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# Advanced Solar Charge Controller: Integrating MPPT Technology and Online Data Logging for Efficient Energy Management

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**Abstract:** The increasing significance of photovoltaic (PV) power systems stems from the fact that most renewable energy sources are clean and virtually limitless. These systems are intricately designed to harness solar energy with utmost efficiency. Maximum Power Point Tracking (MPPT) is a pivotal technique to optimize power extraction across diverse conditions. This paper introduces a solar charge controller with a PIC microcontroller that controls the circuit and generates PWM signals to regulate the DC-DC converter. An innovative facet of this system lies in integrating a Wi-Fi module for data storage, enabling the transmission of solar panel data to the cloud. Notably, this work introduces a novel approach utilizing a Fuzzy Logic Controller (FLC) for MPPT, enhancing the precision of power tracking from the solar panel. To validate the efficacy of the proposed MPPT controller employing fuzzy logic, a simulation model is simulated using MATLAB. Furthermore, the practical implementation of the entire hardware setup substantiates the feasibility and functionality of the developed system.

**Keywords:** Charge Controller; MPPT Technique; PV System and Microcontroller; Buck-Boost Converter; Fuzzy Logic; Voltage and Current Sensor; Efficient Energy Management; Online Data Logging.

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## 1. Introduction

Electricity has become an indispensable facet of daily life in the technology-driven era, with global demand steadily rising. The energy we rely on predominantly emanates from conventional and non-conventional sources. Conventional resources, like fossil fuels and oil extracted from the earth, have historically powered the world [18]. However, these processes inflict harm upon the environment's habitats and contribute to climate change by releasing greenhouse gases. As awareness of global warming and the depletion of conventional resources intensifies, there's a growing emphasis on environmentally friendly power generation [19]. This involves harnessing energy from natural resources such as the sun, wind, water, and the earth's internal heat [20]. Renewable energy resources, characterized by cleanliness, daily availability, and inexhaustibility, have become pivotal in mitigating environmental impacts [21]. The pivotal shift towards replacing non-renewable energy sources with renewables revolves around efficiently harvesting energy and delivering maximum power at minimal costs for specific loads

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[22]. The exploration and implementation of technologies that enhance the efficiency of harnessing renewable energy underscore a global commitment to a sustainable and greener future [23].

Sunlight stands out as a prominent and abundant energy source, offering a substantial amount of readily available energy globally [24]. Its key advantage lies in being a clean and eco-friendly solution, as it doesn't emit greenhouse gases, mitigating the risk of global warming and environmental degradation. Solar photovoltaic (PV) energy, harnessed from the sun, has emerged as a leading sustainable power source [25]. Despite its potential, the efficiency of PV systems remains a challenge in ongoing research efforts. PV arrays typically exhibit efficiency rates ranging from 12% to 26% in converting solar irradiance to electricity, highlighting the need for improved reliability and effectiveness [26]. To address this, adopting the maximum power point tracking (MPPT) technique in PV systems becomes crucial [27].

When a PV panel is directly connected to a load, the system's operating point often deviates from the maximum power point (MPP) found on the I-V curves [28]. The MPPT technique is employed to adjust the output voltage and current of the solar PV module, optimizing the operating point to attain maximum power. Various MPPT methods exist, but the Perturb and Observe (P&O) algorithm is the most commonly used [29]. However, it has limitations, as it may induce oscillations around the MPPT and exhibit relatively slow tracking speeds during operation [30]. Hence, ongoing research endeavours seek to refine and advance MPPT algorithms for more efficient and effective solar energy utilization [31].

The method suggested in [1] introduces an innovative, intelligent control approach for maximizing power point tracking (MPPT) in a photovoltaic system, specifically tailored to adapt to varying temperature and insolation conditions. The proposed method leverages a fuzzy logic controller implemented in a DC-DC converter device [32]. The paper outlines the various stages of designing this controller, presenting the simulation results for thorough evaluation [33]. The fuzzy logic control (FLC) approach for regulating maximum power point tracking (MPPT) in a photovoltaic (PV) system is studied in [2]. The technique utilizes fuzzy logic control to determine the magnitude of incremental current within the current command for MPPT. The outcomes of the study reveal that the proposed algorithm exhibits superior performance in terms of the convergence time of the maximum power point (MPP) when compared to the conventional Perturb and Observation (P&O) technique [34].

This research works on the comprehensive design and implementation of a solar charge controller integrating Maximum Power Point Tracking (MPPT) based on fuzzy logic control [35]. This innovative controller is engineered to deliver the desired power output efficiently under diverse weather conditions [36]. Given the remote locations of solar panel installations, a robust monitoring system becomes indispensable to ensure the proper functioning of the photovoltaic cells [37]. A data logging feature enhances this controller by uploading real-time power generation, voltage, and current data to the web, facilitating remote monitoring and performance assessment [38].

## 2. Literature Review

Cheikh et al. [1] employ fuzzy logic control for Maximum Power Point Tracking (MPPT) in renewable energy systems, addressing uncertainties and imprecise data. The study discusses the efficacy of fuzzy logic in optimizing power output from renewable sources.

Kar and Patra [2] designed and analyzed an MPPT charge controller, exploring methodologies for achieving effective maximum power point tracking. The study includes an in-depth performance analysis of the controller.

Pradhan and Panda [3] assess an MPPT controller's performance using model predictive control, specifically applied to photovoltaic systems. The study evaluates the controller's efficiency and reliability under different conditions.

