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SIMULATION AND COMPARATIVE ANALYSIS OF HYBRID RENEWABLE ENERGY SYSTEM FOR ENHANCED ENERGY EFFICIENCY

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Abstract: Solar energy is a fantastic clean power source, but its weather-dependent nature makes it highly unpredictable. To beat this volatility and keep the power flowing, we designed and tested a hybrid Photovoltaic-Fuel Cell (PV–FC) system in MATLAB/Simulink. A key part of the puzzle was finding the best way to lock onto maximum solar power, so we put three popular Maximum Power Point Tracking (MPPT) techniques to the test under identical conditions: Perturb and Observe (P&O), Incremental Conductance (INC), and Particle Swarm Optimization (PSO). Our simulations show that the intelligent PSO algorithm is the clear winner, reaching an impressive 97.65% tracking efficiency compared to 94.02% for INC and 90.96% for P&O. It responds much faster to environmental shifts, and when the sun dips, the integrated fuel cell seamlessly steps in to smooth out the supply. Ultimately, this hybrid setup proves to be a highly reliable blueprint for standalone grids, rural electrification, and a more resilient green energy infrastructure.

Keywords: Photovoltaic System, Fuel Cell, MPPT, Particle Swarm Optimization, Hybrid Energy System, MATLAB/Simulink.

I. INTRODUCTION

Energy demand is increasing rapidly due to population growth, industrial development, and the widespread use of electrical equipment. At the same time, the depletion of fossil fuel resources and environmental concerns have encouraged the use of renewable energy sources for power generation. Among the various renewable energy technologies available today, solar photovoltaic (PV) systems have become one of the most popular choices because solar energy is freely available, environmentally friendly, and easy to utilize for electricity generation [1].

Although PV systems offer many advantages, their output power depends on solar irradiance and temperature. Changes in weather conditions, cloud cover, and day–night cycles can cause variations in the power generated by the PV array [2]. As a result, the system may not always operate at its maximum efficiency. To overcome this problem, Maximum Power Point Tracking (MPPT) techniques are used to extract the maximum available power from the solar panel under different operating conditions [3]. Several MPPT methods have been developed for photovoltaic systems. Perturb and Observe (P&O) and Incremental Conductance (INC) are among the most commonly used techniques because of their simple structure and easy implementation [4]. However, these methods may produce oscillations around the maximum power point and may not perform effectively when environmental conditions change rapidly. Intelligent optimization techniques such as Particle Swarm Optimization (PSO) have been introduced to improve tracking performance and increase power extraction from PV systems [5]. Another limitation of a standalone PV system is its inability to generate power during periods of low solar irradiance or at night. To reduce dependence on a single energy source and improve power availability, fuel cells can be integrated with photovoltaic systems to form a hybrid renewable energy system [6]. Proton Exchange Membrane Fuel Cells (PEMFCs) are widely used because of their high efficiency, fast response, compact size, and clean operation [7]. In this work, a Hybrid PV–Fuel Cell Renewable Energy System is modelled and simulated using MATLAB/Simulink. The system includes a PV array, DC–DC boost converter, MPPT controller, and PEM fuel cell. Three MPPT techniques, namely Perturb and Observe (P&O), Incremental Conductance (INC), and Particle Swarm Optimization (PSO), are implemented and compared under the same operating conditions. The performance of each technique is evaluated using output voltage, output power, tracking efficiency, and waveform characteristics. The results show that the PSO-based MPPT method provides better tracking performance and higher efficiency than the P&O and INC techniques. The hybrid PV– Fuel cell system can therefore provide a more effective solution for renewable energy applications such as standalone power systems, rural electrification, and microgrids.

II. DESCRIPTION

The Hybrid PV–Fuel Cell Renewable Energy System is designed to improve energy utilization from solar power while reducing dependence on a single energy source. The system combines a photovoltaic (PV) array, MPPT controller, DC–

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DC boost converter, PEM fuel cell, and load. The PV array acts as the primary source of power generation, while the fuel cell provides supplementary power during periods of reduced solar irradiance. To ensure maximum power extraction from the PV array, different MPPT techniques are implemented and analysed. The complete system is developed and simulated using MATLAB/Simulink to evaluate its performance under identical operating conditions.

