Study and simulation of Intelligent and Conventional MPPT Algorithms for Hybrid System

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ABSTRACT Renewable Energy Resources (RES) research has expanded dramatically over the last decade as a result of constraints on conventional energy sources such as high power costs, environmental pollution, and increased maintenance requirements. Renewable alternatives—such as solar, wind, hydro, fuel cells, and biomass—provide clean, sustainable, and widely available options, with solar and wind being particularly numerous. This article analyzes the viability of a hybrid renewable power generating system that combines solar energy, a fuel-based system, and a battery backup. Since solar energy generation changes with weather conditions, the hybrid arrangement improves system dependability and efficiency under different environmental circumstances. To improve performance, a P&O maximum power point tracking (MPPT) controller is used. By adaptively altering the duty cycle of the input module, the controller allows the system to continually function at its maximum power point. Simulation findings show that the suggested fuzzy method improves efficiency and operational stability, emphasizing its value as a sustainable power-generating solution.

INDEX –TERMS- PV Emulator, fuel, battery, Aurdino, fuzzy, P&O,.

1. INTRODUCTION

The extraordinary increase in global energy consumption has made it imperative to develop sustainable, clean, and efficient alternatives to traditional fossil fuel-based power generation. Conventional power sources are not only depleting but also considerably contributing to greenhouse gas emissions, rising electricity bills, and environmental deterioration. Renewable Energy Sources (RES), such as solar, wind, hydro, fuel cells, and biomass, have emerged as key options to meet future energy demands [1], [2]. Renewable energy is expected to account for more than half of global power generation by 2035 [3]. Despite this bright prognosis, obstacles remain since renewable resources, particularly solar and wind, are inherently intermittent and unpredictable, making consistent power generation and system integration problematic [4-5]. Among the diverse range of renewable technologies, photovoltaic (PV) systems have received a lot of attention due to their scalability, adaptability, low installation costs, and continual developments in semiconductor materials [6, 7]. However, the nonlinear current-voltage (I-V) characteristics of PV arrays cause output power changes in response to irradiance and temperature conditions [8], [9]. This makes it difficult to collect the greatest amount of power from PV systems. To address this constraint, Maximum Power Point Tracking (MPPT) approaches are commonly used [10], [11]. Conventional MPPT algorithms, such as Perturb and Observe (P&O) and Incremental Conductance (IC), have been extensively utilized because of their simplicity of implementation and low processing needs [12], [13]. These approaches disturb the PV array's operating point in order to determine the maximum power point (MPP). However, they have limitations such as steady-state oscillations around the MPP, decreased efficiency during rapid irradiance fluctuations, and delayed convergence under dynamic weather circumstances [14], [15]. Such constraints impede their capacity to provide maximum performance, particularly in real-time applications. To solve these limitations, improved MPPT algorithms have been developed employing artificial intelligence (AI) and soft computing methodologies [16], [17]. These techniques include learning, adaptability, and intelligent decision-making capabilities, enabling controllers to deal with the nonlinearities and uncertainties inherent in PV systems. Fuzzy Logic Control (FLC) is a popular AI-based controller because it replicates human reasoning using linguistic variables and membership functions [18], [19], and [20]. FLC does not require a perfect mathematical model of the PV system, making it ideal for real-time MPPT applications with changing weather conditions. Fuzzy-based MPPT algorithms have shown quicker convergence, increased robustness, and better tracking efficiency than traditional methods [21], [22]. Furthermore, hybrid techniques that mix classic methods like P&O and fuzzy logic control combine the simplicity of traditional algorithms with the adaptability of intelligent systems. These hybrid MPPT controllers successfully minimize oscillations, enhance dynamic responsiveness, and provide increased stability [23], [24], [25]. Aside from standalone PV systems, hybrid renewable energy systems that combine solar PV with fuel cells and battery storage units are rapidly being investigated [26–27]. Such hybrid arrangements provide a continuous power supply by combining the complementary qualities of several energy sources, improving system dependability and efficiency. In this scenario, the integration of sophisticated MPPT controllers becomes even more important in order to maximize power production and maintain steady operation. As a result, this study looks at the design and performance of a hybrid PV-fuel cell system with MPPT, with a particular emphasis on the comparison of traditional P&O and fuzzy logic methodologies. The study intends to emphasize the benefits of fuzzy logic control in enhancing convergence speed, stability, and overall tracking efficiency for hybrid renewable energy systems. A hybrid fuel–solar electric system generally requires a higher initial investment compared to a single large-scale system. However, both fuel cell (FC) and solar photovoltaic (PV) technologies become relatively more cost-effective when deployed as part of a hybrid configuration rather than as two smaller independent systems. The proposed hybrid system integrates PV, FC, and battery storage units. During daytime, the PV system harnesses abundantly available solar energy, while at night the fuel cell serves as a backup power source, ensuring a continuous supply of electricity, as illustrated in Fig. 1 Hybrid power generation systems, which combine multiple energy sources, significantly improve the ability to meet load demands consistently. They also provide higher generation capacities compared to stand-alone systems. Importantly, such hybrid arrangements deliver stable and fluctuation-free outputs, regardless of weather conditions or solar variability.

This study presents a comprehensive analysis and design of a hybrid energy system with an intelligent controller to provide continuous power delivery despite the intermittent nature of PV, fuel cell, and DC sources. The suggested technique improves efficiency, continuity, dependability, and overall system performance.

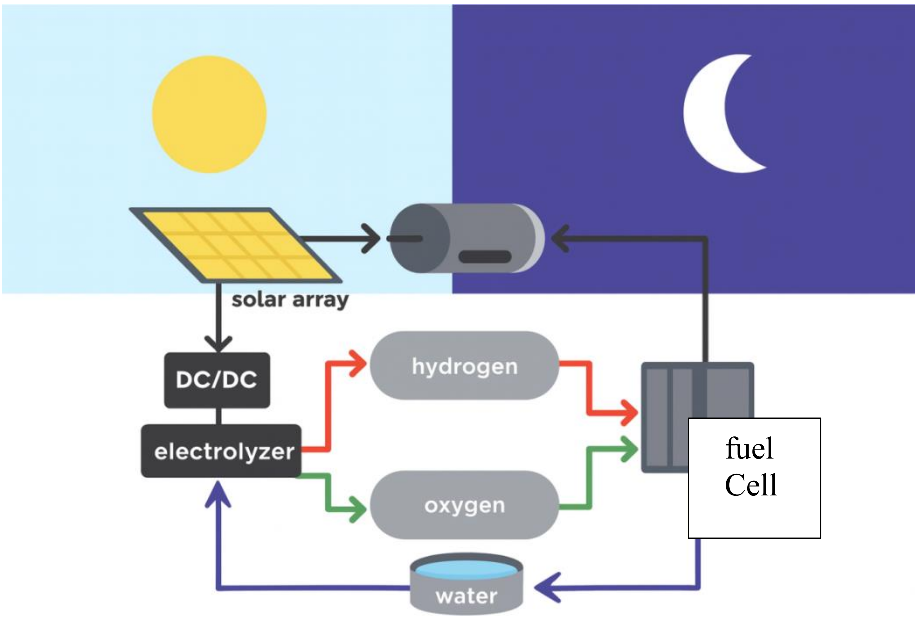

Figure.1 Solar –Fuel –battery (Hybrid) system

1.1 (PV-Battery –Fuel) Hybrid

In this work, a solar PV system is employed as the primary energy source, while a fuel cell is integrated to form a hybrid configuration and also serve as a backup, since solar energy is not continuously available. In addition, a battery unit is included as an auxiliary backup source. The system is connected to voltage and current sensing modules for real-time measurement, and the measured signals are supplied to both the relay and the Arduino controller.

