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Modeling and Simulation of PV System with P&O MPPT for Dynamic Load Conditions

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ABSTRACT

Nowadays, solar energy is gaining more popularity in the world due to its significant nature of being green and sustainable. Yet, many are concerned about power generation because its efficiency is low. So, by using advanced algorithms like MPPT, we can improve the efficiency of solar power generation through PV panels. The Perturb and Observe (P&O) MPPT algorithm is one of the most commonly used techniques due to its simplicity and cost-effectiveness. However, its performance is affected by load variations and rapidly changing environmental conditions, leading to power losses. This paper analyzes the effectiveness of the P&O MPPT algorithm for different load conditions and explores various modifications to enhance tracking accuracy. The integration of MPPT with power converters further improves system efficiency. Simulation and experimental results demonstrate the feasibility of implementing P&O MPPT in real-world PV systems. Future advancements in adaptive MPPT strategies will be crucial in maximizing solar energy utilization.

Abbreviations

PV	Photovoltaic
MPPT	Maximum Power Point Tracking
MPP	Maximum Power Point
PWM	Pulse Width Modulation
P&O	Perturb and Observe
V_{PV}	Voltage generated by Photovoltaic Panel
I_{PV}	Current generated by Photovoltaic Panel
V_{OC}	Open Circuit Voltage
I_{SC}	Short Circuit Current
V_{mp}	Voltage at Maximum Power Point
I_{mp}	Current at Maximum Power Point
R_{sh}	Shunt Resistance
R_s	Series Resistance

1. Introduction

The use of renewable energy sources has emerged as an essential strategy for lowering greenhouse gas emissions and decreasing reliance on traditional energy sources. The environmental benefits, ease of installation, and sustainability of solar photovoltaic (PV) systems make them a popular choice among renewable energy technologies. There are a number of factors, including temperature and sun irradiation, that affect the efficiency of photovoltaic panels and the amount of power they produce[1]. However, the consistent and effective operation of these systems is severely hampered by the inherent fluctuation in load demands and climatic circumstances. Maximum Power Point Tracking (MPPT) algorithms [2] are used to overcome these difficulties and guarantee that PV systems provide the most power possible.

The Perturb and Observe (P&O) approach is one of the most well-known MPPT strategies due to its simplicity and convenience of use. In order for the P&O algorithm to converge towards the Maximum Power Point (MPP) [3] it regularly modifies the PV system's operating voltage and tracks the resulting change in power output. Despite being widely used, the traditional P&O approach has drawbacks, especially when dynamic load changes and quickly changing climatic conditions are present. These restrictions include decreased tracking efficiency and oscillations around the MPP.

To address these shortcomings, recent research efforts have concentrated on improving the P&O algorithm. With the introduction of adaptive step-size techniques, tracking performance is enhanced and steady-state oscillations are decreased by dynamically adjusting the perturbation step size according to operating conditions. Additionally, hybrid approaches that combine

P&O with intelligent control methods, like fuzzy logic controllers [5], have shown better results in terms of stability and convergence speed under changing situations.

The integration of PV systems with energy storage options, such as battery systems, has also been investigated to increase the reliability of power distribution under dynamic load conditions. Sliding mode control in conjunction with P&O is one of the advanced control schemes [6] that have been suggested to guarantee stable operation and effective power tracking in such hybrid systems. Compare to the conventional MPPTS the P and O MPPT its very simple, low cost, easy implementation and continue to work under steady state conditions.

The purpose of this article is to examine how well the P&O MPPT technique performs in dynamic load scenarios while assessing the effectiveness of new improvements and hybrid control schemes. The study aims to provide light on how to optimize MPPT algorithms for increased dependability and efficiency in PV systems functioning under varying load and environmental circumstances through extensive simulations and analyses.

This study uses MATLAB/Simulink to model and simulate a photovoltaic (PV) system using a DC-DC boost converter and P&O MPPT. Due to its low computing cost, openness, and ease of implementation, the P&O algorithm is one of the most popular maximum power point tracking (MPPT) methods [7]. This approach continues by perturbing the PV voltage and observing the subsequent power changes to track the maximum power point (MPP), assuring efficient utilization of solar energy [8-9]. To regulate the DC-DC boost converter's switching operation, the P&O MPPT controller sends out a duty cycle signal that controls a Pulse Width Modulation (PWM) generator.

The DC-DC boost converter is an essential power electronic interface that ramps up the PV panel voltage to match the needed load voltage. Enhancing boost converter performance in solar PV systems through detailed modeling and the impact of filtering capacitors. Their findings improve voltage stability, reduce ripple, and optimize overall power conversion efficiency[10-11] and [12] focuses on minimizing voltage ripple in boost converters, improving output quality. [13] Introduces a fast and adaptive MPPT algorithm for maintaining maximum power under rapidly changing irradiance conditions.

A variable resistive load is included in the model to examine the system's performance under different load circumstances. This paves the way for monitoring the MPPT algorithm's efficacy, voltage management, and power output in real time [14-15]. Confirming the efficacy of the MPPT-controlled PV system in maximizing power extraction and assuring consistent energy supply [16-17], the simulation results show that the system achieves a high efficiency of around 95.38%.