Putra et al. [4] conducted a comparative analysis of solar charge controllers, specifically comparing the performance of MPPT and PWM controllers on solar panels. The paper discusses the advantages and limitations of each controller type, providing recommendations based on a comparative analysis.

Pandiarajan et al. [5] focus on the mathematical modelling of a photovoltaic module using Simulink, emphasizing its relevance in understanding the behaviour of photovoltaic modules.

Xiao et al. [6] propose a topology study of photovoltaic interfaces for maximum power point tracking. The paper explores different interface structures and their impact on power point tracking efficiency in photovoltaic systems.

Kumar and Usmam [7] concentrate on the design analysis of a DC-DC boost converter, a crucial component for voltage regulation in solar energy systems. The study includes experimental validation to confirm the converter's effectiveness.

Pongsakor et al. [8] explore the application of fuzzy logic control for MPPT in photovoltaic systems, providing a detailed analysis of the fuzzy logic control scheme and discussing its advantages in optimizing power output.

Esram and Chapman [9] compare various techniques for maximum power point tracking in photovoltaic arrays, offering a comprehensive review of existing MPPT techniques and highlighting strengths and weaknesses.

Venkateshkumar [10] investigates the application of fuzzy controllers for MPPT in photovoltaic power systems. The study discusses the design and implementation of the fuzzy controller, evaluating its real-world performance.

Kumaraswamy and Iqbal [11] discuss simulation and hardware implementation aspects of an MPPT charge controller in photovoltaic systems, providing insights into challenges and solutions encountered in practical implementation.

Sahraei et al. [12] focus on developing a persistent and adaptive power system for solar-powered sensors in Internet of Things (IoT) applications, discussing unique challenges in providing power to IoT devices using solar energy.

Ramya [13] presents a case study on energy conservation, likely discussing specific strategies or technologies employed to conserve energy.

Yap et al. [14] offer a comprehensive review of artificial intelligence-based MPPT techniques for solar power systems, discussing various AI methods and their applications in optimizing solar power systems.

Lakshmi and Sindhu [15] propose an artificial neural network-based MPPT algorithm for solar PV systems, detailing the architecture and assessing its performance compared to traditional MPPT methods.

The insights derived from an extensive review of literature on Maximum Power Point Tracking (MPPT) methodologies in solar energy systems, with references to studies such as Cheikh et al. [1], Kar and Patra [2], Pradhan and Panda [3], Putra et al. [4], Pandiarajan et al. [5], Xiao et al. [6], Kumar and Usmam [7], Pongsakor et al. [8], Esram and Chapman [9], Venkateshkumar [10], Kumaraswamy and Iqbal [11], Sahraei et al. [12], Ramya [13], Yap et al. [14], and Lakshmi and Sindhu [15], form a robust foundation for our research paper. This comprehensive exploration covers diverse control strategies, charge controller analyses, and critical component studies, providing a thorough understanding of contemporary research in the field. The identified gap in the absence of a standardized comparative framework for diverse MPPT techniques is a key research focus, emphasizing the need for further investigation, potentially through a meta-analysis or systematic review. This knowledge contributes significantly to our research endeavours, guiding future advancements and facilitating the development of a unified evaluative paradigm in solar energy systems [39].

In the realm of solar energy systems, a series of studies have significantly advanced our understanding and optimization of Maximum Power Point Tracking (MPPT) [40]. However, a conspicuous void in the existing body of knowledge is the absence of a unified approach or standardized methodology for systematically comparing and evaluating diverse MPPT techniques [41]. The prevailing trend in most studies tends to focus on specific dimensions, presenting an opportunity for prospective research to undertake a more exhaustive and comparative analysis [42]. This analysis should encompass critical factors such as efficiency, adaptability to diverse conditions, and real-world applicability. A meta-analysis or systematic review, synthesizing insights from multiple studies, holds the potential to pinpoint the most effective and versatile MPPT strategies tailored to various solar energy scenarios.

**3. Methodology**

The functional block diagram of the proposed work is shown in Figure 1.

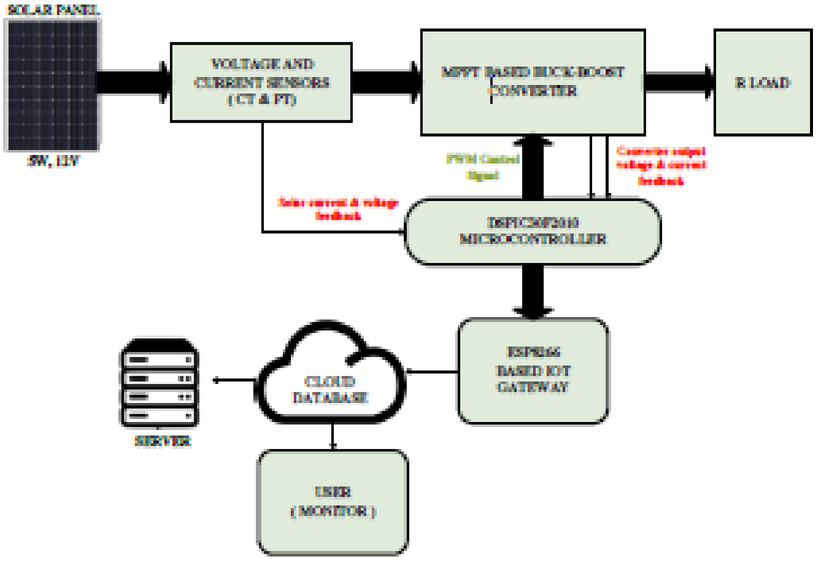


**Figure. 1:** Functional block diagram of the proposed MPPT – SCC

Figure 2 illustrates the block diagram of the proposed solar charge controller, comprising a PV panel, a DC-DC converter, and an R-load. The PV panel exhibits nonlinear I-V characteristics, potentially varying with time in response to sudden changes in irradiance. The primary objective of this paper is to regulate the voltage of the solar panel to ensure optimal operation at its maximum power point. Drawing insights from the comprehensive literature survey of the existing works [3] – [7], comparing various Maximum Power Point Tracking (MPPT) techniques, it is noted that a fuzzy logic-based system offers continuous power tracking with minimal fluctuations and faster tracking times when compared to traditional MPPT methods. Therefore, this paper proposes and implements a fuzzy logic controller to effectively track the maximum power point in the photovoltaic system. The proposed system is subjected to simulation using MATLAB/Simulink.