BLOCK DIAGRAM

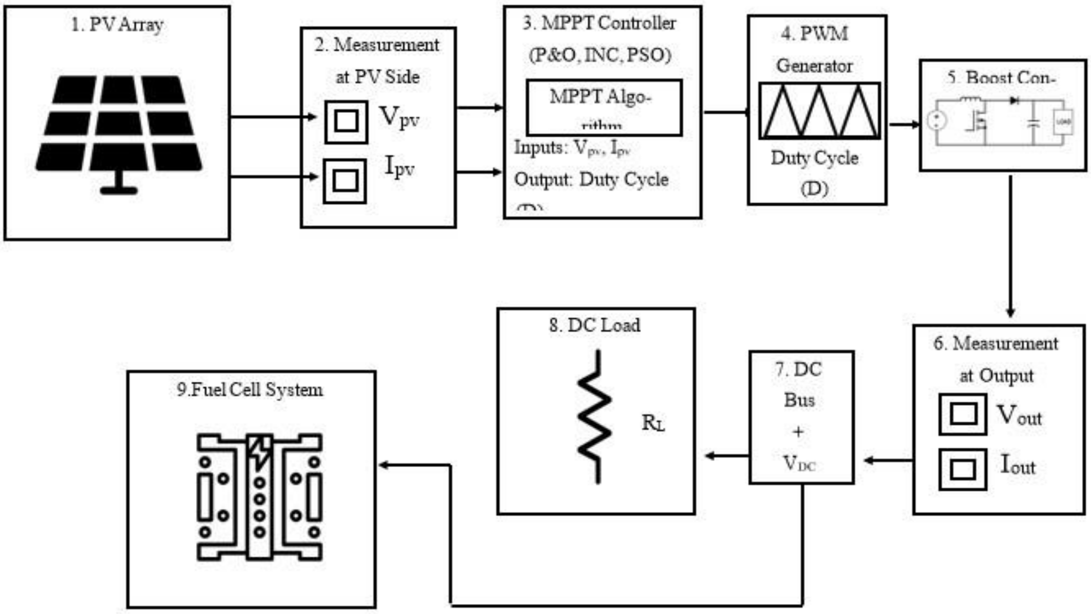

Fig. 1 Block Diagram of Hybrid System

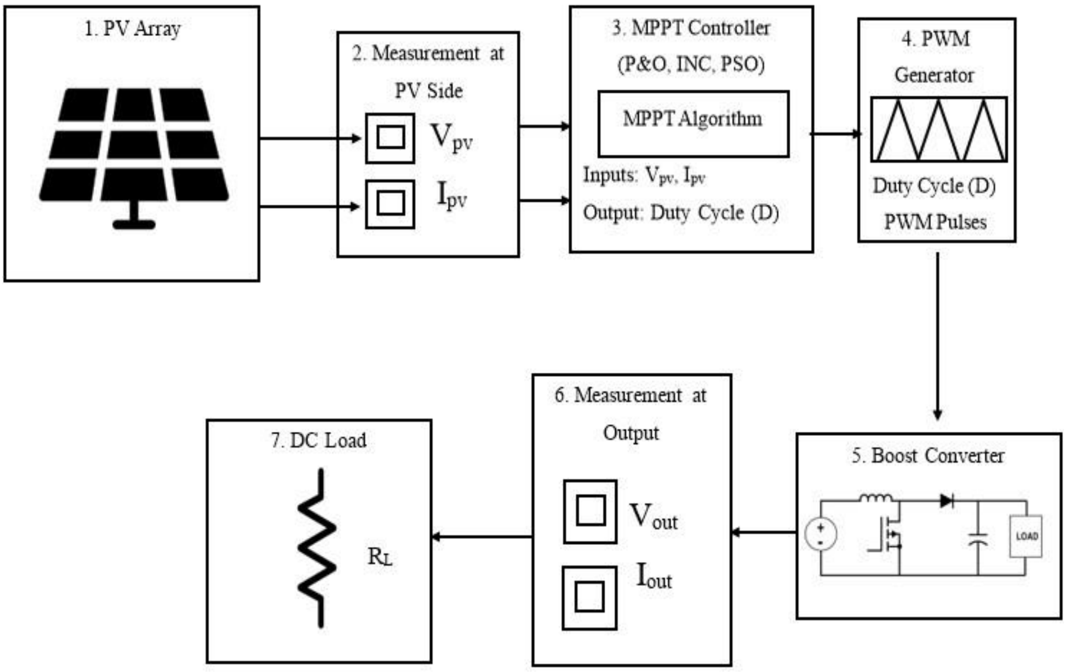

Fig. 2 Block Diagram of PV System

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Table 1 Key Parameters of Fuel Cell

Category	Parameter	Value
Model	Type	PEMFC
Electrical	Nominal Voltage	45V
	Nominal Current	133.3A
	Maximum Power	6 KW
	Number of Cells	65
Performances	Stack Efficiency	55%
	Fuel Cell Resistance	0.078Ω
Operating conditions	Temperature	65°C
	Fuel Pressure	1.5atm
Fuel Characteristics	Hydrogen Purity	99.95%
System behaviour	Hydrogen Utilization	95.56%
	Air Flow Rate	300 Ipm

Photovoltaic (PV) Array

The photovoltaic array converts solar energy directly into electrical energy through the photovoltaic effect. It serves as the primary power source in the hybrid system. The output power of the PV array depends on environmental conditions such as solar irradiance and temperature. Variations in these parameters can significantly affect the voltage and current generated by the system. Therefore, efficient control techniques are required to ensure maximum utilization of the available solar energy.

Table 2 Internal Parameters of PV Module

Parameter	**Symbol**	**Value**
Light Generated Current	I_L	4.6092 A
Diode Saturation Current	I_0	1.2907×10^{-10} A
Diode Ideality Factor	n	1.5397
Shunt Resistance	R_{sh}	412.7878 Ω

MPPT Controller

The Maximum Power Point Tracking (MPPT) controller is used to extract the maximum available power from the PV array under changing environmental conditions. It continuously monitors the operating point of the solar panel and

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adjusts the converter duty cycle to maintain operation near the maximum power point. The use of MPPT improves overall system efficiency and enhances power extraction from the PV source.

Perturb and Observe (P&O)

Perturb and Observe is one of the most commonly used MPPT techniques because of its simple structure and easy implementation. The algorithm periodically perturbs the operating voltage of the PV array and observes the corresponding change in output power. Based on the direction of power variation, the operating point is adjusted toward the maximum power point. Although simple and effective, the method may produce oscillations around the maximum power point during steady-state operation.

Incremental Conductance (INC)

The Incremental Conductance method determines the location of the maximum power point by comparing incremental conductance with instantaneous conductance. The algorithm uses voltage and current measurements to track changes in operating conditions and adjust the duty cycle accordingly. Compared to the P&O method, Incremental Conductance generally provides improved tracking accuracy and better performance during rapid changes in solar irradiance.