This paper is structured as follows: First, the Introduction section outlines the need for photovoltaic (PV) systems with Maximum Power Point Tracking (MPPT) and provides a brief overview of their operation. Next, the System Design, Modeling, and Simulation sections present a detailed explanation of the overall system architecture, including the functionality and operation of each individual component. Following this, the Results and Discussion section analyzes the system's performance under various conditions. These include single load scenarios with both constant and varying irradiation, as well as variable load conditions under constant and varying irradiation levels. Additionally, system efficiency is evaluated and compared across these different cases.

2. System design, modeling and simulation

2.1 System design and modelling

The system architecture comprises a photovoltaic (PV) panel, a Maximum Power Point Tracking (MPPT) controller utilising the Perturb and Observe (P&O) algorithm, and a DC-DC boost converter as shown in Fig 1. The interplay of these components is critical for achieving optimal energy extraction from the photovoltaic module, as well as for facilitating efficient power conversion to the load. The simulation model has been developed utilising MATLAB/Simulink, incorporating a range of measurement blocks designed to assess system performance across diverse operating conditions. The model's major objective is to achieve consistent voltage supply to the load while controlling the solar output voltage and optimizing power extraction using the MPPT technique.

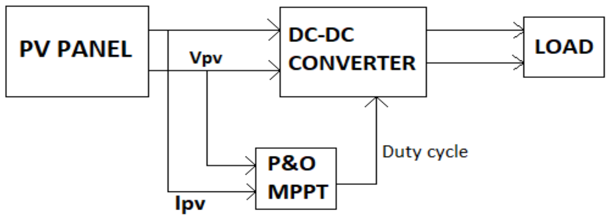

Fig. 1 Block diagram of schematic structure.

The photovoltaic panel is characterised as a current source that is affected by fluctuations in solar irradiance and temperature conditions. The PV model as shown fig 2 employs a single-diode equivalent circuit, which incorporates a current source to represent the photocurrent, a diode to capture the nonlinear characteristics, and both series and parallel resistances to address internal losses. The simulation facilitates the incorporation of dynamic input conditions, specifically with irradiance calibrated at 1000 W/m² and a temperature maintained at 25°C, thereby emulating real-world variations effectively. The photovoltaic panel generates a voltage (V_{PV}) and current (I_{PV}), which are subsequently directed to the maximum power point tracking controller for the purpose of identifying the optimal operating point. The power output is calculated using the equation $P_{pv} = V_{pv} \times I_{pv}$. The control system continuously monitors this value, adjusting the boost converter's duty cycle in accordance with the observed data.

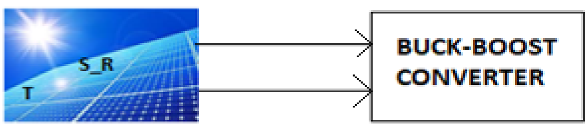

Fig. 2 PV panel with solar irradiation and temperature as input. (S_R means solar irradiation, T means temperature).

The MPPT controller is integral to optimising power extraction from the photovoltaic panel, particularly in the context of fluctuating environmental conditions. The P&O algorithm functions by intermittently adjusting the photovoltaic voltage and analysing the consequent variation in power output. In instances where there is an augmentation in power, the perturbation continues in the same trajectory; conversely, should there be a reduction in power, the perturbation alters its direction to align with the Maximum

Power Point (MPP). The Maximum Power Point Tracking (MPPT) controller block diagram as shown in fig 3 and it generates a duty cycle signal, which is then fed into a Pulse Width Modulation (PWM) generator operating at a frequency of 500 Hz. The PWM signal regulates the switching operation of the boost converter, thereby guaranteeing that the system functions at the optimal power point for maximum efficiency. The efficacy of the MPPT algorithm is evidenced by the system's elevated efficiency, achieving approximately 95.38% as demonstrated in the simulation outcomes.

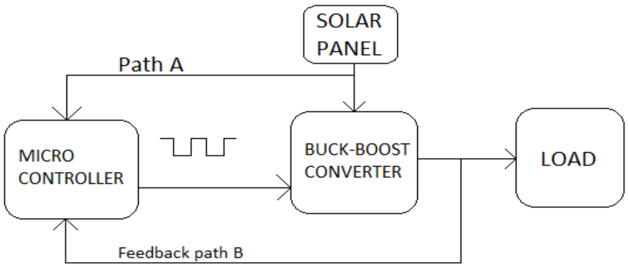

Fig. 3 MPPT block diagram.

The DC-DC boost converter functions to elevate the output voltage of the photovoltaic panel, ensuring it aligns with the necessary load voltage specifications. The system comprises an inductor, a power semiconductor switch, a diode, and capacitors. The inductor serves a crucial function in the energy storage process during the activation phase and subsequently releases this energy upon deactivation of the switch, thus contributing to an elevation in the output voltage. The diode serves to inhibit reverse current flow, whereas the capacitors function as filters to mitigate voltage ripples. By continuously adjusting the duty cycle, the system ensures that the voltage remains stable and meets the load requirements. The system includes a variable resistive load to analyze performance under different conditions. The resistive load allows the examination of power output, voltage stability, and overall system efficiency.