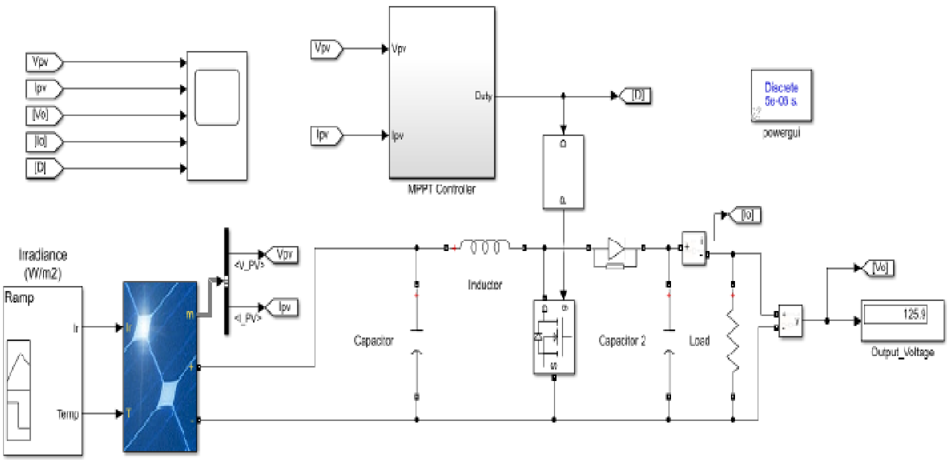


**Figure 2:** Simulation circuit of the proposed MPPT Solar Charge Controller

### 3.1. Solar PV Array Characteristics

The Photovoltaic (PV) cell transforms solar energy from the sun into Direct Current (DC). Individual PV panels are interconnected in series and parallel configurations to achieve the desired power output, creating a Solar PV array. The I-V curve is a graphical representation of the solar panels' performance, illustrating the dynamic relationship between voltage and current under prevailing irradiance and temperature conditions [8]. Figure 3 showcases the equivalent circuit of the solar cell.

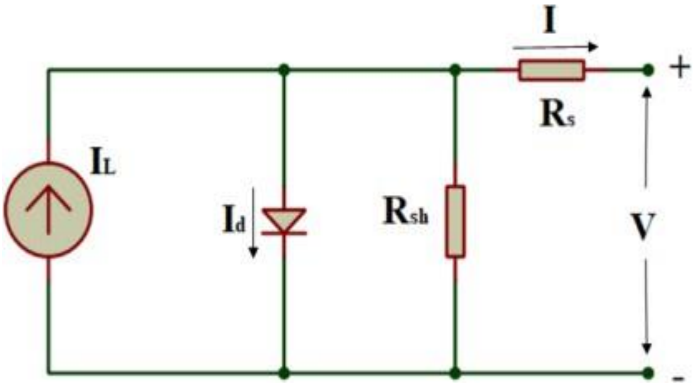


**Figure 3:** Equivalent Circuit of Solar cell

Also, the I-V curve gives information on operating the solar panel at its optimal peak power point. The I- V characteristics of the diode in the PV module is given by

$$Id=I0[\exp(Vd/\ VT)-1] \quad (1)$$

$$VT=(\ kT\ /\ q\ )\times nI\ \times Nc \quad (2)$$

Where,

| | | |
|---|---|---|
| Id | - | Diode Current (A) |
| Vd | - | Diode voltage (V) |
| Io | - | Diode saturation current (A) |
| nI | - | Diode ideality factor, a number close to 1.0 |
| k | - | Constant = 1.3806e-23 J.K-1 |
| q | - | Electron charge = 1.6022e-19 C |
| T | - | Cell temperature (K) |
| Nc | - | Number of cells connected in series in a module |

This paper uses a 215W solar array built of parallel modules, with each string consisting of modules connected in series. Table 1 gives the electrical specifications of 1Soltech 1STH-215-P Solar Panel. Figure 4 shows the I-V characteristics at different irradiances (1000 W/m2, 800 W/m2, 600 W/m2) at a specific temperature of 25ºC.

