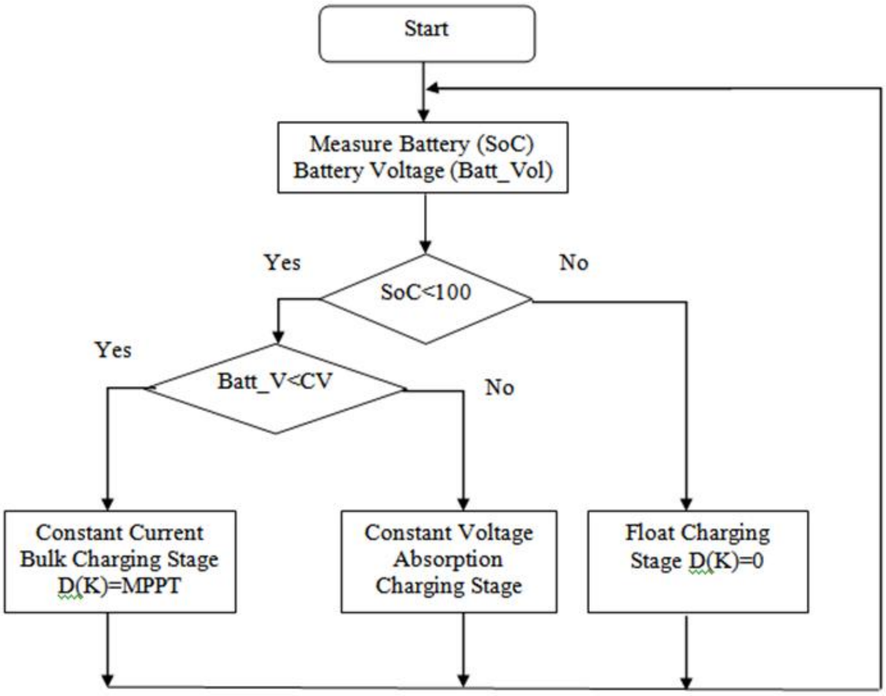


Fig 11. Charging process of BCC

When the battery's voltage is below the specified CV set point, the charger will shift to the MPPT CC bulk charging stage. Conversely, if the battery's voltage is equal to or higher than the set point, the MPPT functionality will be deactivated, and the charger will switch to the CV absorption charging stage. The graphical depiction of this process is shown in Figure 12.

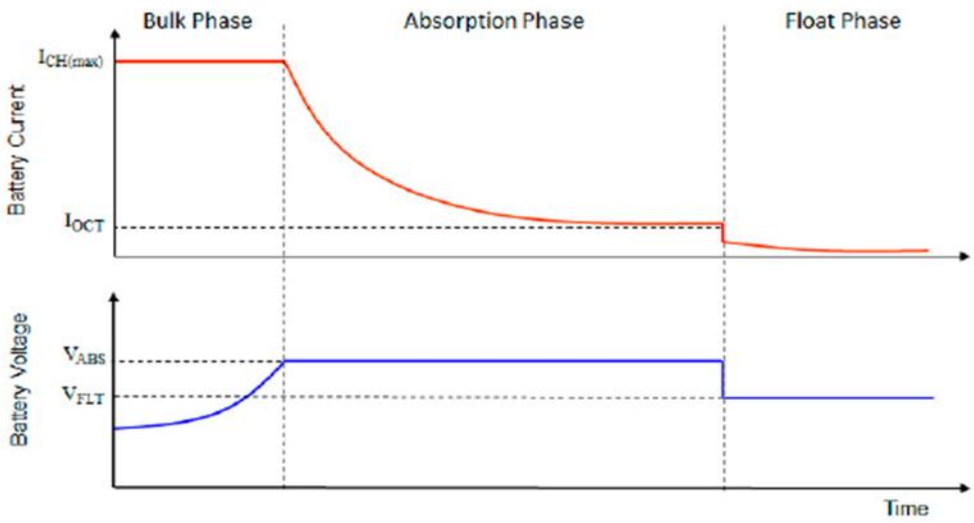


Fig 12. Battery charging characteristic

4. Results and Discussion

The performance analysis of the MPPT BCC for a standalone photovoltaic system framework was effectively carried out within the MATLAB/Simulink environment. The simulation was implemented in discrete mode . The evaluation of the model's performance is categorized into four key aspects: tracking performance of MPPT, performance of battery during charging, overall effectiveness, and a comparison against a commercial MPPT BCC. The MATLAB model utilized various parameters, which are mentioned in Table 4.