Particle Swarm Optimization (PSO)

Particle Swarm Optimization is an intelligent optimization-based MPPT technique inspired by the collective behaviour of birds and fish schools. In this method, multiple particles search for the optimal operating point by continuously updating their positions based on individual and group experiences. The PSO algorithm offers fast convergence, reduced oscillations, and improved tracking efficiency. Simulation results show that PSO achieves better power extraction performance compared to conventional MPPT methods.

DC–DC Boost Converter

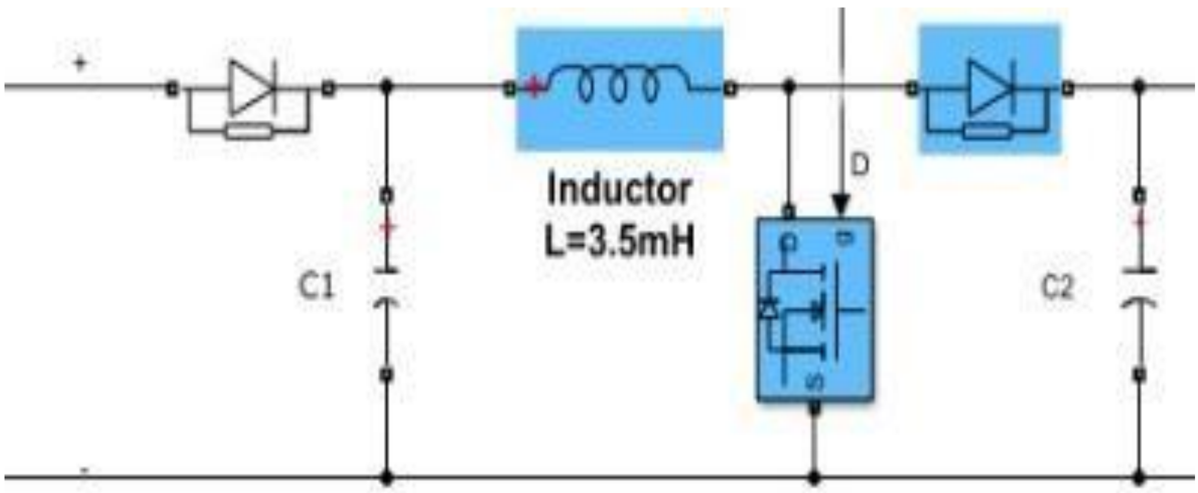

Fig. 3 Circuit Diagram of Boost Converter

A DC–DC boost converter is used to increase the output voltage of the photovoltaic array to the required level. The converter operates under the control of the MPPT algorithm and ensures efficient power transfer between the PV array and the load. By regulating the duty cycle, the boost converter helps maintain the desired operating conditions and improves overall system performance.

III. SIMULATION RESULTS

The proposed Hybrid PV Fuel Cell Renewable Energy System was developed and simulated using MATLAB/Simulink. The system was analysed under standard operating conditions with an irradiance of 1000 W/m² and a temperature of 25°C. Three MPPT techniques, namely Perturb and Observe (P&O), Incremental Conductance (INC), and Particle Swarm Optimization (PSO), were implemented and compared. The performance of each technique was evaluated using voltage response, power response, waveform characteristics, and tracking efficiency.

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A. PV System Output Characteristics:

The photovoltaic array was simulated to analyse its output characteristics under standard environmental conditions. The generated voltage and power waveforms confirm the proper operation of the PV model. The output of the PV array varies according to the operating point determined by the MPPT controller. The obtained results demonstrate the ability of the photovoltaic system to generate electrical power effectively under the specified irradiance and temperature conditions.