**Table 1:** Electrical Specifications of 1Soltech 1STH-215-P Solar Panel

| **Module Specifications** | **Rating** |
|---|---|
| Maximum Power (W) | 215W |
| Open circuit voltage Voc (V) | 36.3V |
| Voltage at maximum power point Vmp (V) | 29V |
| Short-circuit current Isc (A) | 7.84A |
| Current at maximum power point Imp (A) | 7.35A |
| Parallel strings | 2 |
| Series-connected modules per string | 2 |

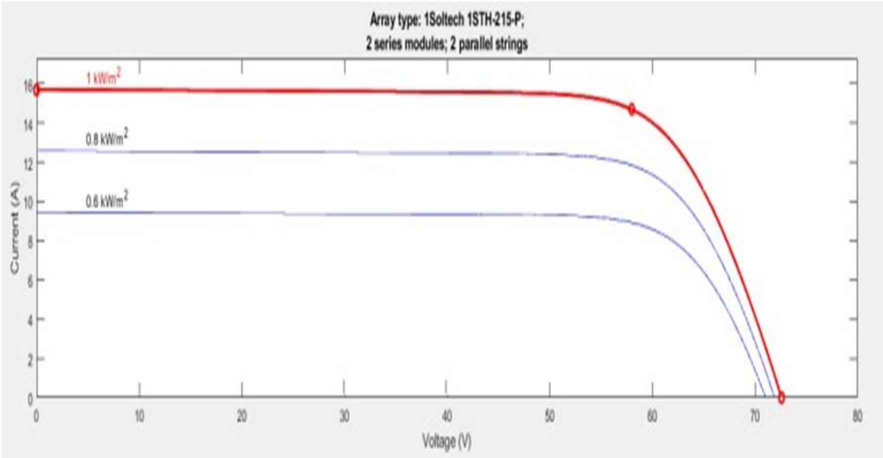


**Figure 4:** I-V curves of the panel at different values of irradiance

### 3.2. DC-DC Converter

Maximum power transfer from a PV module to the load relies on a DC-DC converter. It serves as a crucial intermediary component in the design of the MPPT system [9]. Essentially, the DC-DC converter bridges the connection between the load and the PV module. Various types of DC-DC converters exist, with major types including buck, boost, and buck-boost converters. This paper specifically implements a Buck-Boost converter, a combination of buck and boost converters. The unique functionality of a Buck-Boost converter allows for the adjustment of voltage levels, facilitating both step-up and step-down operations as needed for optimal power transfer in the context of a PV system (Figure 5).

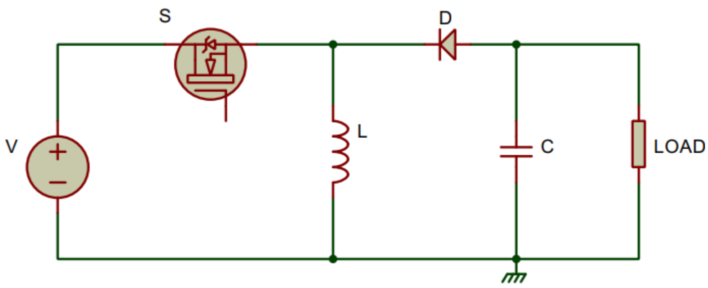


**Figure 5:** Buck-Boost Converter Circuit

The input voltage of a buck-boost converter is contingent upon the duty ratio, which is defined as the ratio of the input voltage to the output voltage. In the boost mode of operation, the output voltage is elevated, surpassing the input voltage. Conversely, in the buck mode, the output voltage consistently remains lower than the input voltage [10].

Certain parameters must be well-understood for the effective design of a buck-boost converter. These parameters include:

- Input voltage
- Output voltage
- Switching frequency
- Forward voltage drop of the rectifier diode
- Inductor current ripple

Design

Output Current, $$Io = \frac{P}{Vo} \quad (3)$$

Current Ripple, $$\Delta I = 0.05 \times Io \times \frac{Vo}{Vin} \quad (4)$$

Voltage Ripple, $$\Delta V = 0.01 \times Vo \quad (5)$$

Inductance, $$L = \frac{Vin\ (Vo - Vin)}{\Delta I \times fs \times Vo} \quad (6)$$

Capacitor, $$C = \frac{Io(Vo - Vin)}{fs \times \Delta Vo \times Vo} \quad (7)$$

### 3.3. Maximum Power Point Tracking

MPPT mostly depends on the amount of sunlight falling on the solar panel, its temperature, and the electrical characteristics of the load.

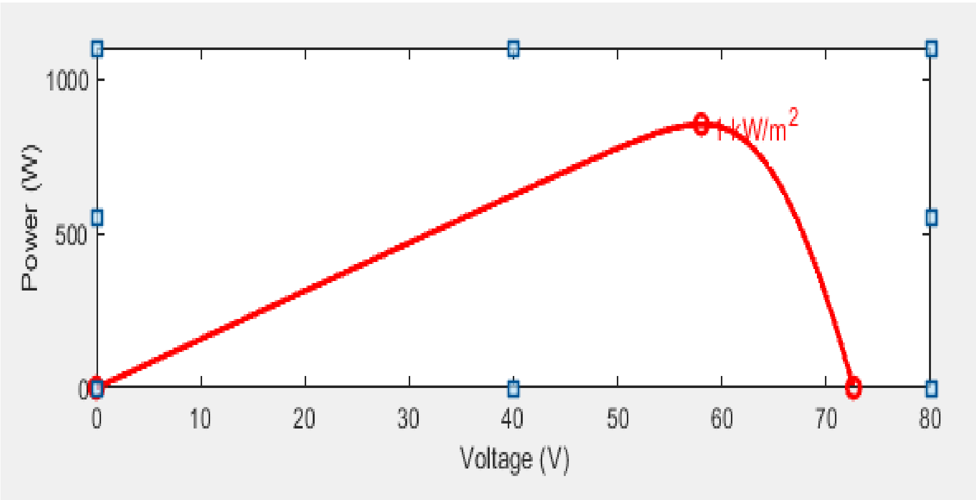


**Figure 6:** P-V Characteristics

Figure 6 illustrates the maximum power point under 1000W/m2 irradiance conditions. An MPPT, functioning as a DC-DC converter, is pivotal in aligning the grid and solar panel match. The fuzzy logic algorithm is employed here to adjust these matches dynamically. The duty cycle is instrumental in governing the DC-DC converter, and any alteration in the duty cycle triggers a corresponding change in the output voltage [11]. In response to variations in panel current, the voltage undergoes adjustments, such as an increase in voltage with a decrease in current and vice versa. Elevating the duty cycle results in an increase in current within the solar panel. Various techniques exist for MPPT implementation, and this paper specifically opts for the fuzzy logic technique.