2.2 P&O MPPT algorithm

The Perturb and Observe (P&O) Maximum Power Point Tracking (MPPT) algorithm is a famous method used in solar power systems to optimize energy extraction from photovoltaic (PV) panels. One of its main goals is to find and keep the operating point, called the Maximum Power Point (MPP), where the PV panel makes the most power. To make the program work, from the flow chart as shown in fig 4, the voltage or current of the PV system is changed slightly on a regular basis, and the change in power output is then observed. If the power goes up after the change, the algorithm will keep making changes in the same way. If the power goes down, on the other hand, the direction of the perturbation changes. In this looping process, the voltage and current are measured, the power ($P = V \times I$) is calculated, and the next change is made through a comparative analysis of the current power reading against the preceding power reading. The P&O algorithm is easy to use and doesn't require a lot of computing power, but it does have some problems. For example, it can oscillate around the MPP, which can cause small power losses, and it can be hard to use when the weather changes quickly. Even with these problems, the P&O algorithm is still widely used because it works well and is reliable in stable environments. The Simulink model comprises a photovoltaic (PV) panel integrated with a Perturb and Observe (P and O) Maximum Power Point Tracking (MPPT) system, along with various loads as illustrated in Figure 5. The model parameters are detailed in Table 1.

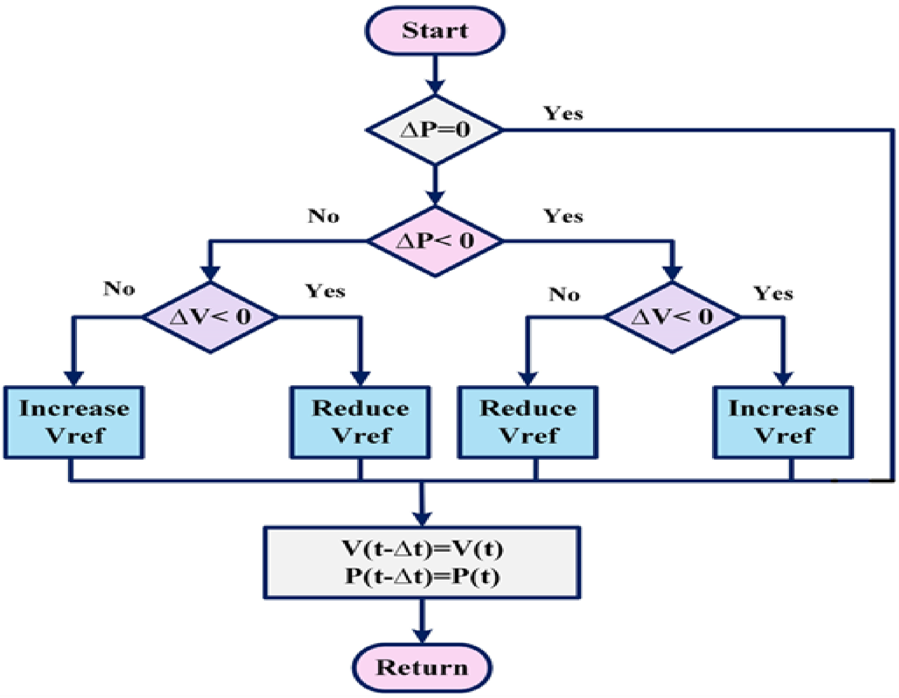

Fig. 4 P&O MPPT algorithm flowchart.

2.3 Simulink model

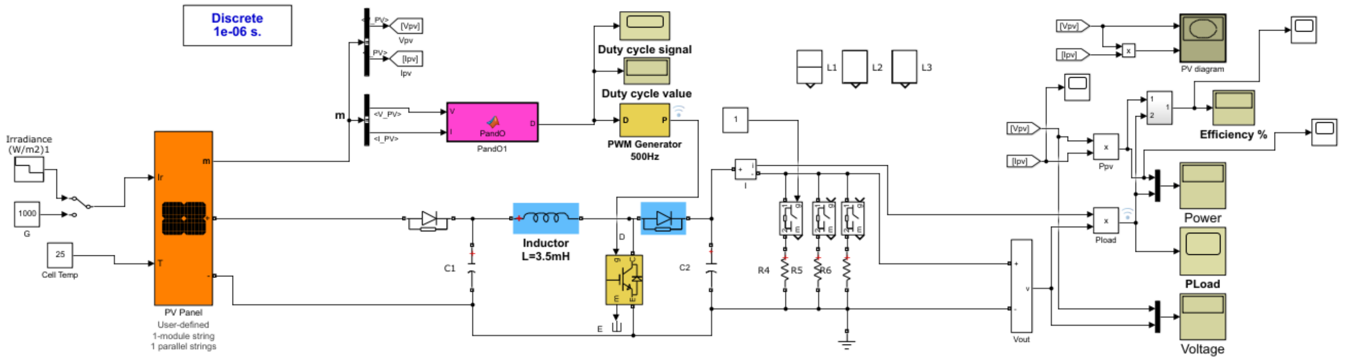

Fig. 5 Simulation diagram of PV system with P&O MPPT for variable loads.

Table 1 Simulink parameters.