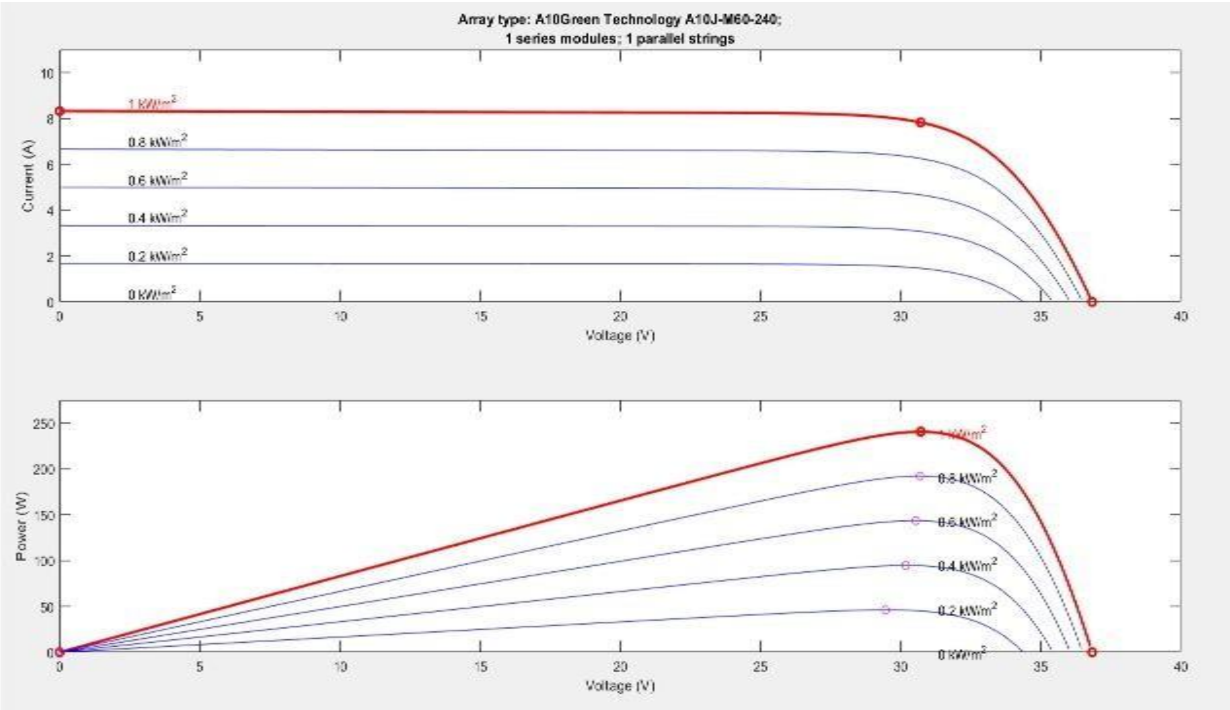

Fig. 4 I-V and P-V Characteristics of PV Panel Figure above shows the current and power output of the panel increase significantly, while voltage changes slightly.

B. Perturb and Observe (P&O) MPPT Results

The Perturb and Observe algorithm was implemented to track the maximum power point of the photovoltaic system. The method continuously perturbs the operating voltage and observes the resulting change in output power. Based on the power variation, the operating point is adjusted toward the maximum power point.

The simulation results indicate that the P&O algorithm successfully tracks the maximum power point and improves energy extraction from the PV array. However, small oscillations are observed around the maximum power point due to the continuous perturbation process. The voltage and power waveforms obtained from simulation verify the effectiveness of the algorithm under constant operating conditions.

The tracking efficiency achieved by the P&O technique was found to be **90.96%**.

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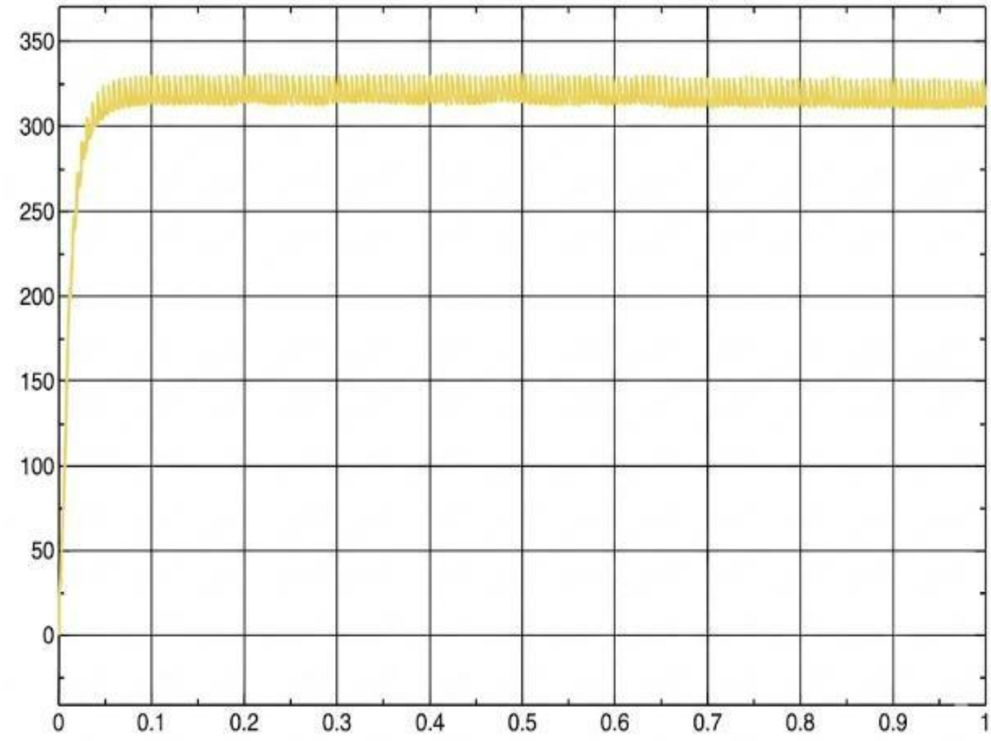

Fig. 5 Load Voltage vs Time graph

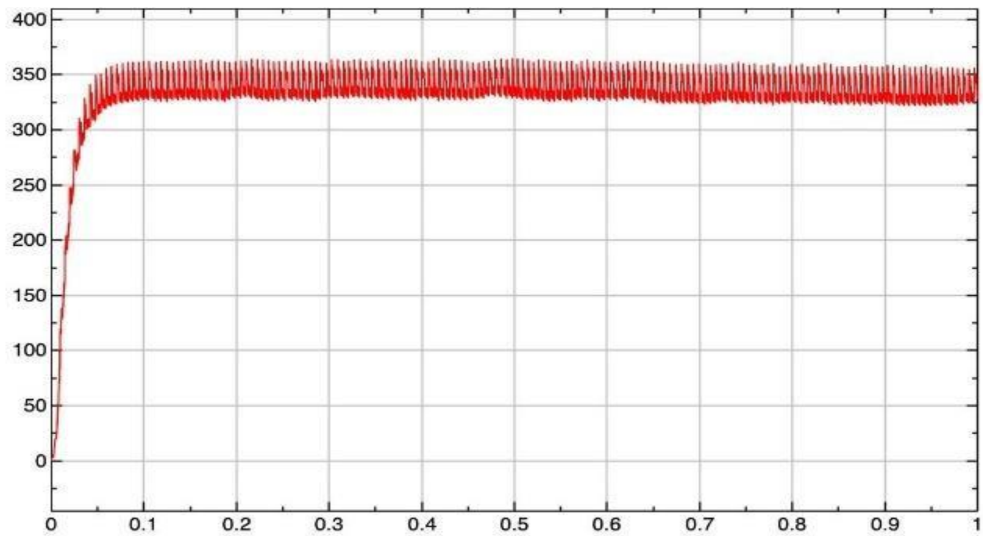

Fig. 6 Load Power vs time graph

Fig. 5 and **Fig. 6** show the voltage and power responses obtained using the P&O MPPT algorithm.