Table 4. PV, Buck converter topology and battery parameters

Parameter	Value
PV panel	250W
PV Voltage (Vmpp)	30.9V
PV Current (Impp)	8.1A
No. of panels in series connection	4
No. of panels in parallel connection	2
Total PV power connected	2 kW
PV output capacitor (C1)	1000uF
Buck converter inductance (L)	10mH
Buck output capacitor (C2)	1000uF
Switching frequency of buck converter	1000 Hz
Lead Acid Battery Voltage and Ah rating	48V, 30 Ah
Li-ion Battery Voltage and Ah rating	48V, 30 Ah

The cut-off voltage for a 48V nominal lead-acid battery is considered to be 57.6V and charged with 3A constant current or C10 rating whereas for the li-ion battery is considered to be 54.6 V and charged with 30A constant current or C1 rating during the bulk phase. These values are verified from the specifications of commercial MPPT BCCs.

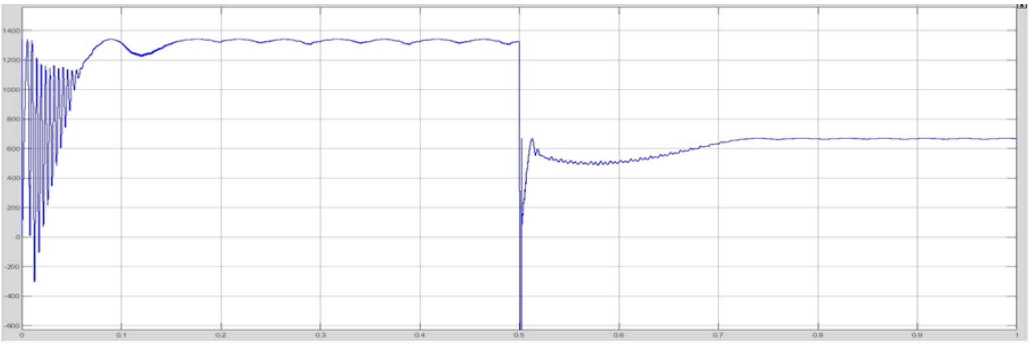


Fig 13. The output power of Fuzzy MPPT during transient irradiance

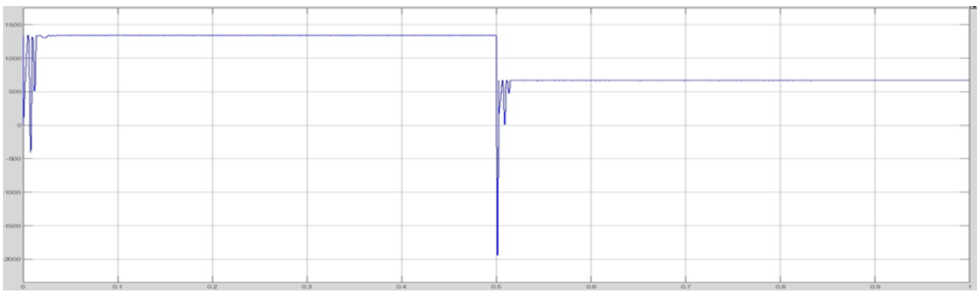


Fig 14. The output power of INC MPPT during transient irradiance

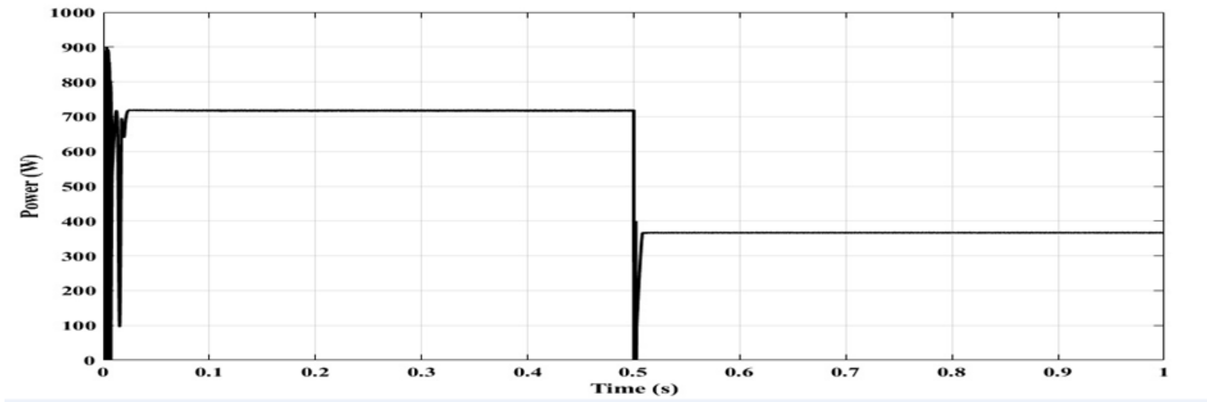


Fig 15. The output power of Fuzzy MPPT during transient irradiance

Figures 13-15 show the power output of P&O, INC and Fuzzy MPPT techniques which suggests that Fuzzy MPPT has the least oscillations during transients. Moreover, the efficiency of Fuzzy MPPT is maximum as tabulated in Table 5

Table 5. Efficiency of MPPT Charge Controllers

Method	Charge Controller Efficiency
P&O	98.1%
INC	99.2%
Fuzzy	99.7%

Table 6. Time required for charging the battery

Method	Time Taken to Charge from 0 to 100% (Hrs)
P&O for lead-acid battery	5
P&O for Li-ion battery	1.15
INC for lead-acid battery	4.48
INC for Li-ion battery	1.13
FLC for lead-acid battery	4. 35
FLC for Li-ion battery	1.10

Table 6 shows the battery charging time required for charging lead and lithium-ion batteries using MPPT techniques. A notable observation is that the Fuzzy MPPT technique exhibits the fastest charging time against the P&O and INC techniques. The Fuzzy MPPT controller demonstrates swift responsiveness when there are abrupt changes in solar irradiation levels, allowing it to efficiently track the MPP under prevailing conditions. This is obtained by dynamically adjusting the buck converter's duty cycle, ensuring the battery receives the precise voltage and current necessary for optimal performance and seamless operation.