### 4. Fuzzy Logic Technique

This paper uses a photovoltaic system with an MPPT system based on fuzzy logic. Fuzzy logic, extensively employed in various industrial processes, operates by selecting and validating rules that integrate user inputs with desired outputs. This methodology significantly contributes to achieving the maximum power point of the PV system more efficiently, with reduced overshoot and minimized voltage fluctuation following the recognition of the Maximum Power Point (MPP), compared to alternative techniques.

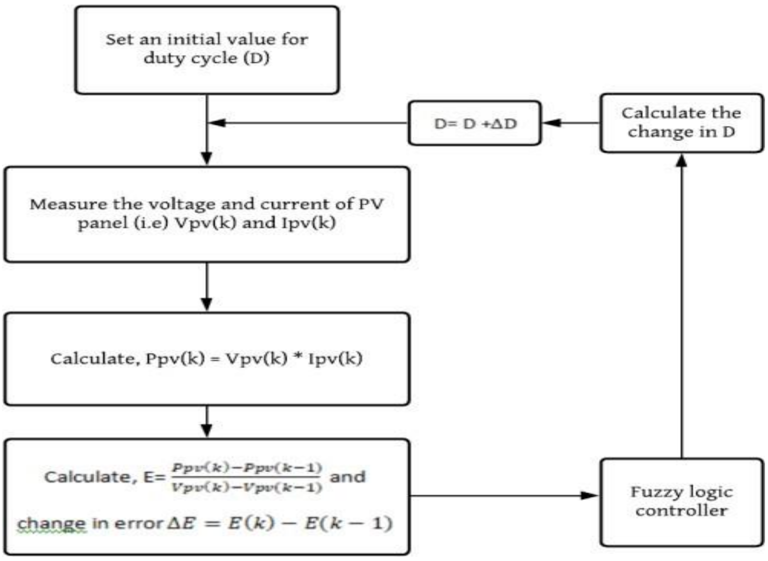


**Figure 7:** Flowchart of fuzzy logic technique

The effectiveness and design of the fuzzy controller depend on the input and output selected for the system. The output of the fuzzy controller is the duty cycle for the MOSFET switch of the Buck-Boost converter. Here, the fuzzy system uses the change in PV power output ($\Delta P$PV) and variations of voltage ($\Delta V$PV) as the input variables [12]. Figure 7 shows the flowchart of the fuzzy logic controller. Figure 8 exhibits the fuzzy logic controller for the MPPT design.

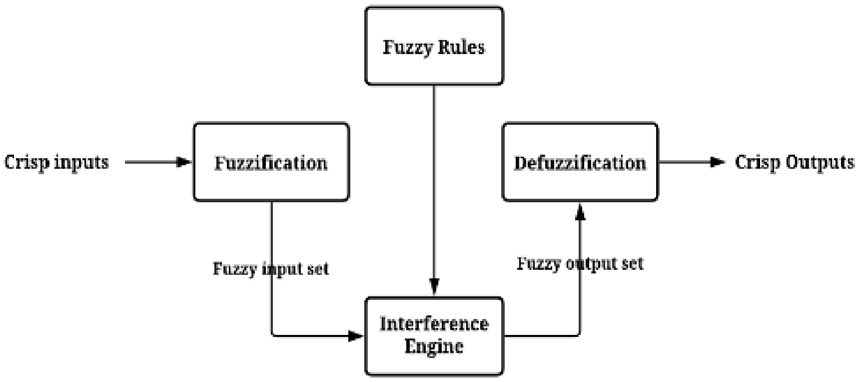


**Figure 8:** Fuzzy logic controller for the MPPT design

Figure 8 shows the main parts of the fuzzy controller, such as fuzzification, fuzzy rules, interference engine and defuzzification.

### 4.1. Fuzzification

In the proposed system, the input variables are expressed in linguistic terms, encompassing five fuzzy subsets identified as NB (Negative Big), NS (Negative Small), ZE (Zero), PS (Positive Small), and PB (Positive Big). Figures 9 to 11 show the membership functions of the relevant input and output variables.