C. Incremental Conductance (INC) MPPT Results

The Incremental Conductance algorithm was implemented and evaluated under the same simulation conditions. This technique determines the location of the maximum power point by comparing incremental conductance with instantaneous conductance.

Simulation results show improved tracking performance compared to the P&O method. The voltage and power responses exhibit reduced oscillations and better adaptation to operating conditions. The algorithm is able to maintain operation closer to the maximum power point, resulting in improved power extraction from the PV array.

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The tracking efficiency obtained using the Incremental Conductance method was **94.02%**.

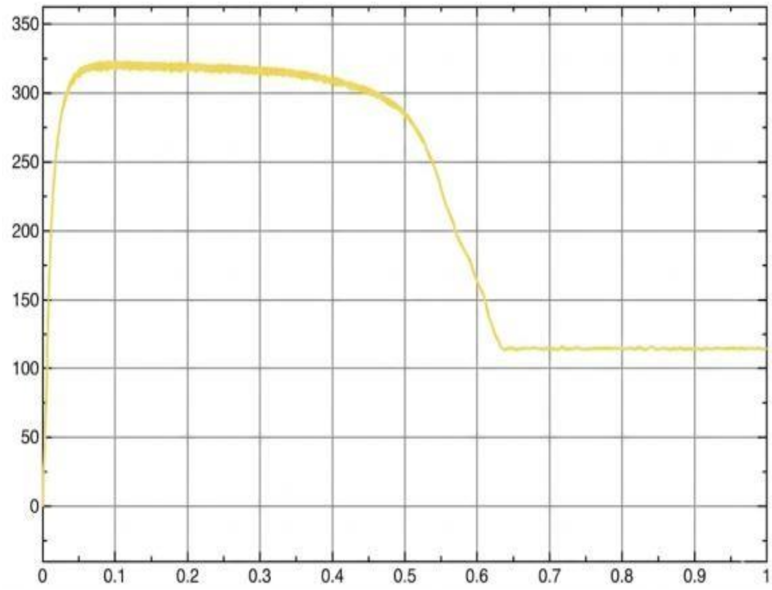

Fig. 7 Load Voltage vs Time Graph

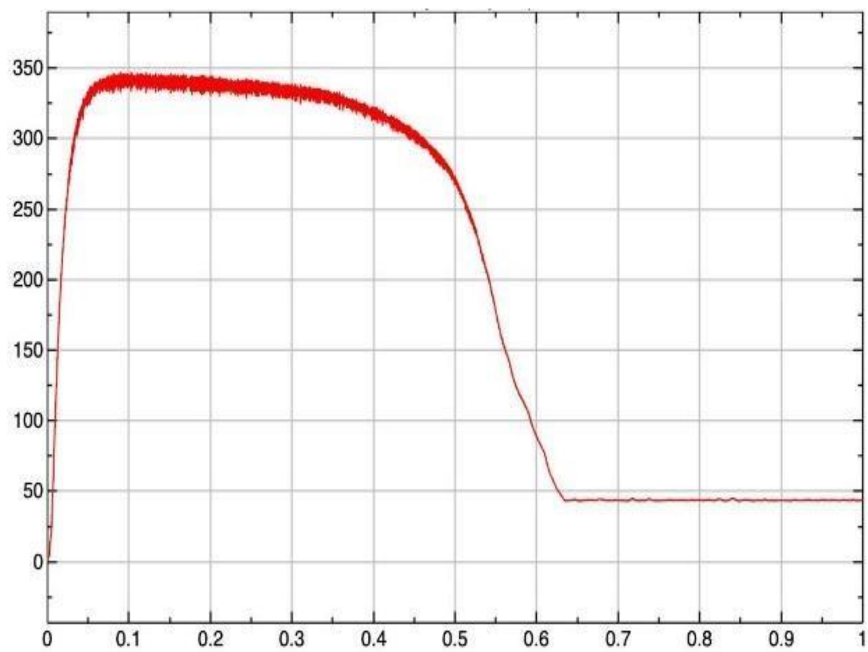

Fig. 8 Load Power vs Time Graph

Fig. 7 and **Fig. 8** present the voltage and power waveforms obtained using the INC MPPT technique.

D. Particle Swarm Optimization (PSO) MPPT Results

Particle Swarm Optimization was implemented as an intelligent optimization based MPPT technique. The algorithm uses a population of particles that continuously search for the optimal operating point by updating their positions according to individual and collective experience.

The simulation results demonstrate superior tracking performance compared to the conventional MPPT methods.

The voltage and power waveforms show faster convergence and reduced oscillatory behaviour. The PSO algorithm effectively identifies the optimal operating point and extracts the maximum available power from the photovoltaic system.

The highest tracking efficiency of **97.65%** was achieved using the PSO technique.