PV PANEL SPECIFICATIONS (SYSTEM PARAMETERS)	
Module type	User defined
Maximum power	250 W
Cells per module	60
Open circuit voltage *Voc* (v)	37.3
Short circuit current *Isc* (A)	8.66
Voltage at maximum power point *Vmp* (v)	30.7
Current at maximum power point *Imp* (A)	8.15
Shunt resistance *Rsh* (ohms)	240.6015
Series resistance *Rs* (ohms)	0.23732
Inductor value	3.5 mH
Irradiations	1000, 800, 600, 400
Diode ideality factor	1.0189
Diode saturation current I_o (A)	4.1579e-10
Light generated current I_L *(A)*	8.7062
Load values	Load1 = 50 ohms Load2 = 60 ohms Load3 = 100 ohms

3. Simulation results

3.1   Teoritical values for 250w PV panel

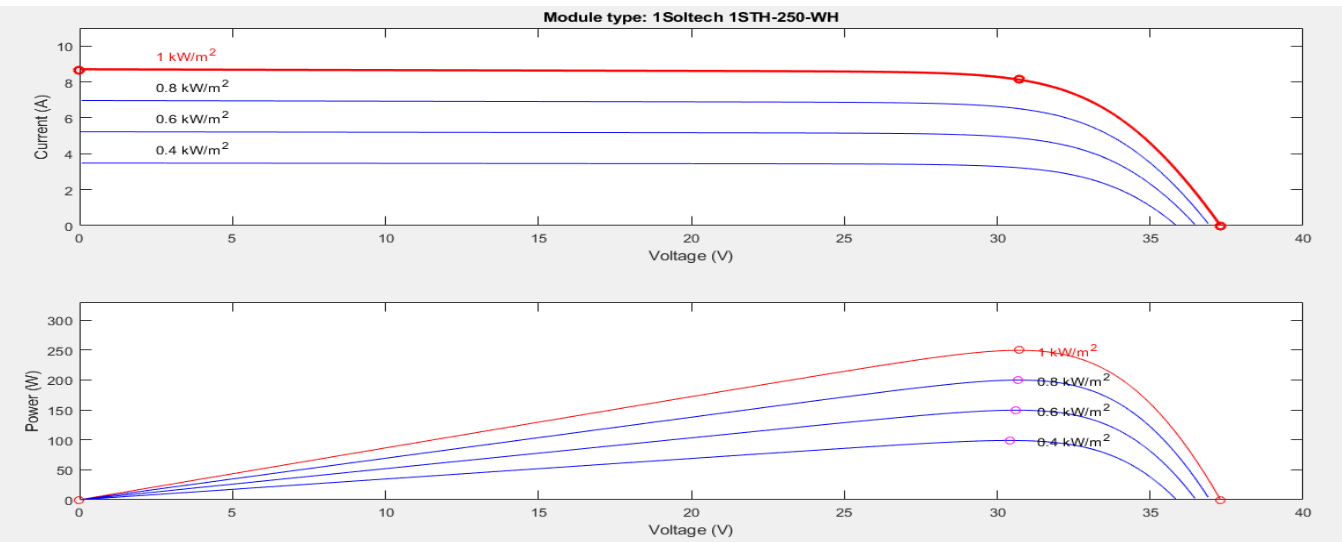

Fig. 6 Theoritical values current–voltage and power-voltage characteristics of PV module.

The figure 6 represents the **c**urrent-voltage and power-voltage characteristics of a **1**Soltech 1STH-250-WH photovoltaic (PV) module under different solar irradiance levels. These curves help analyze the performance of a PV panel under varying sunlight conditions.

In Figure 6, the first graph (*I-V* characteristics) displays the connection between a PV module's current and voltage at various irradiance levels. The short-circuit current (*Isc*) rises as irradiance increases, while the open-circuit voltage (*Voc*) stays mostly the same. This means that higher irradiance leads to higher current output, which in turn leads to more power being produced. The bottom graph (P-V characteristics) shows power-voltage relationships. Although the Maximum Power Point (MPP) fluctuates slightly with irradiance, the voltage at MPP remains steady (~30-35V). Solar power generation depends on sunlight intensity and MPPT regulation, as higher irradiance increases peak power output.