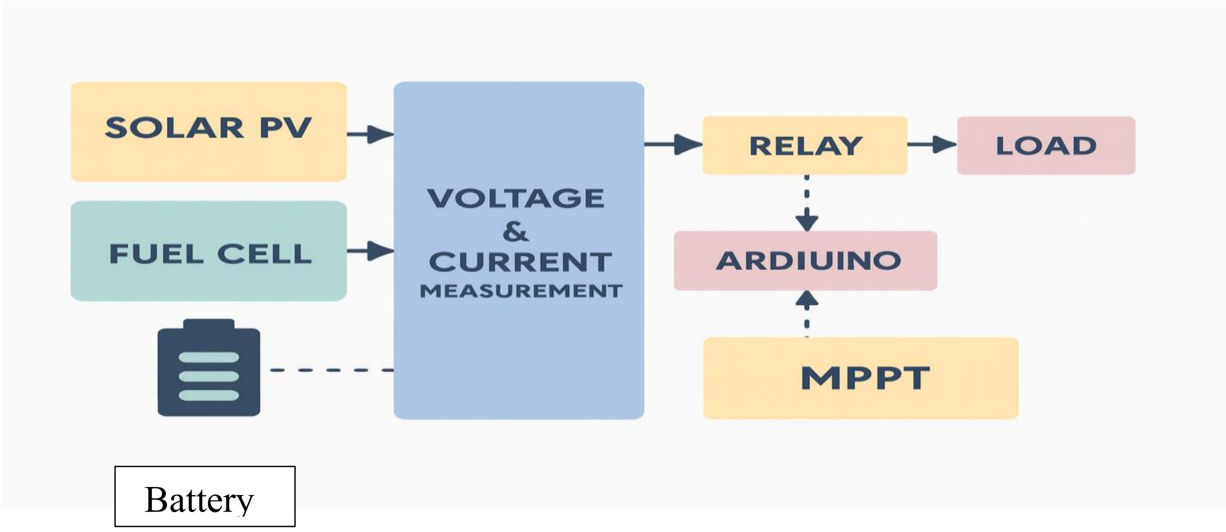

Figure.2 Hybrid (Block Diagram)

The relay output is then linked to a boost converter, which provides power to the load. The Arduino controls the switching function of the boost converter to guarantee maximum power transmission. For maximum power point tracking (MPPT), the Perturb and Observe (P&O) algorithm is used, and its performance is compared to that of a Fuzzy Logic Controller. This comparative analysis focuses on the efficiency gains realized by the hybrid system architecture above Figure-2 depicts the overall system architecture and modeling, which includes each subsystem and is discussed in depth in the parts that follow.

1.1.1 Photovoltaic Emulator

A photovoltaic (PV) emulator is a programmable power supply that simulates the behavior of solar panels under various operating situations. The emulator's rapid transient response allows it to adapt quickly to load changes while preserving output along the I-V characteristics of the chosen solar panel, as seen in Fig. 3. This adaptability allows it to replicate solar panels from various manufacturers as well as differences induced by time of day, seasonal impacts, and geographical location of installation. The PV Emulator uses an internal algorithm to modify the open-circuit voltage (VOC) and short-circuit current (ISC) to match the properties of the chosen panel under specific environmental variables such as temperature and solar irradiation. Predicting the precise reaction of a PV system is difficult since its power output is determined by a number of dynamic and interconnected elements. The emulator tackles this issue by taking into account real-time weather conditions, time of year, sun position, panel orientation, and unique panel technology in order to precisely simulate predicted panel output. In addition, the emulator is capable of storing up to twenty-five I–V curves in its memory, with programmable time intervals as short as one hour. This feature allows it to simulate a complete day's I–V characteristics for PV inverter testing, as well as dynamic I–V curve transient testing.

Figure.3 Emulator (solar) (Image from NITTTR lab)

Major attributes of PV Emulator include:

- Four channels, each rated for 0–50 V at 8 A.
- Simultaneous and independent operation of multiple channels.
- Ability to configure channels in series or parallel.
- Fast transient response for accurate solar panel simulation.
- Built-in profiles for standalone operation without requiring a computer or internet connection.
- Free cloud-based application software for control and detailed monitoring of simulations.
- Manual control capability to define custom I–V curves for user-specific solar panel conditions.

1.1.2 Fuel Emulator

Due to their low emissions and great power density, fuel cells are regarded as one of the most promising sustainable and renewable energy sources. They may be used as clean energy solutions for a variety of applications, such as residential structures, transportation systems, and portable electronics. However, a number of auxiliary parts are needed for actual fuel cell systems, including humidification systems, temperature control, pressure regulation mechanisms, and oxidant (air/oxygen) and fuel (hydrogen) supply units. The cost of the fuel cell stack, the cost of pure hydrogen, and the membrane's lifespan—which is dependent on the number of operating hours—all have an impact on the fuel cells' economic feasibility.

Figure.4 Emulator (Fuel) (Image from NITTTR lab)

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The following key terminologies are associated with fuel cell operation:

PEM Fuel Cell: An apparatus that electrochemically transforms hydrogen and oxygen

In to electricity and water is called a proton exchange membrane (PEM) fuel cell.

- **Reactants:** Materials that initiate a chemical reaction. In the case of fuel cells, the reactants are hydrogen and oxygen, which generate electricity during the process.
- **Humidification:** Refers to the moisture level required for the proper functioning of the fuel cell system.
- **Blower:** Provides air supply to the fuel cells while simultaneously helping to regulate and reduce stack temperature.
- **Mass Flow per Minute:** Indicates the total hydrogen flow rate through the fuel cell stack.
- **HFCT:** Horizon Fuel Cell Technologies, a well-known developer of commercial fuel cell systems.

1.1.3 Battery

Batteries work by using electrochemical discharge processes to transform chemical energy into electrical energy. One or more cells make up a battery, and each cell has four necessary parts: an electrolyte, a separator, a positive electrode, and a negative electrode.
Primary cells and secondary cells are the two general groups into which cells fall. After their reactants run out, primary cells must be replaced since they are not rechargeable. Secondary cells, on the other hand, are rechargeable and need a DC charging source in order to fully charge their reactants. Carbon-zinc (Leclanché or dry cell), alkaline-manganese, mercury, zinc, silver-zinc, and other lithium-based cells, including lithium-thionyl chloride, lithium-sulfur dioxide, and lithium-manganese dioxide, are common examples of primary cells. Conversely, secondary cells comprise lithium-ion, nickel-cadmium, nickel-iron, nickel-hydrogen, nickel-metal hydride, silver-zinc, nickel-cadmium, and lead-lead dioxide (lead-acid) batteries.

Figure.5 Battery (Image from Internet)

1.2 Perturb &Observe

One of the most popular MPPT strategies is the Perturb and Observe (P&O) algorithm because of its simplicity and convenience of usage. This technique involves varying the operating voltage while measuring the solar panel's voltage and current. The power acquired at the prior operating point is then contrasted with the comparable power. The subsequent disturbance will proceed in the same direction if the power at the new voltage is higher than the preceding value. If not, the direction of disruption is inverted.

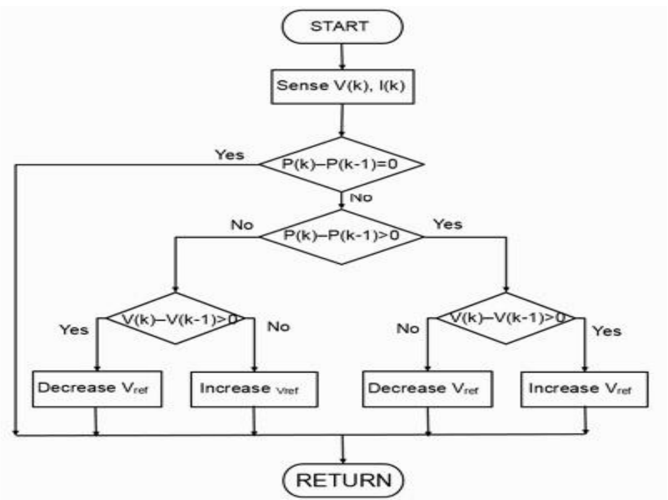


Figure.6 Algorithm (P&O)

1.3 **Fuzzy Logic Method**

An artificial intelligence-based technique called the Fuzzy Logic Controller (FLC) is used to maximize a solar panel's power output, increasing the system's overall efficiency. As shown in Fig. 7, the algorithm runs in three primary stages: fuzzification, rule evaluation, and defuzzification.