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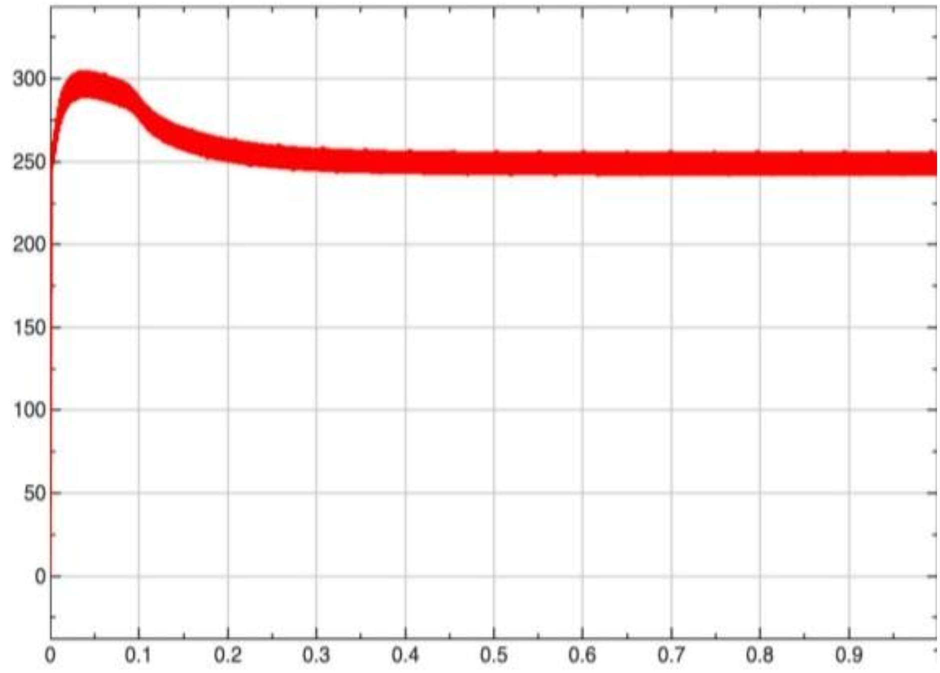

Fig. 9 Load Voltage vs Time Graph of PSO

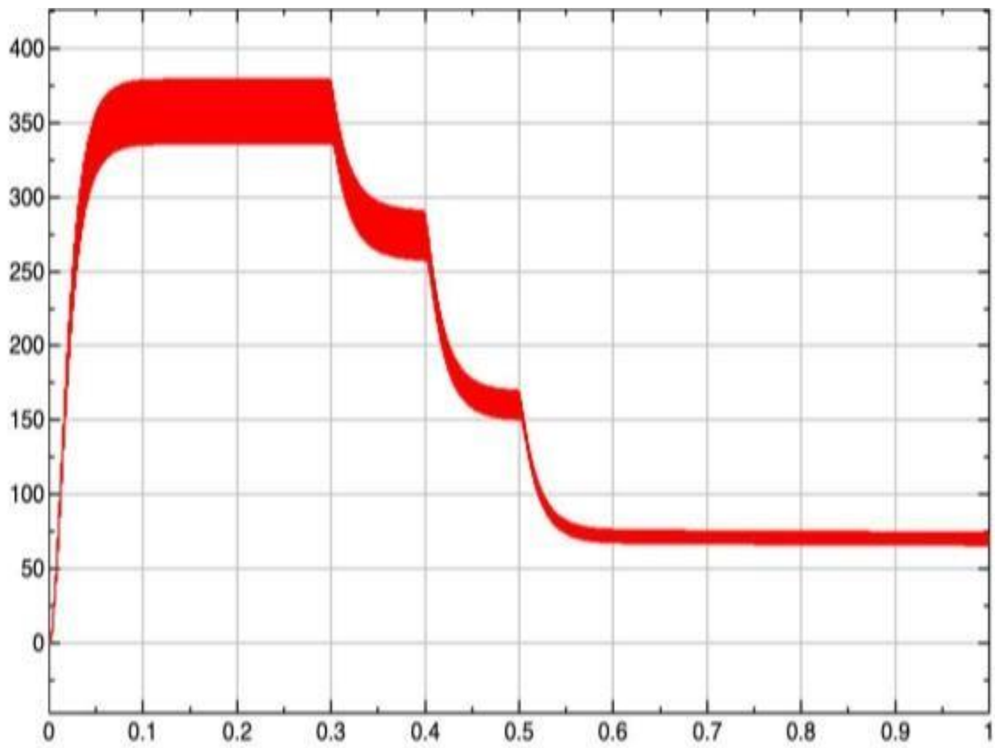

Fig. 10 Load Power vs Time Graph of PSO

Fig. 9 and **Fig. 10** show the voltage and power characteristics obtained using the PSO-based MPPT controller.

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E. Comparative Analysis of MPPT Techniques

A comparative analysis was performed to evaluate the effectiveness of the three MPPT techniques under identical operating conditions. The performance comparison was based on tracking efficiency and power extraction capability.
From the results, it is evident that the PSO algorithm provides the highest tracking efficiency among the three techniques. The Incremental Conductance method performs better than P&O, while the conventional P&O algorithm exhibits comparatively lower efficiency due to oscillations around the maximum power point.