3.2 Single load conditions

Case 1: At 1000 W/m² MPPT

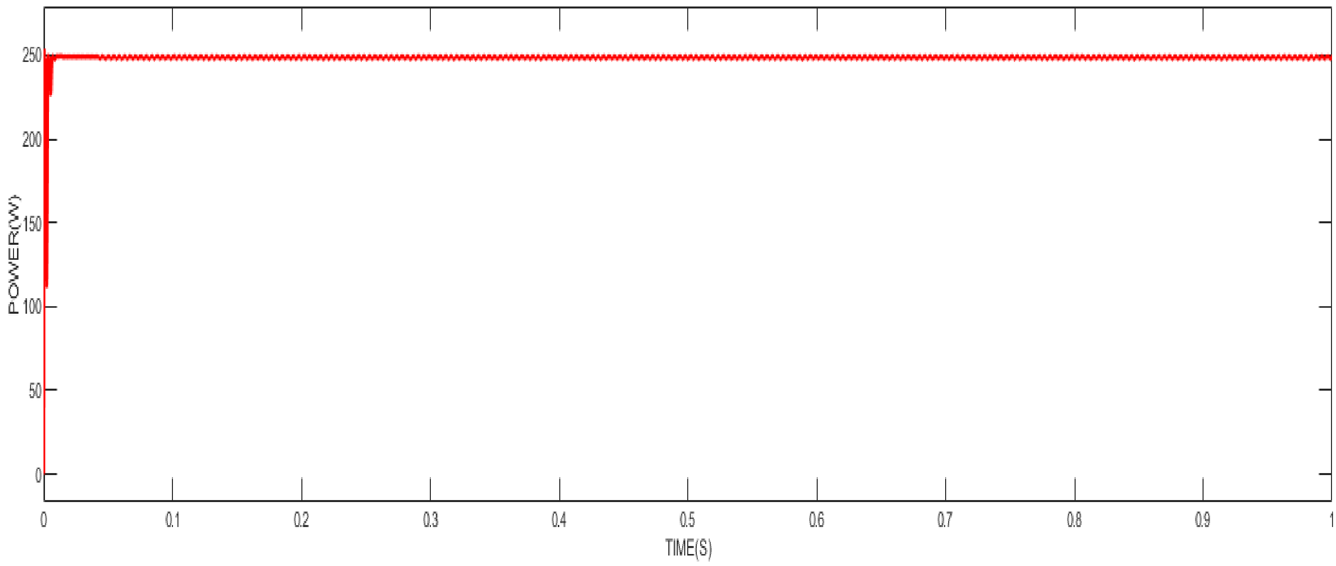

Fig. 7 MPPT response at 1000W/m².

The graph shows the Maximum Power Point Tracking (MPPT) response. Power rises rapidly and stabilises around 250W, showing that the MPPT algorithm quickly reaches and maintains the maximum power point (MPP) for best PV system performance. The below figure 8&9 shows the corresponding current and voltage value.

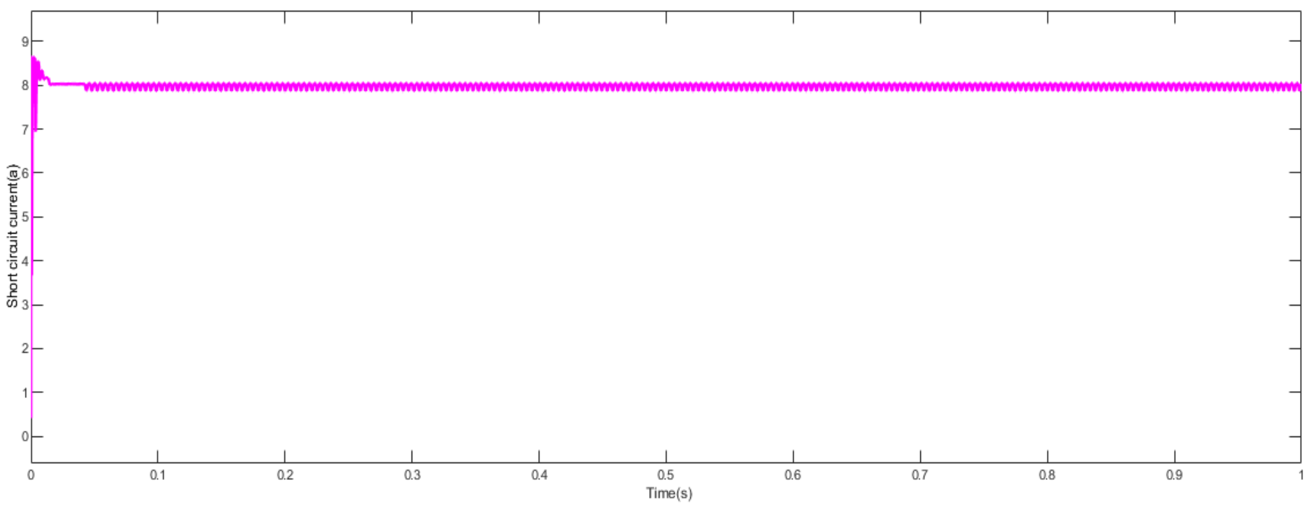

Fig. 8 PV current.