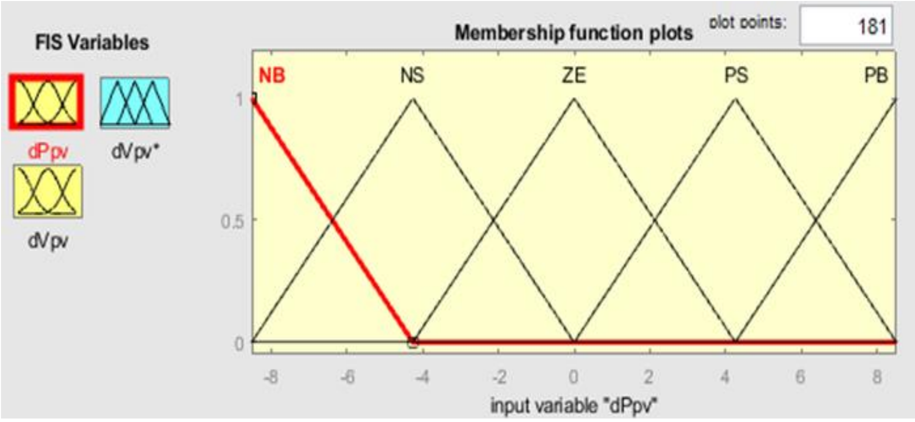


**Figure 9:** Membership function of the first input variable (Δ*P*PV)

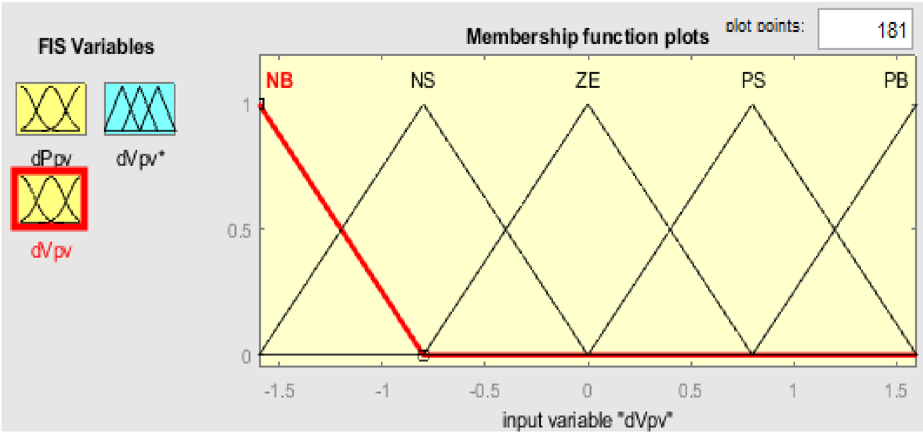


**Figure 10:** Membership function of the second input variable (Δ*V*PV)

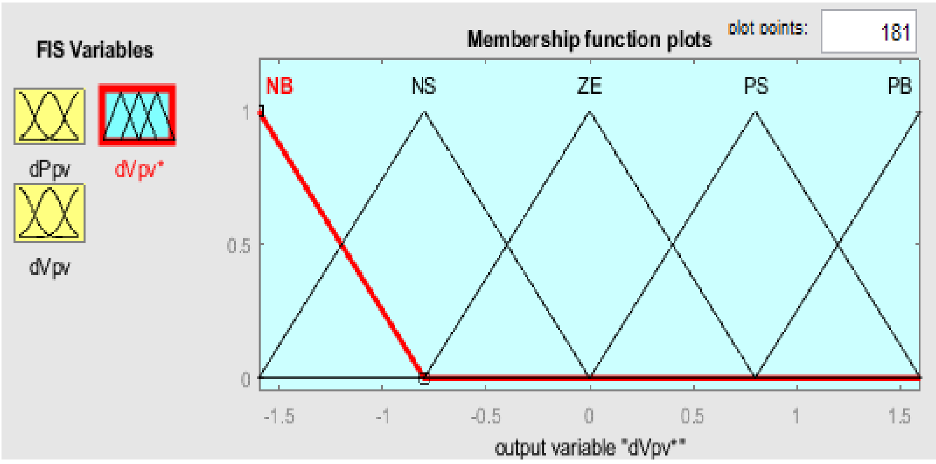


**Figure 11:** Membership function for duty cycle ratio

### 4.2. Interference Engine

The algorithm employed in the system gathers a set of fuzzy rules, which are derived through the analysis of system behaviour. Fuzzy interference is conducted using Mamdani's method with the min-max composition. The inference system is delineated into three key components: rule base, database, and reasoning mechanism. The rule base comprises if-then rules governing the Fuzzy LogicController's (FLC) proper operation. Linguistic variables, obtained after the fuzzification of input variables, are utilized by the controller to execute these rules. The interference system processes the given rules, delivering the required result based on this analysis. Figure 8 illustrates the desired relationship between input and output variables. Table 2 exhibits the fuzzy logic rules for the proposed algorithm.

### 4.3. Defuzzification

In the defuzzification process, the input is a fuzzy quantity transformed into a crisp quantity suitable for application in the system. This paper employs the centroid method for the defuzzification process. Figure 12 showcases the simulation of the fuzzy controller.

**Table 2:** Fuzzy Logic Rules for Algorithm

| * ($\Delta V_{PV}^*$) (o/p) | ($\Delta V_{PV}$) 2nd (i/p) | | | | | |
|---|---|---|---|---|---|---|
| ($\Delta P_{PV}$) 1st (i/p) | Fuzzy Rules | NB | NS | ZE | PB | PS |
| | NB | PS | PB | NB | NS | NB |
| | NS | PS | PS | NS | NS | NS |
| | ZE | ZE | ZE | ZE | ZE | ZE |
| | PB | NS | NB | PB | PS | PB |
| | PS | NS | NS | PS | PS | PS |