F. Hybrid PV Fuel Cell System

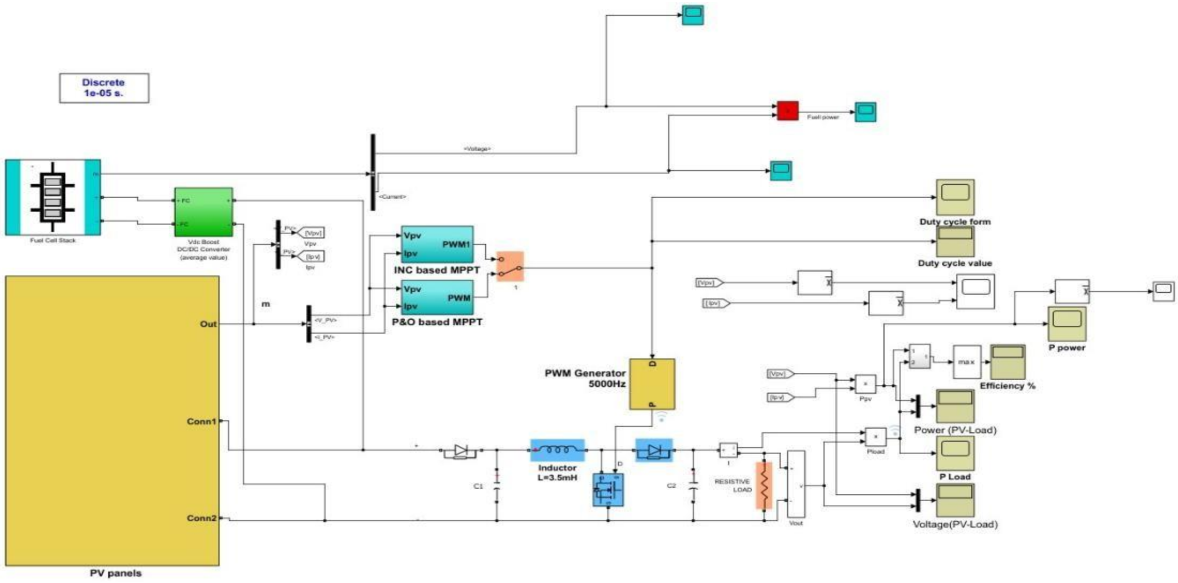

Fig. 11 Simulink Model of the Hybrid System

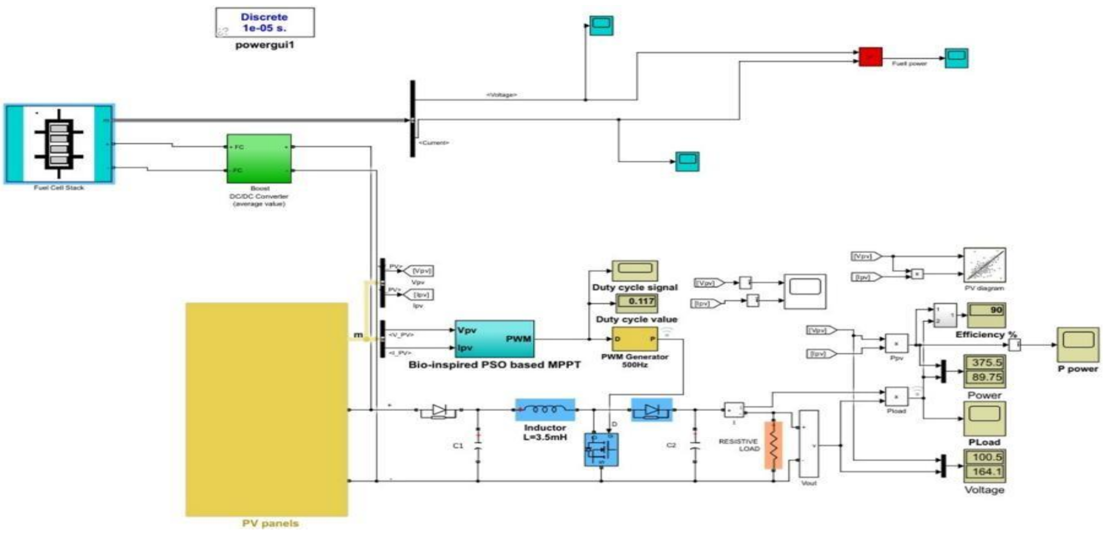

Fig. 12 Simulink Model of the Hybrid System

The PEM fuel cell was integrated with the photovoltaic system to form a hybrid renewable energy system. The fuel cell acts as a supplementary power source and supports energy delivery during periods of reduced solar generation.
Simulation results demonstrate that the hybrid configuration improves the utilization of renewable energy resources and reduces dependence on a single energy source. The combined operation of the PV array and PEM fuel cell provides enhanced energy availability compared to a standalone photovoltaic system.
The overall results confirm that the integration of intelligent MPPT techniques and PEM fuel cell technology contributes to improved system performance and more effective utilization of renewable energy resources.

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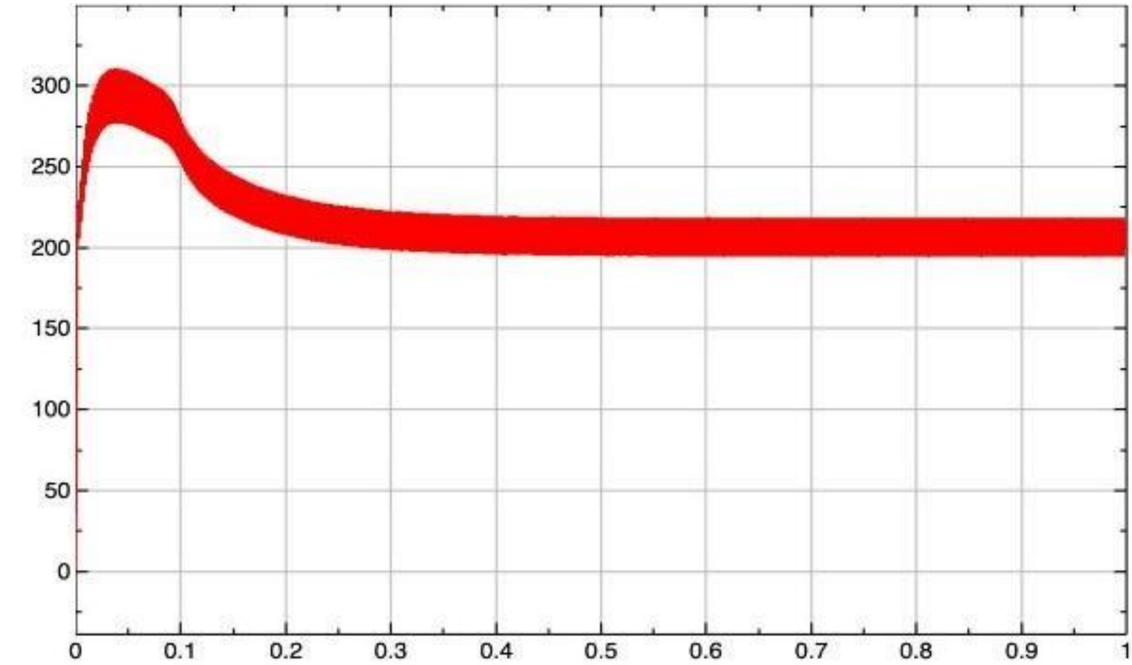