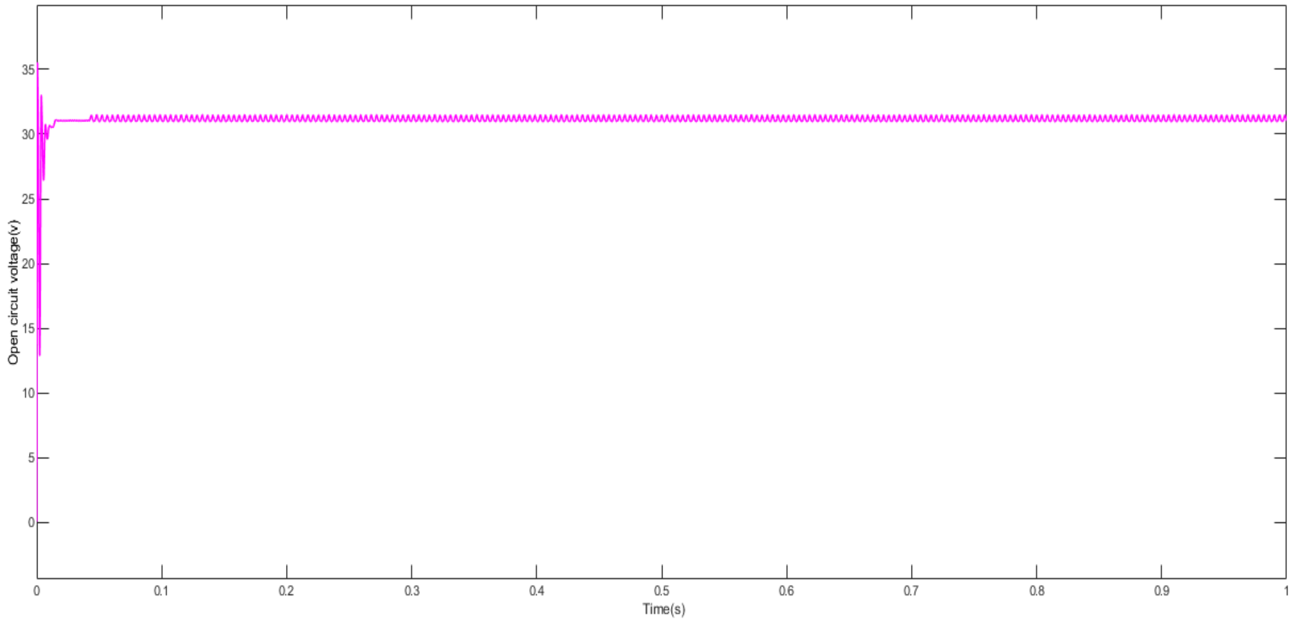

Fig.9 PV voltage.

Case 2: At different irradiations (1000,800,600,400) tracking MPPT

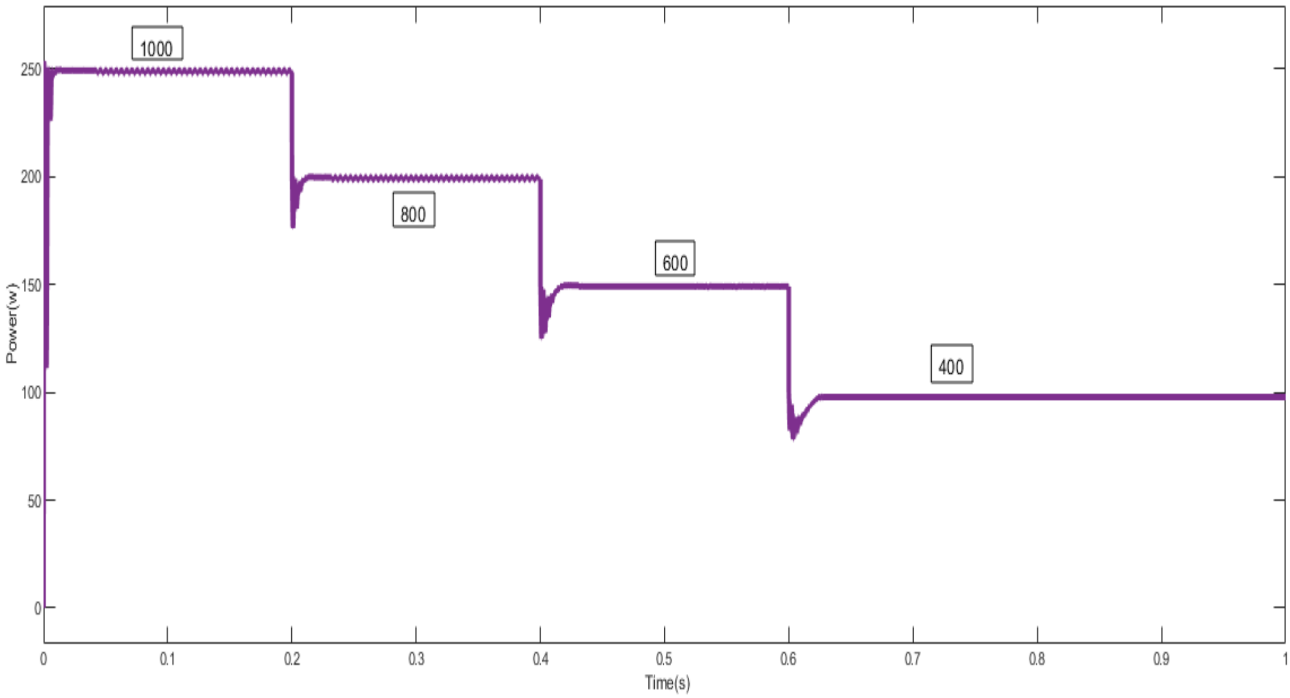

Fig. 10 MPPT tracking at different irradiations.

The figure 10 shows a photovoltaic (PV) system's response to variable irradiation. Initially, at 1000 W/m², the power output is around 250 W. Power reduces proportionally to 160 W as irradiance decreases to 800 W/m². At 600 W/m², power drops to 120 W, and at 400 W/m², it stabilises at 80 W.

Each transition fluctuates briefly before settling, showing the MPPT algorithm's dynamic reaction to irradiance. The technology tracks the maximum power point for each irradiance level for optimal performance in different sunlight circumstances.