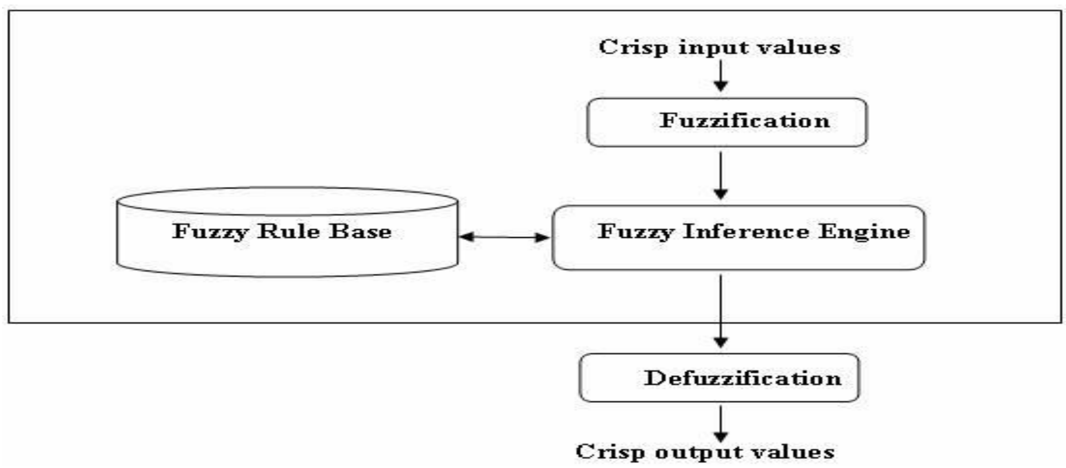


Figure.7 Steps of fuzzy logic

In recent years, fuzzy logic-based Maximum Power Point Tracking (MPPT) techniques have gained significant attention in the field of solar energy systems. The concept of fuzzy logic is inspired by linguistic reasoning and human behavioral patterns, and it does not require complicated mathematical computations. During the fuzzification process, the numerical input variables are transformed into fuzzy inputs using appropriate membership functions. Usually, error (E) and change of error (dE) are the input variables taken into account. The fuzzy technique's logical layout and several kinds of input and output membership functions are depicted in Figures 8, 9, and 10, respectively. Negative large (nl), negative medium (nmd), negative small (nsm), zero (zee), positive small (psm), positive medium (pmd), and positive large (pla) are the membership functions that are used.

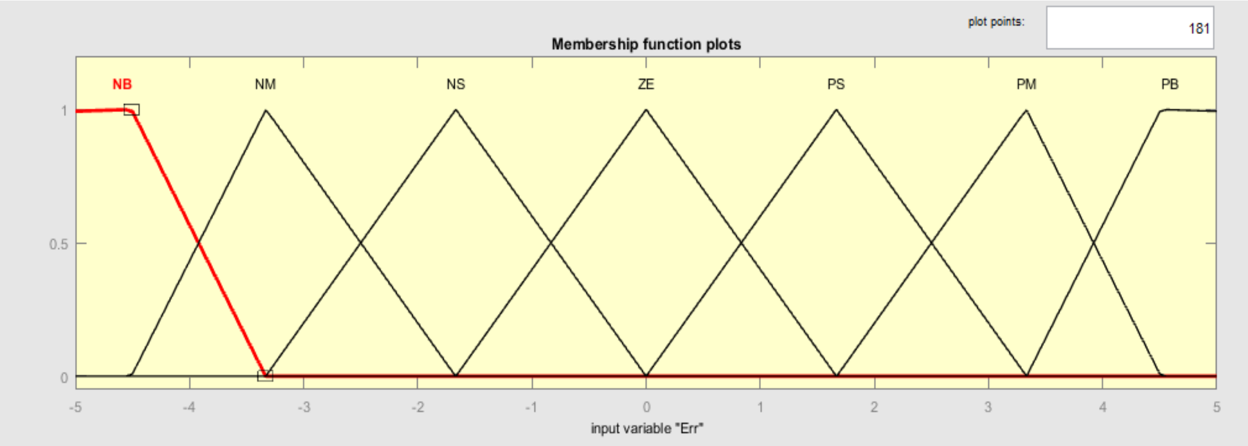


Figure 8. Memebership function of input variables 1

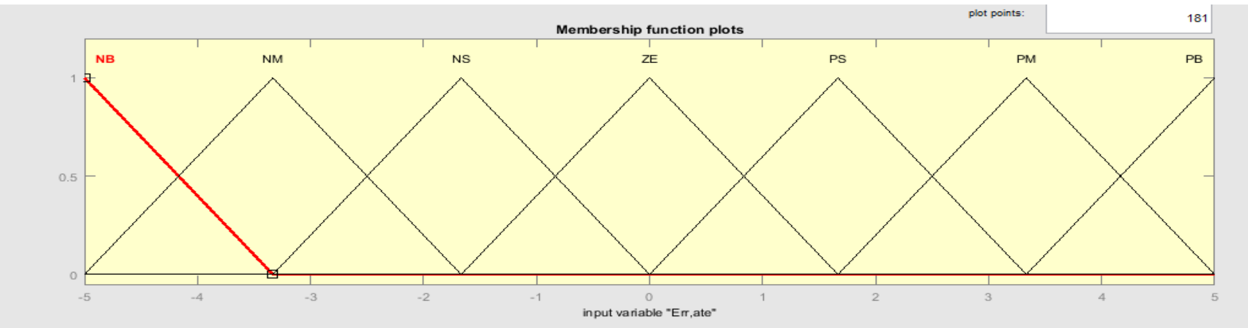


Figure 9. Memebership function of input variables2

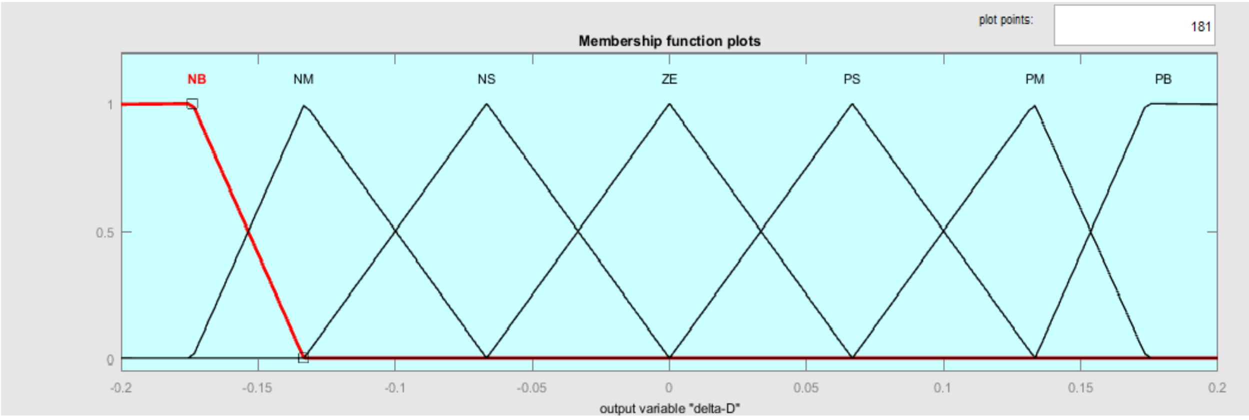
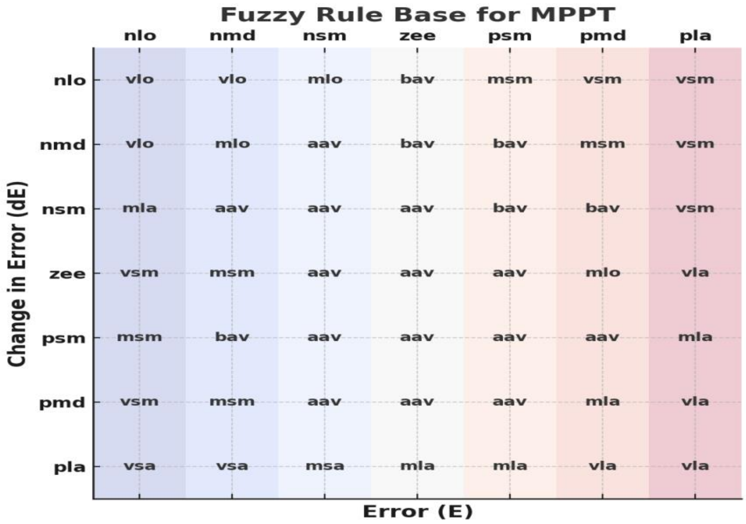


Figure 10. Membership function of output variables



1.3 Experimental Setup

In the hybrid system depicted in Figure 2, a solar emulator is included in the hybrid arrangement. Several solar cells coupled in parallel or series make up a PV module. While the parallel connection is in charge of boosting the current, the series connection is in charge of raising the module's voltage.