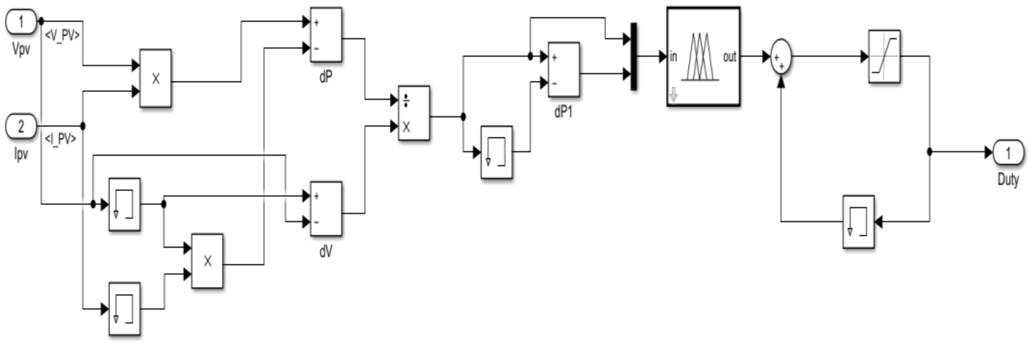


**Figure 12:** Simulation of Fuzzy Controller

The algorithm is explained as follows: initially, the duty cycle is set to D = 0 for the tracking process. Subsequently, the voltage and current inputs for the converter are measured, and the optimal duty cycle, conducive to achieving the maximum power output, is determined based on the anticipated values provided to the fuzzy system. This iterative operation continues, adjusting for variations in current and voltage until the maximum power point is attained.

### 5. Simulation and Results

The complete system is integrated and simulated using MATLAB/Simulink software, as depicted in Figure 2. The performance of the fuzzy logic controller is thoroughly analyzed under diverse irradiance and weather conditions (temperature) (Figures 13 to 16).