3.3 Variable load conditions

Case 3: Dynamic load conditions

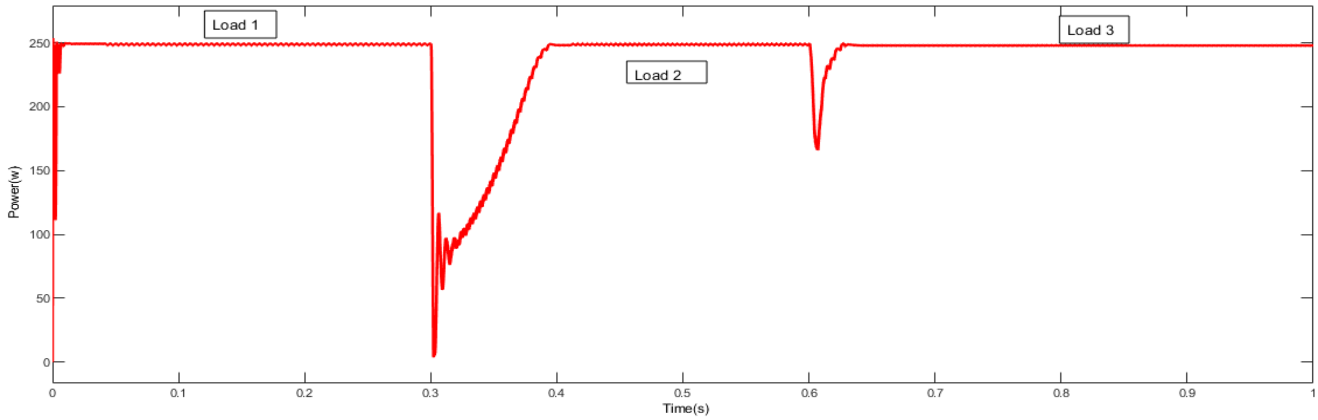

Fig 11: maximum power at three different loads.

Figure 11 shows the PV system's power response to load changes. Power stays at 250 W under Load 1. When load changes, power drops sharply and oscillates before stabilising at a lower value for Load 2.

For Load 3, power drops briefly but quickly recovers, showing the MPPT algorithm's adaptability to dynamic load variations.

Case 4: Variable load with different irradiations

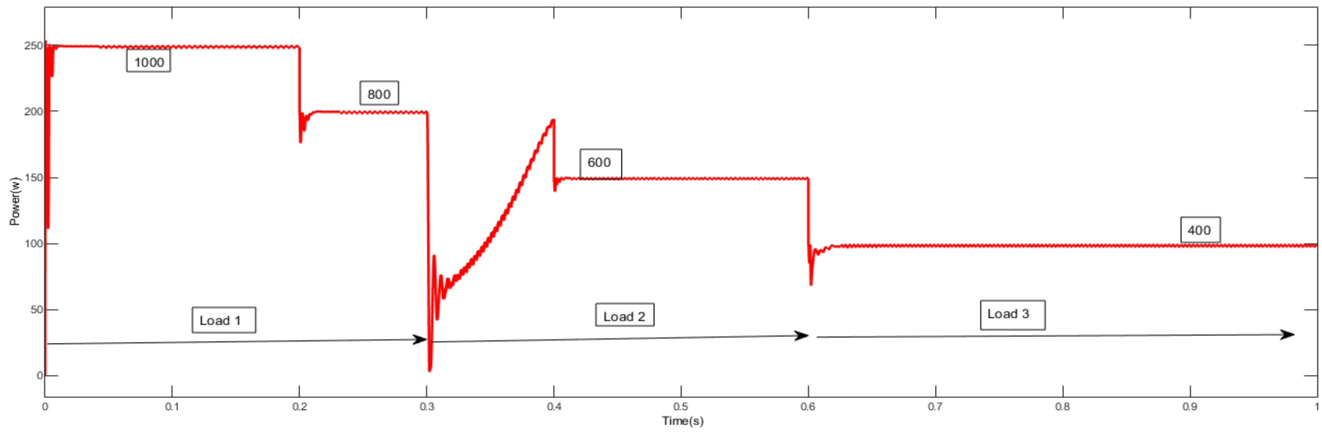

Fig. 12 Maximum power in different loads with different irradiations.

Figure 12 shows PV system reaction to irradiance and load changes. Beginning with Load 1, the system generate 250 W at 1000 W/m² irradiance. Changing to Load 2 causes power dips and oscillations, stabilising at a lower value due to a reduced irradiance of 800 W/m². An additional power drop occurs during the shift to Load 3 at 600 W/m² irradiance. Ultimately, power stabilises at its lowest value at 400 W/m² irradiance. The system tracks the MPP and adapts to load and irradiance changes.