In this study, an input of 80 V DC is used by connecting two channels of 40 V each in series. This 80 V DC supply is then provided to the relay, as illustrated in Fig. 11 and Fig. 12

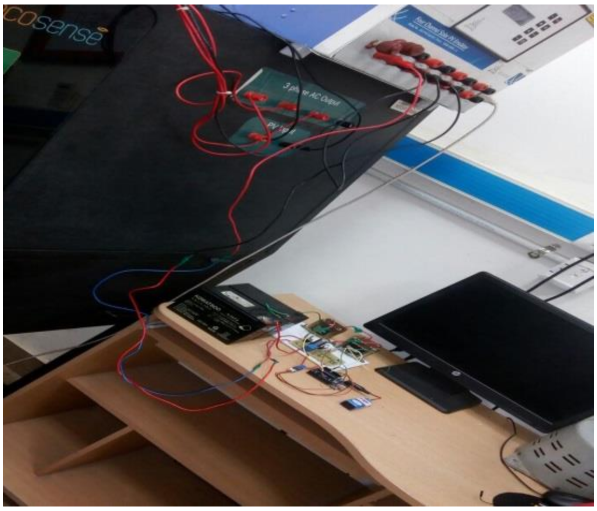


Figure.11 Experimental Setup Image (1)

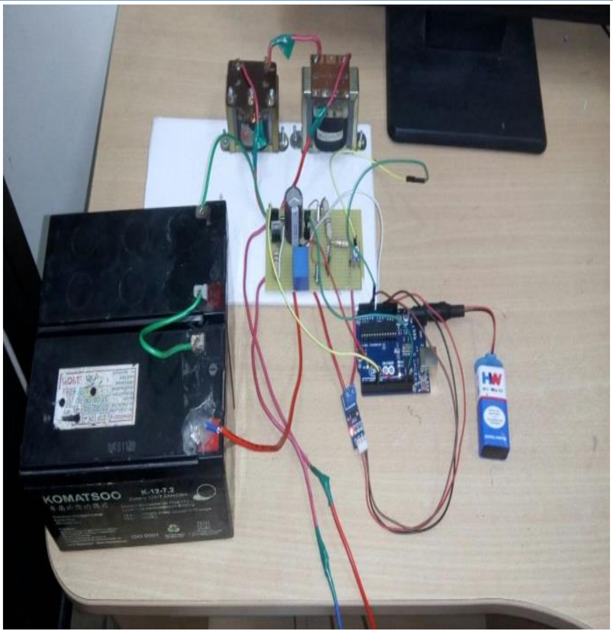


Figure.12 Experimental Setup Image (2)

1.3.1 Experimental setup of Boost (dc-dc step up converter)

A DC load receives the 120 V output DC voltage that the boost converter is intended to generate. The Pulse Width Modulation (PWM) approach is used to regulate the MOSFET's switching function in the converter. Additionally, as shown in Fig. 9, an Arduino microcontroller is used to implement the PWM generation and control.

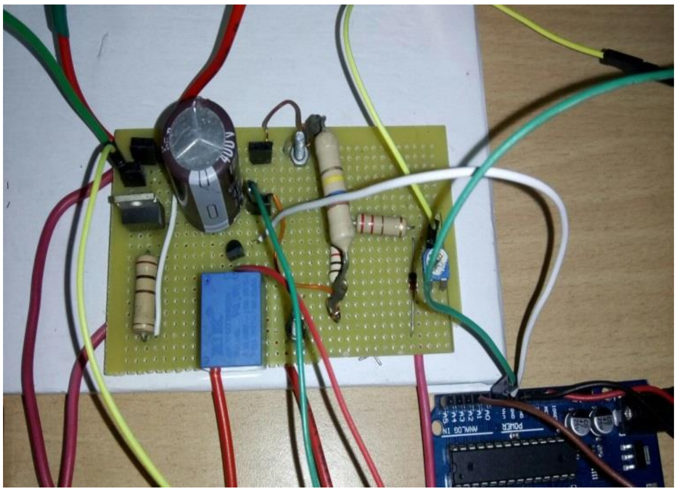


Figure.13 Experimental Setup Image (3)

Table 1: Parameters of the Boost Converter

Element	**Value**
Resistance (R)	100 Ω
Inductor (L)	1 H

Element	Value
Capacitor (C)	120 µF
MOSFET	IR740
Input Voltage	80 V DC(Approx.)
Diode	IN4007

2 Experimental Result & Simulation Result

PV emulator source is used, in which directly DC supply is given to the boost converter and then to the load and graph is obtained without MPPT as shown in fig 11. When the system starts, initially the voltage is zero and the value of voltage increases the power is also increases and current decreases at last the voltage is increase up to 80V and the power is maximum at 60V.

The efficiency of Boost converter is 59%

Case-1 (PV-Alone)

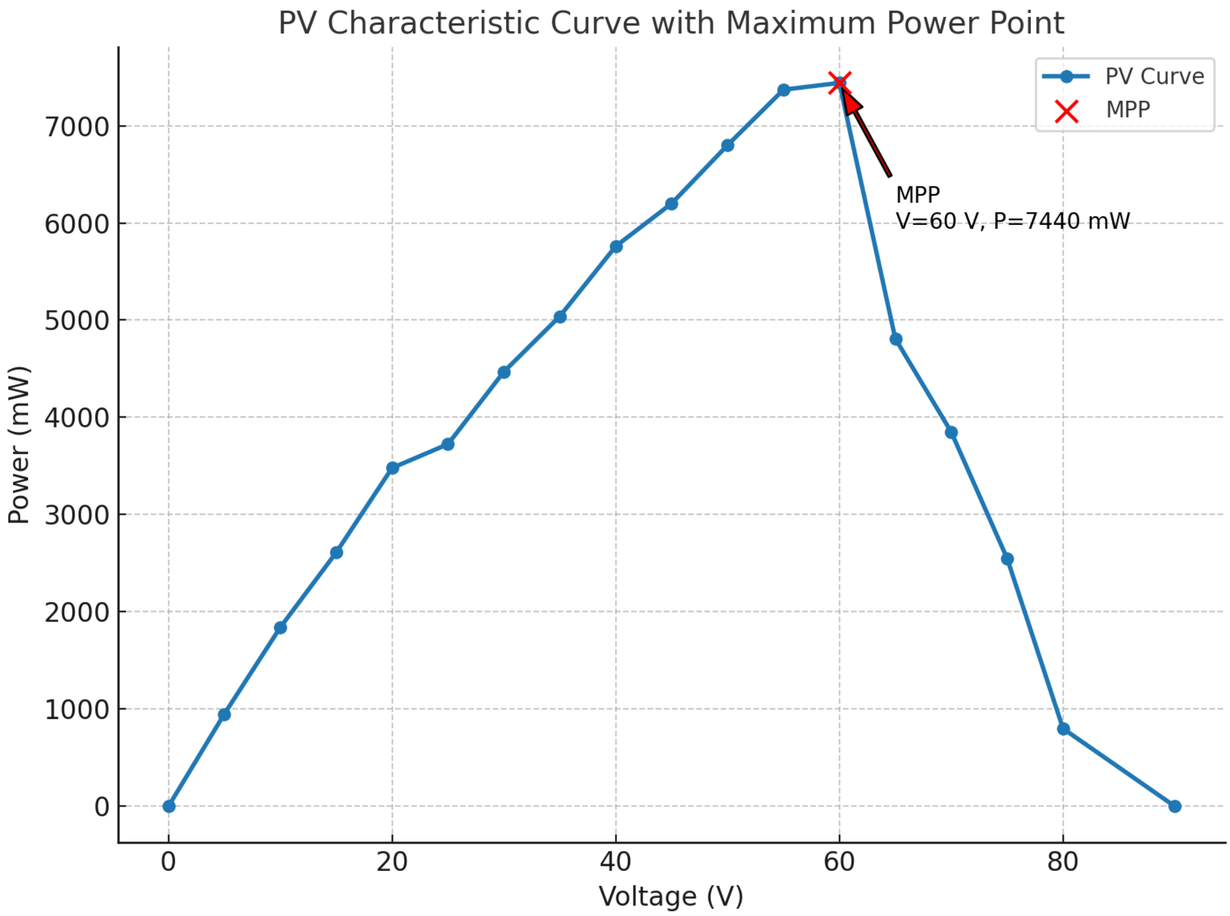


Figure.14 PV Alone

Case-2 PV Alone (Using MPPT)