Table 7. Comparative analysis of SSCs

Sr. No.	SSC controller	Charging Technique	Charge Controller Efficiency (%)	Charging Time (Hr)	Implementation Complexity
1	P&O Controller (Hardware platform) [53]	Constant Current Constant Voltage	78	--	Simple
2	Proposed Controller	Three Stage	99.7	4.35 (lead- acid)	Medium

	(Fuzzy MPPT Controller)			1.10 (li-ion)	
3	P& O Controller	Three Stage	98.1	5 (lead- acid)	Simple
				1.15 (li-ion)	
4	INC Controller	Three Stage	98.2	4.48 (lead- acid)	Medium
				1.13 (li-ion)	

A comparison of SCCs with MPPT functionality is shown in Table 7. The analysis highlights the performance comparison between the suggested Fuzzy MPPT controller and the P&O SCC developed by Unal Yilmaz et al., which utilizes the Arduino Nano board. According to the results, the suggested Fuzzy MPPT controller exhibits superior performance in swiftly and effectively tracking the operating point, as compared to the P&O controller [53]. The performance evaluation considers parameters such as charging time, charge controller efficiency, and implementation complexity. The Fuzzy MPPT-based SCC demonstrates faster battery charging times compared to other SCC controllers. It is designed to charge both lead acid and lithium-ion batteries. Overall, the Fuzzy MPPT controller offers improved performance and efficiency in SCC applications.

5. Conclusion

In Simulink, a detailed circuitry simulation of a Solar PV MPPT BCC is provided. The comparative analysis of three MPPT techniques such FLC, P&O and INC, a converter topology circuit (Buck), and a three-stage BCC is all detailed in detail and is completely repeatable. The MPPT BCC can charge a lead-acid or li-ion battery of 48 V rated voltage by measuring the most possible power from the PV array and utilizing a three-stage charging technique to manage the charging. Solar battery charge controllers based on Fuzzy MPPT exhibit exceptional efficiency, reaching an impressive 99.7%. As a result, they achieve the fastest charging time, enabling the battery to charge 5-10% more quickly compared to other approaches. The future scope of this research work involves the investigation of charge controllers that utilize artificial intelligence techniques and machine learning algorithms.

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