3.4 Efficiency with P and O MPPT

The efficiency of P and O MPPT of PV panel is tested under the following modes

1. At constant irradiation (1000W/m^2)
2. At variable irradiation condition

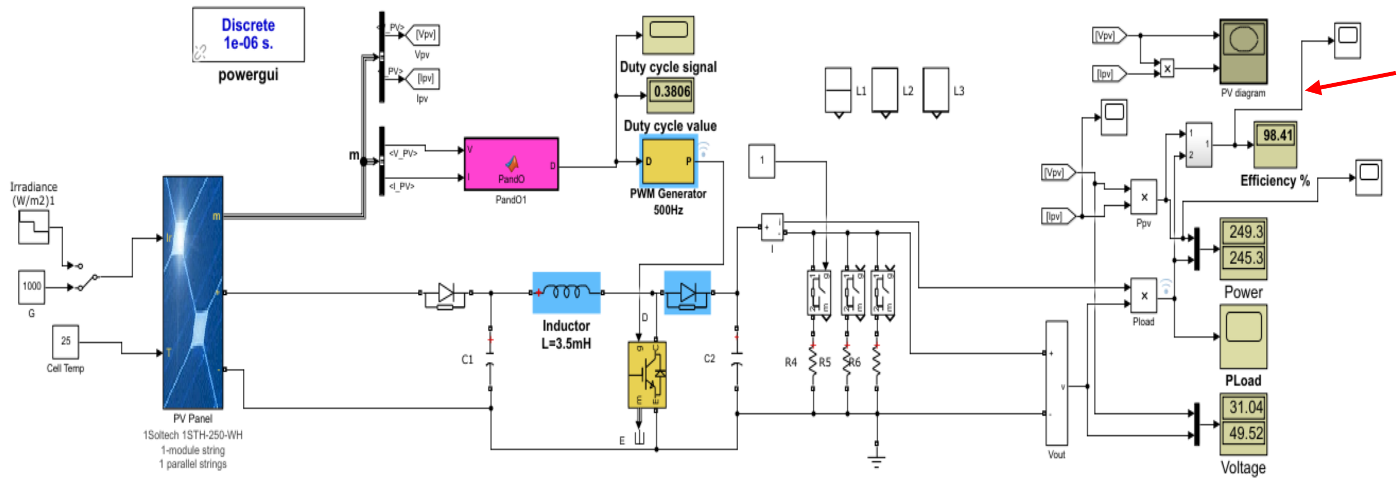

Fig. 13 System efficiency at constant irradiation 1000 W/m^2.

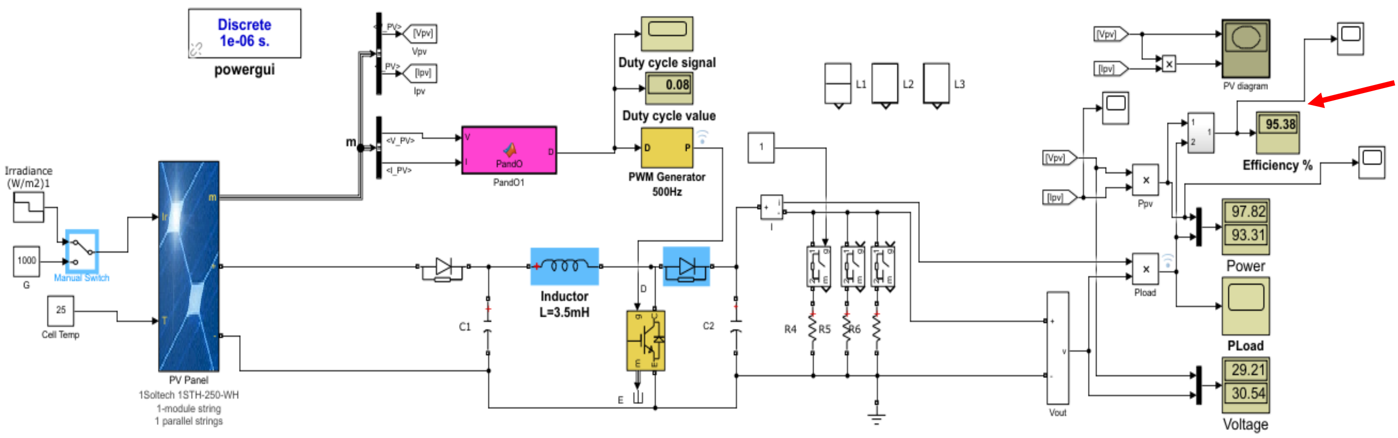

Fig. 14 Efficiency of PV panel with P and O MPPT algorithm at different irradiance conditions.

At constant irradiation (1000 W/m^2) the efficiency shown above in figure 13 is 98.41%. Similarly, at 800 W/m^2, the efficiency is 98.26%, at 600 W/m^2, the efficiency is 98.03% and at 400 W/m^2, the efficiency is 97.89%.

At different irradiation condition, the system efficiency is 95.38% (as shown in figure 14) because the irradiation is constantly changing. So the efficiency is reduced to 95.38%. A comparison table with various references is presented in section 3.5.

3.5 Comparative Analysis of MPPT Efficiency

Table 2 Comparison of MPPT Efficiency Across Different Techniques.

Parameter	Adoptive P and O MPPT [18]	MPPT for Standalone PV system [19]	Proposed Method (This Research)
Efficiency	97.8%	85%	98.4%

As presented in Table 2, the proposed MPPT method in this research demonstrates a higher tracking efficiency (98.4%) compared to both the conventional Perturb and Observe (P&O) method (97.8%) and the MPPT technique used for a standalone PV system (85%) reported in previous studies [18-19].

4. Conclusion

The developed simulation model effectively demonstrates the operation of a photovoltaic (PV) system integrated with an MPPT-controlled boost converter to improve energy extraction under varying conditions. The optimal utilisation of solar energy is guaranteed by the Perturb and Observe (P&O) MPPT algorithm, which efficiently monitors the maximum power point. The boost converter is essential for voltage regulation, as it dynamically adjusts to varying load and irradiance conditions. The results corroborate that the system is able to maintain a high level of efficiency and a consistent power output in spite of fluctuations in the input parameters. Furthermore, the system's adaptability underscores its appropriateness for microgrid and smart grid applications, which necessitate the integration of renewable energy in a reliable and efficient manner. This research emphasises the significance of MPPT techniques in PV systems, thereby enhancing their sustainability and practicality in real-world energy scenarios. The results establish a robust foundation for the further optimization and expansion of solar power applications in modern power networks. Further advance researches can be useful for integration of renewable sources to microgrid or grid.

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