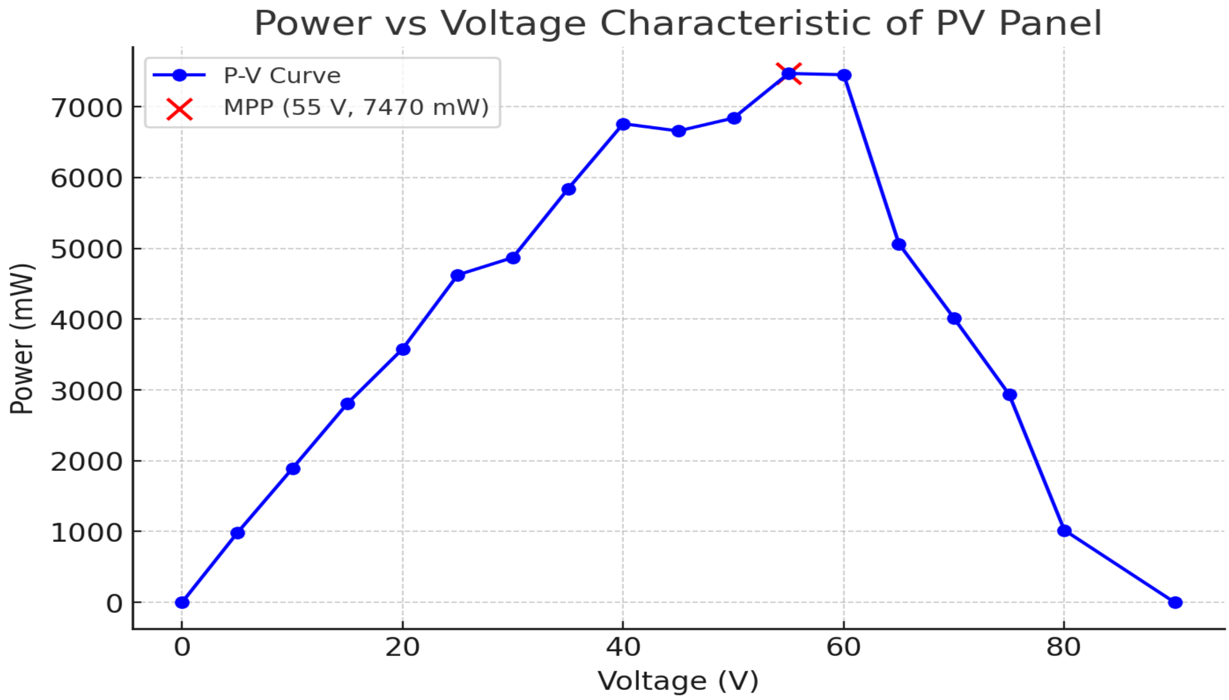


Figure.15 PV characteristics of solar with MPPT

Case-3 Fuel Cell

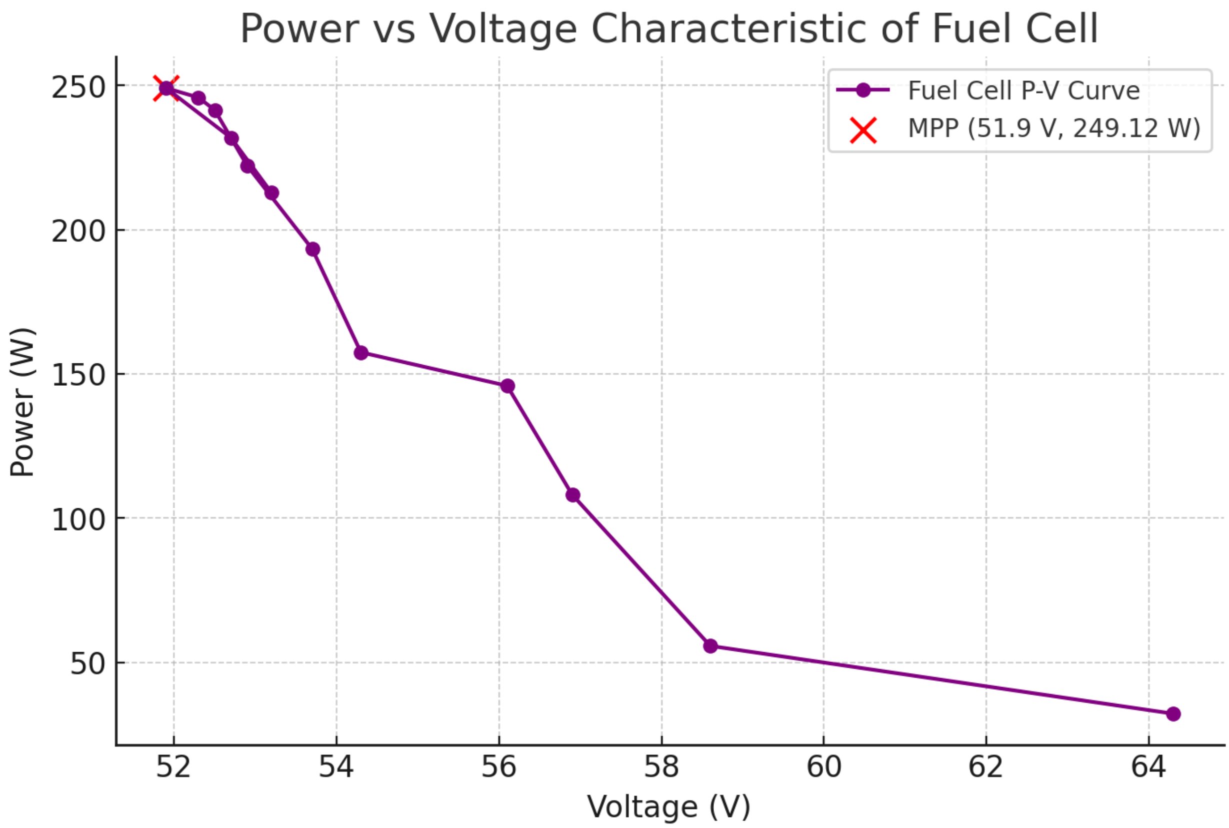


Figure.16 PV characteristics of fuel cell

Simulation Result

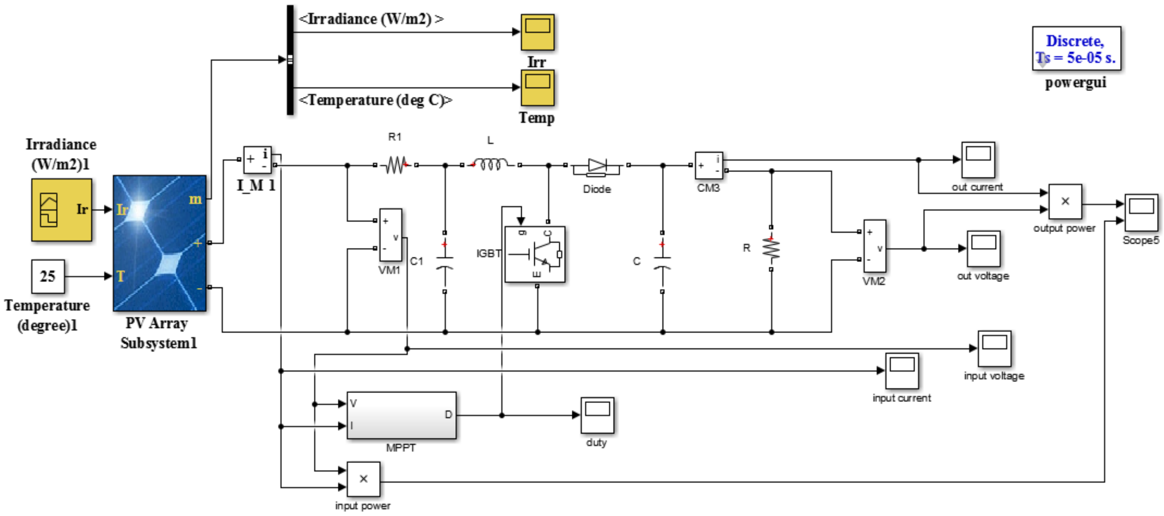


Figure17. Simulink Model of solar using Perturb and Observe technique

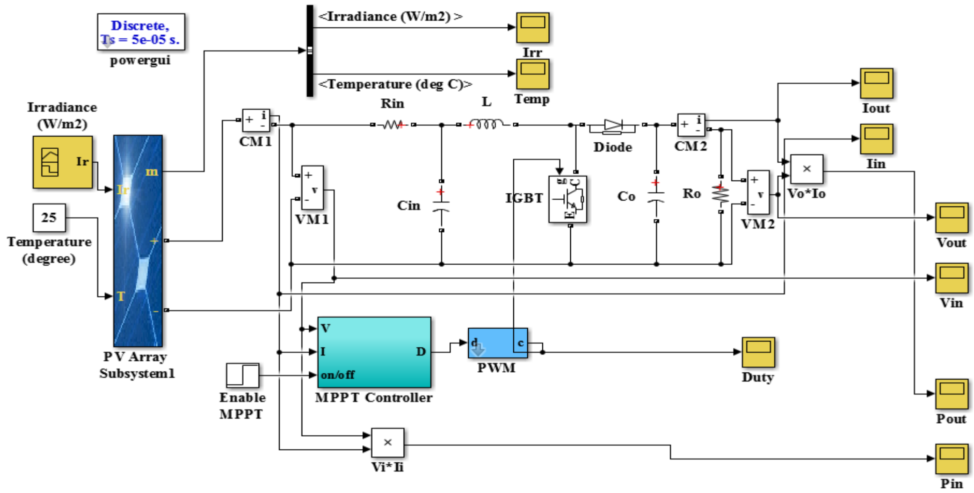


Fig18. Simulink model of Solar PV with fuzzy logic control technique.

The Fig 19, shows the irradiance pattern with constant temperature 25^0 C which is taken as fixed in simulation.