**Case 1:** At various irradiances (1000W/m$^2$, 600W/m$^2$) and constant temperature (25$^o$C)

(i) At 1000W/m$^2$, 25$^o$C

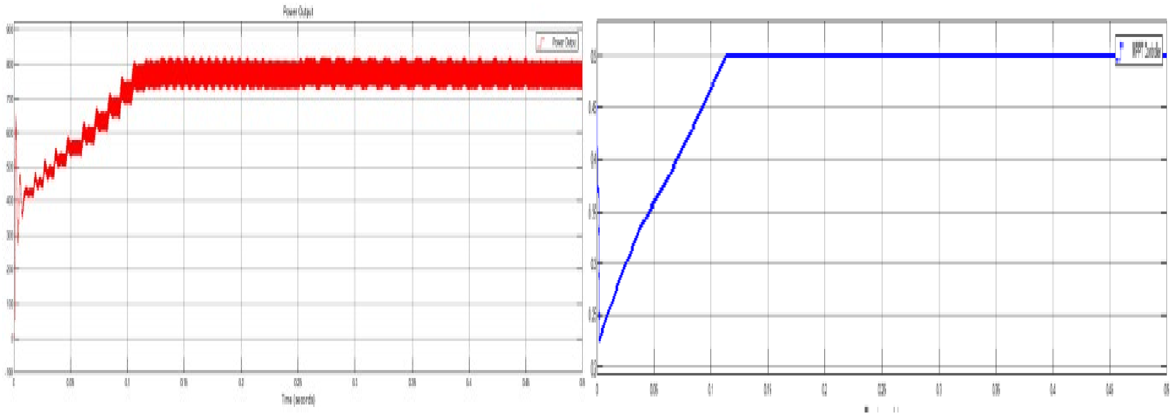

**Figure 13:** Converter power output and duty cycle at 1000W/m$^2$, 25$^o$C

(ii) At 600W/m$^2$, 25$^o$C

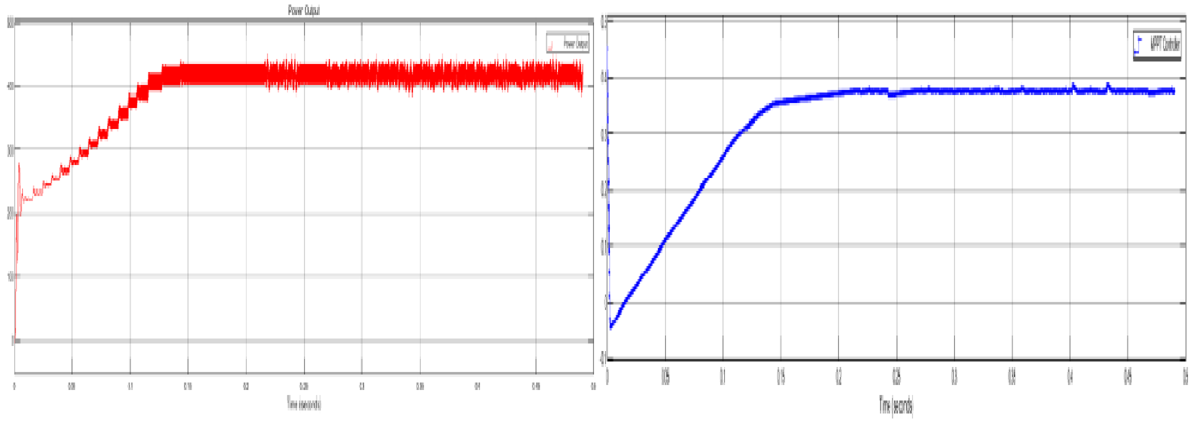

**Figure 14:** Converter power output and duty cycle at 600W/m$^2$, 25$^o$C

**Case 2:** At various temperatures (20$^o$C, 35$^o$C) and constant irradiance (1000W/m$^2$)

(i) At 1000W/m$^2$, 20$^o$C

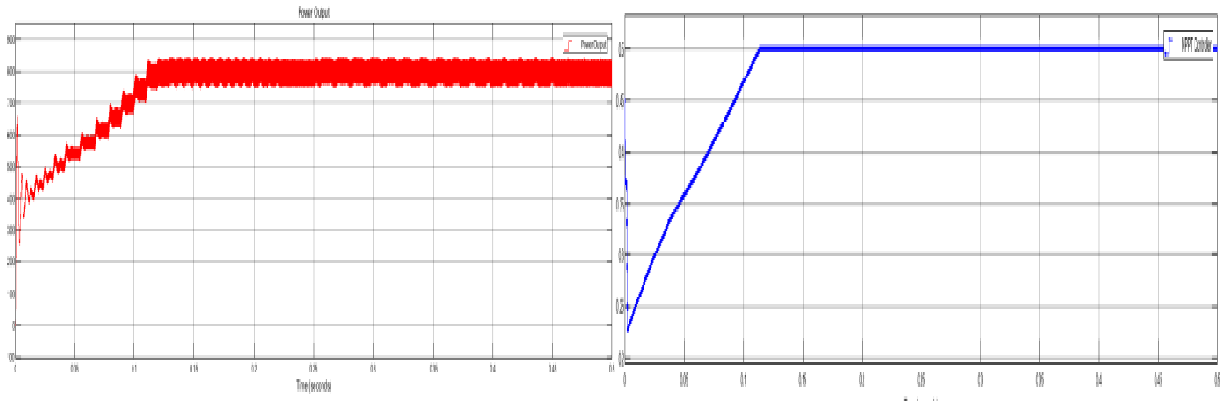

**Figure 15:** Converter power output and duty cycle at 1000W/m$^2$, 20$^o$C

(ii) At 1000W/m$^2$, 35$^o$C

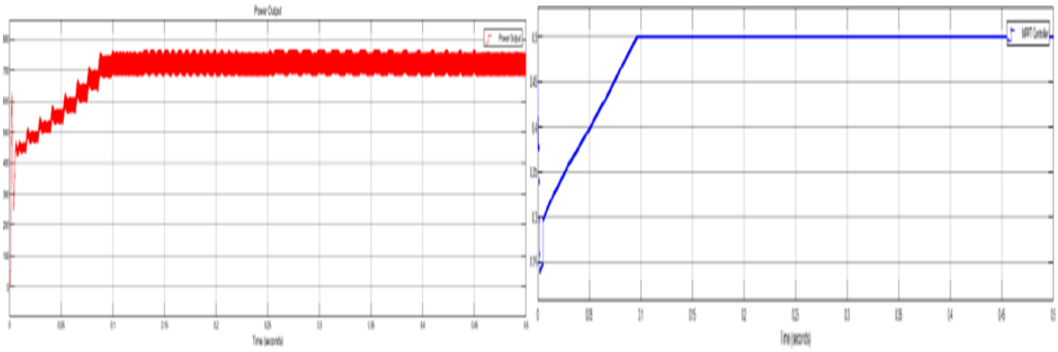

**Figure 16:** Converter power output and duty cycle at 1000W/m$^2$, 35$^o$C

### 5.1. Hardware Implementation

A downscaled laboratory prototype is constructed, utilizing a 5W solar panel as the input source [14]-[17]. The proposed controller is implemented on the dsPIC30F2010 microcontroller to generate Pulse Width Modulation (PWM) signals that regulate the Buck-Boost Converter. Voltage and current sensors, employing Current Transformers (CT) and Potential Transformers (PT), are incorporated to measure the solar panel's voltage and current. The microcontroller and driver circuit are powered through a 230/12V AC step-down transformer. To facilitate remote monitoring, an ESP8266 gateway is integrated into the hardware. This gateway collects information on output voltage, current, and power from the converter circuit. The collected data is then displayed on a monitor, enabling users to monitor the charge controller remotely [13]. The hardware setup is shown in Figure 17.

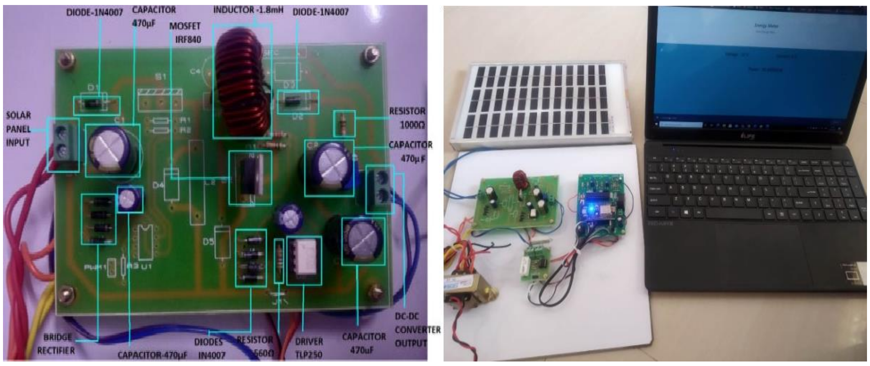


**Figure 17:** Hardware Kit

## 6. Conclusion

In order to improve both power and efficiency, this research aims to examine the integration of a photovoltaic (PV) system with a fuzzy logic controller. Simulations of the proposed system are performed with MATLAB, and the results are studied under various irradiances and weather conditions. Based on the data, it appears that fuzzy logic is an extremely efficient method for monitoring and optimizing the output of the system in a variety of different settings. This controller's rule base is straightforward, contributing to increased computing performance and demonstrating the controller's usefulness. In addition, a prototype of the system that is being suggested is built and developed, and it includes a feature that allows for online data logging. In a genuine photovoltaic (PV) system, it is predicted that the suggested controller will produce favourable results, particularly with the assistance of a digital signal processor. This concept can be adapted to other renewable energy resources as well.

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**Ethics and Consent Statement:** The consent has been obtained from the colleges during data collection and has received ethical approval and participant consent

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