Fig. 13 Load Voltage vs Time Graph

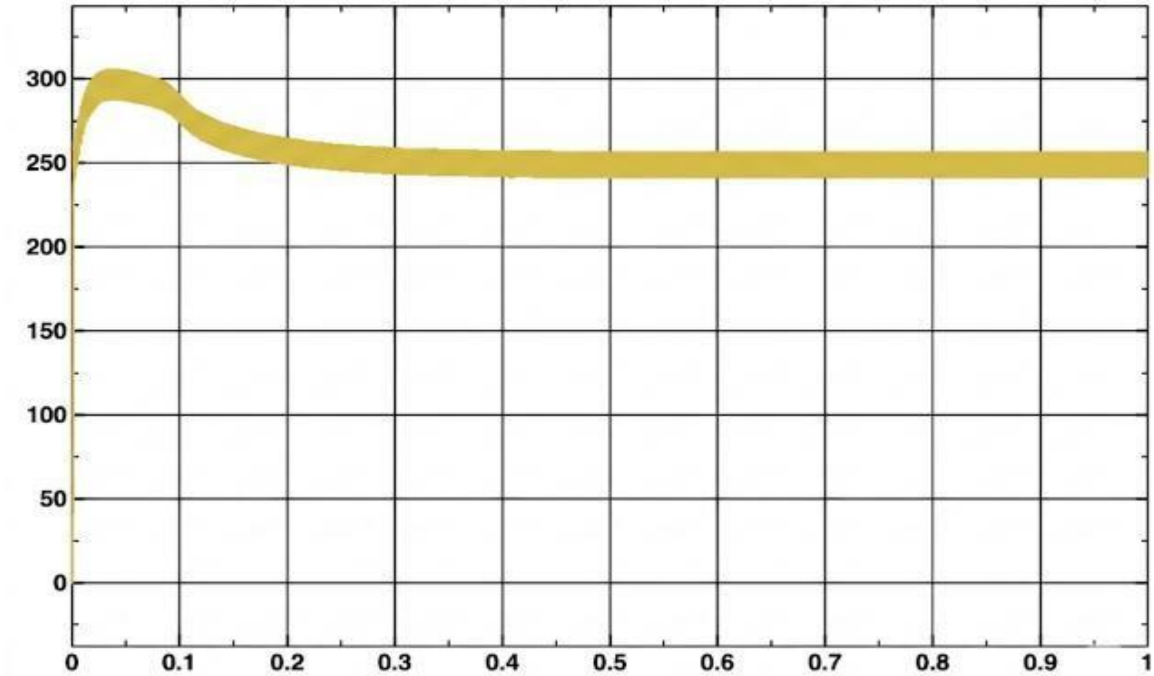

Fig. 14 Load Power vs Time Graph

Fig. 12 and Fig. 13 show the output voltage and power responses of the Hybrid PV–Fuel Cell system. The results demonstrate effective coordination between the PV array and fuel cell, improving overall energy availability.

IV. CONCLUSION

In this work, a Hybrid PV–Fuel Cell Renewable Energy System was modelled and simulated using MATLAB/Simulink. Three MPPT techniques, namely Perturb and Observe (P&O), Incremental Conductance (INC), and Particle Swarm Optimization (PSO), were implemented and compared under identical operating conditions. The simulation results showed that the PSO algorithm achieved the highest tracking efficiency of 97.65%, followed by INC with 94.02% and P&O with 90.96%. Comparative analysis of voltage and power waveforms confirmed the improved tracking performance and power extraction capability of the PSO technique. The integration of the fuel cell reduced dependence

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on a single energy source and supported power availability during periods of reduced solar generation. Therefore, the proposed hybrid system provides an effective approach for improving renewable energy utilization and can be applied in standalone power systems, rural electrification projects, and other sustainable energy applications.

Following is the performance analysis of simulation results at irradiance of 1000 W/m^2 at constant temperature of 25◦C

Table 3 Quantitative Performance Analysis of MPPT Algorithms

S. No.	Algorithm	Actual Voltage (V)	Load Voltage (V)	Actual Current (A)	Load Current (A)	Actual Power (W)	Load Power (W)	Efficiency (%)
1.	P&O	101.2	317.1	3.64	1.057	368.5	335.2	90.96
2.	INC	114.1	114.3	0.4059	0.3809	46.3	43.53	94.02
3.	PSO	103.3	324.6	3.319	1.082	351.1	342.9	97.65

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