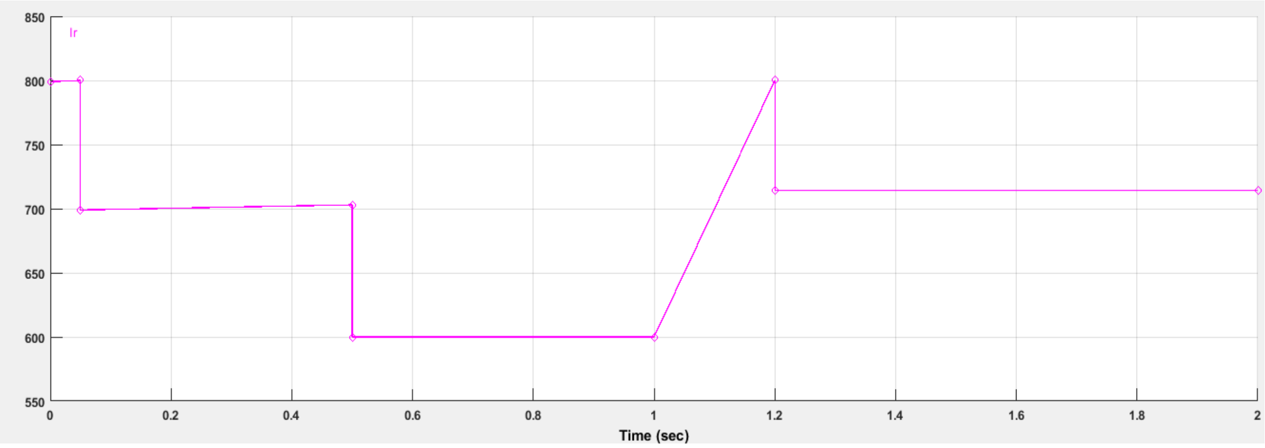


Figure 19. irradiation pattern

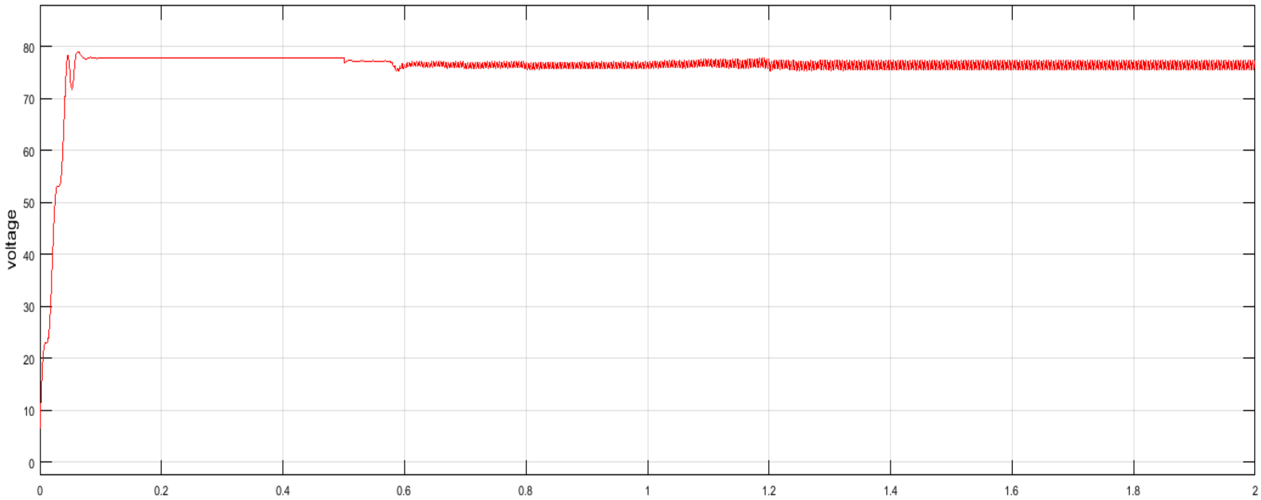


Figure. 20 Output Voltage without MPPT

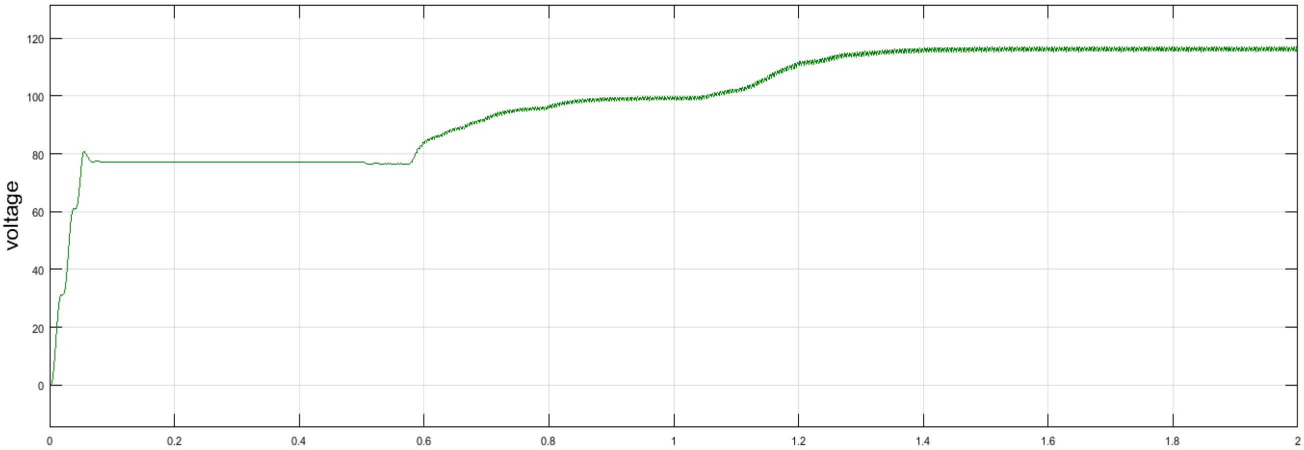
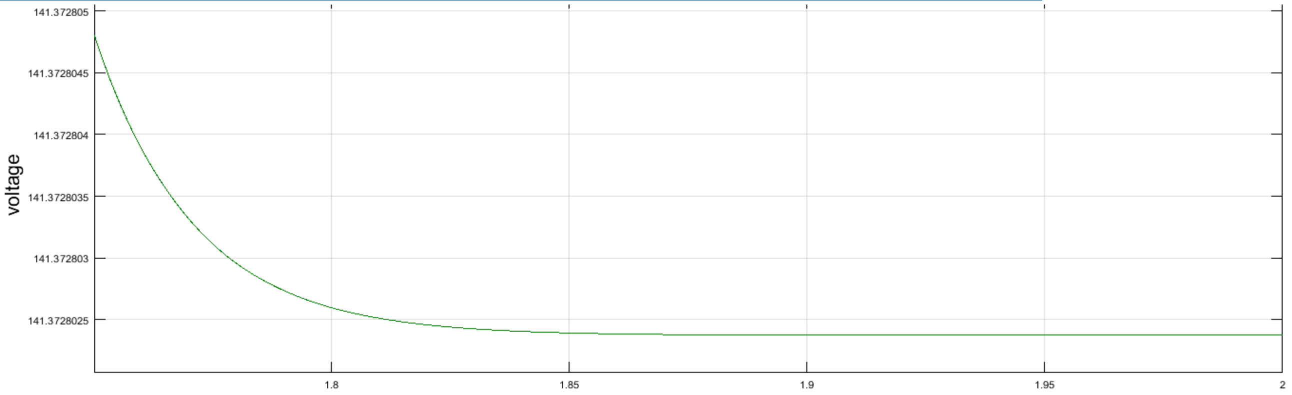
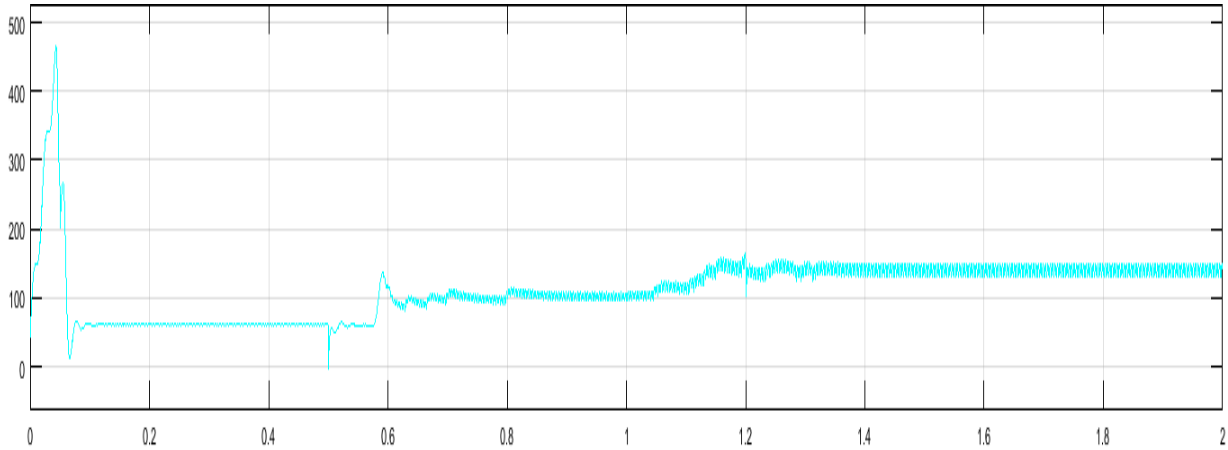


Figure 21 Output Voltage with P&O MPPT



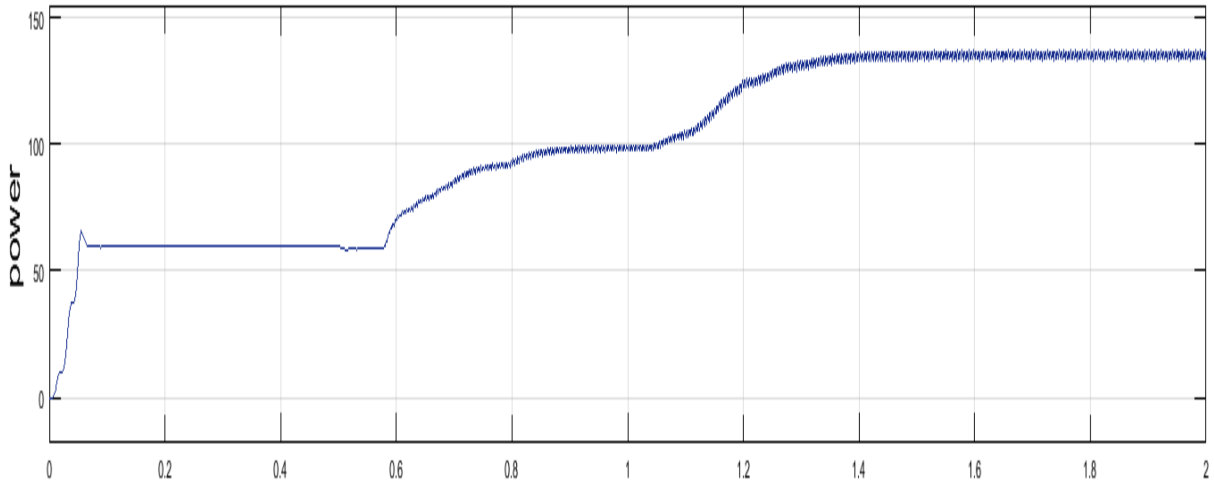
time

Figure. 22 Output Voltage with Fuzzy MPPT



time

Figure 23 Power without P&O MPPT



time

Figure 24 Power P&O MPPT

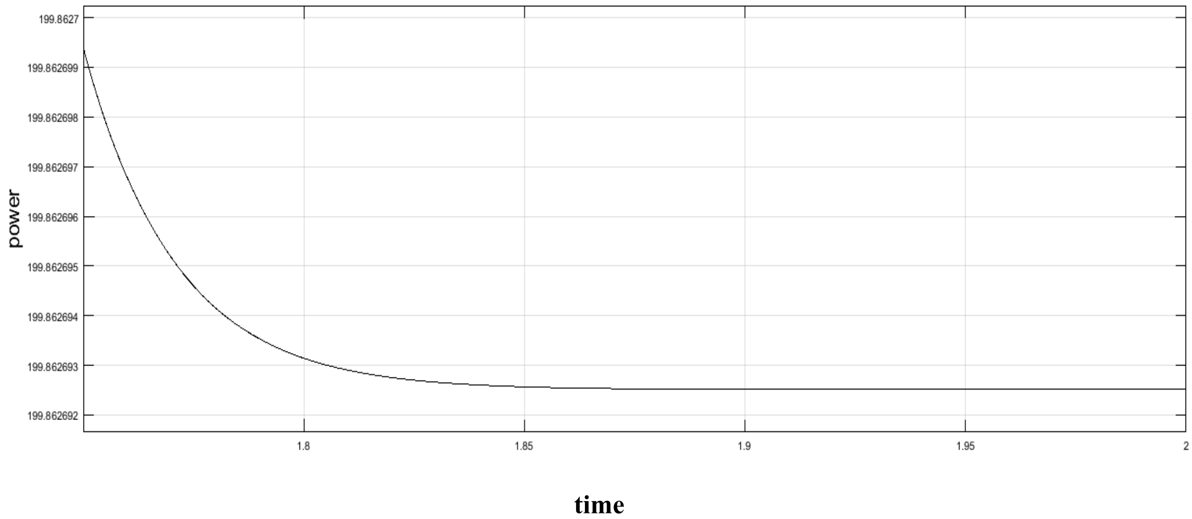


Figure 25 Power with Fuzzy MPPT

MATLAB 2016 software was used to construct and simulate the suggested photovoltaic (PV) model. The irradiance fluctuation and associated output voltages under three distinct conditions—without MPPT control, with Perturb and Observe (P&O) MPPT, and with fuzzy logic-based MPPT—are shown in Figures 19–25. The output voltage was found to be around 80 V in the simulated scenario without MPPT. The output voltage rose to about 120 V when the P&O MPPT approach was used. Moreover, the output voltage increased dramatically to 141 V after fuzzy logic MPPT was used. Tables 6–8 present a thorough comparative examination of these findings.

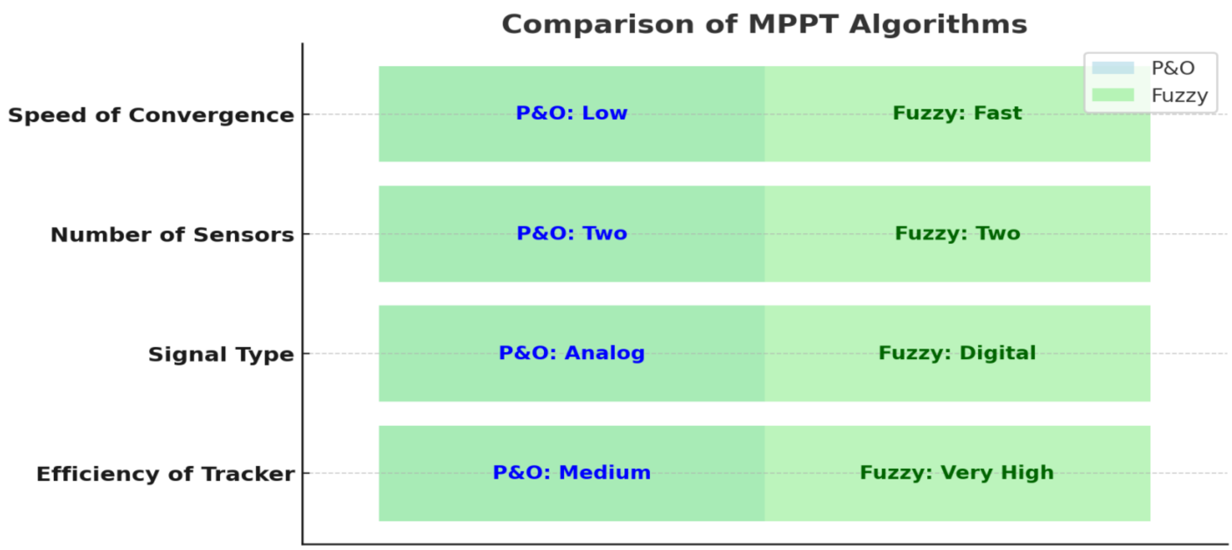


Figure 26 Power with Fuzzy MPPT

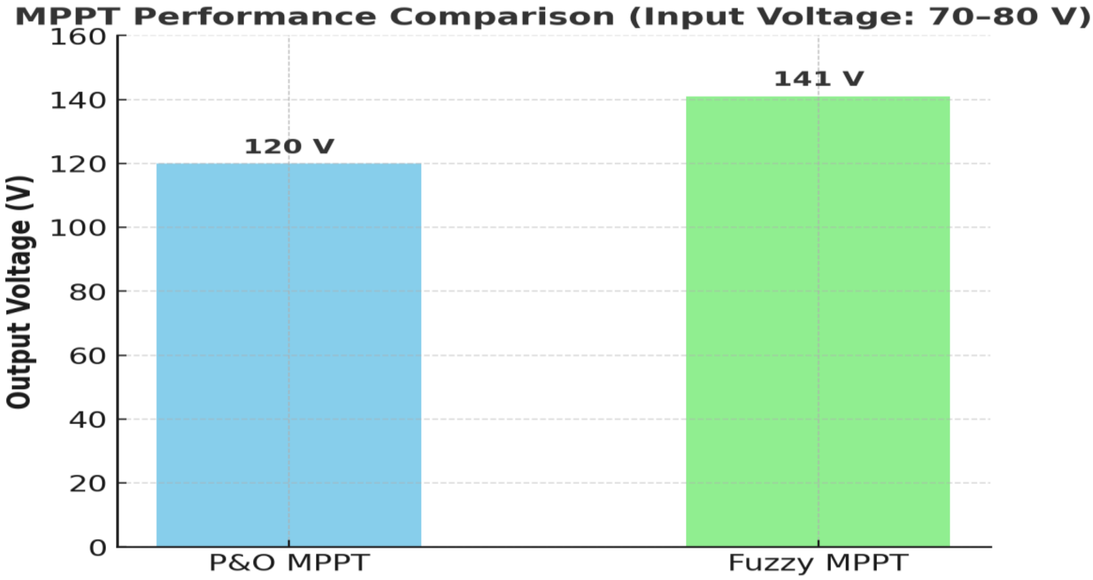


Figure 27 Power with Fuzzy MPPT

The efficiency of both MPPT techniques is presented in Table 8. P&O shows, the input power is 113 W and the corresponding output power is 99 W. Similarly, for the fuzzy logic-based MPPT, the input power is 212 W, while the output power is 199 W.

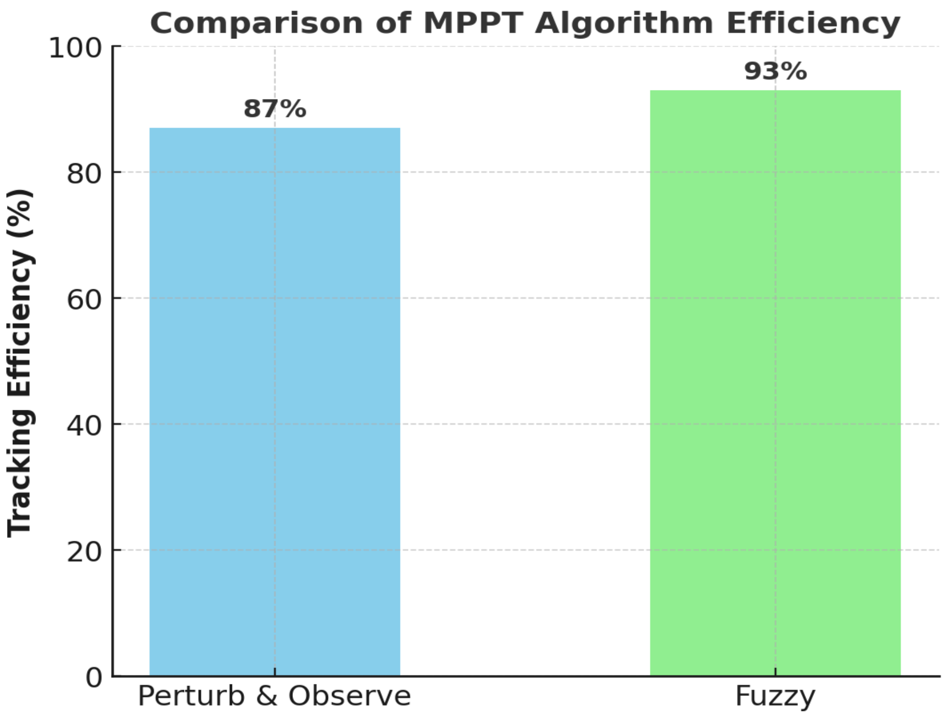


Figure 28 Power with Fuzzy MPPT

Conclusion

In this study, a hybrid system that combines fuel cells, solar photovoltaics, and a DC source has been created as a component of renewable energy resources. Using Arduino, a straightforward and inexpensive maximum power point tracking (MPPT) method was applied to the solar subsystem. The hybrid system, which consists of a battery, fuel cell, and solar array, is intended to increase efficiency and power rating while providing steady electricity. In order to improve converter performance, system dependability, and overall efficiency, MPPT methods and the switching converter are crucial. A 120 V output voltage is produced by the system, which is appropriate for a number of uses. This work used the MATLAB 2016 Simulink toolbox to model and assess several MPPT control strategies, including fuzzy logic and Perturb and Observe (P&O), under various temperature and irradiance circumstances. To improve power extraction from the PV and hybrid system, the suggested model and boost converter parameters were adjusted. Based on simulation results showing the system's performance, it can be said that fuzzy logic MPPT is more appropriate for solar system applications since it offers faster tracking capabilities and more efficiency than P&O.

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