Performance Evaluation of Solar Photovoltaic System under Variable Environmental Conditions Using MATLAB/Simulink

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Abstract — Solar photovoltaic (PV) technology has become one of the most promising renewable energy solutions for sustainable electricity generation due to its clean operation, low maintenance, and abundant availability of solar energy. However, the electrical performance of photovoltaic systems is strongly influenced by environmental factors, particularly solar irradiance and operating temperature. Variations in these parameters alter the current–voltage (I–V) and power–voltage (P–V) characteristics of PV modules, resulting in changes in output power and overall system efficiency. Therefore, evaluating the performance of PV systems under different environmental conditions is essential for improving their reliability and energy harvesting capability. This study presents a MATLAB/Simulink-based comparative performance analysis of a solar photovoltaic system under varying irradiance and temperature conditions. A PV array integrated with a Boost DC–DC converter and a Perturb and Observe (P&O) Maximum Power Point Tracking (MPPT) controller is developed to investigate system behaviour under realistic operating conditions. The model is simulated at irradiance levels of 1000, 800, 600, 400, and 200 W/m², while the operating temperature is varied to examine its influence on the electrical characteristics of the PV array. Important performance parameters, including output voltage, output current, output power, and maximum power point (MPP), are analysed and compared. Simulation results indicate that an increase in solar irradiance significantly enhances the generated current and output power, whereas higher operating temperatures mainly reduce the output voltage and overall conversion efficiency. The implemented P&O-based MPPT algorithm effectively tracks the maximum power point under all tested environmental conditions, thereby improving the energy extraction capability of the photovoltaic system. The comparative analysis demonstrates the strong dependence of PV performance on environmental conditions and highlights the importance of accurate simulation before practical deployment. The proposed MATLAB/Simulink model provides an efficient and reliable platform for analysing photovoltaic system performance under different climatic conditions. The outcomes of this study can assist researchers and system designers in optimizing solar PV installations and serve as a basis for future investigations involving advanced MPPT techniques, intelligent control strategies, and grid-connected photovoltaic applications.

Keywords: Solar Photovoltaic (PV), MATLAB/Simulink, Environmental Conditions, Solar Irradiance, Temperature, Maximum Power Point Tracking (MPPT), Perturb and Observe (P&O), Boost Converter, DC Bus Voltage, Comparative Performance Analysis

I. INTRODUCTION

The rapid increase in global energy demand, coupled with environmental concerns and the depletion of fossil fuel resources, has accelerated the transition toward renewable energy technologies. Among the available renewable energy sources, solar photovoltaic (PV) systems have emerged as one of the most attractive solutions because they generate electricity directly from sunlight without producing greenhouse gas emissions during operation. Continuous improvements in photovoltaic materials, power electronic converters, and control techniques have significantly enhanced the efficiency, reliability, and commercial viability of PV systems, leading to their widespread deployment in residential, commercial, and utility-scale applications.

Despite these advantages, the performance of a photovoltaic system is strongly influenced by environmental conditions. The electrical characteristics of a PV array vary continuously with changes in solar irradiance and cell temperature, causing significant variations in output voltage, current, and power. Under low irradiance conditions, the generated current decreases considerably, while elevated cell temperatures reduce the output voltage and overall conversion efficiency. These variations make it essential to evaluate the behaviour of PV systems under different operating conditions to ensure reliable and efficient energy generation.

To maximize the available solar energy, modern photovoltaic systems commonly employ Maximum Power Point Tracking (MPPT) techniques together with DC–DC power converters. MPPT controllers continuously adjust the operating point of the PV array to extract the maximum possible power despite environmental variations. Therefore, performance analysis under different irradiance and temperature conditions provides valuable information for designing efficient photovoltaic systems and selecting suitable control strategies.

In this work, a MATLAB/Simulink-based photovoltaic model integrated with a Boost DC–DC converter and a Perturb and Observe (P&O) MPPT algorithm is developed to investigate the influence of changing environmental conditions on system performance. Comparative simulations are carried out under different irradiance levels and operating temperatures to evaluate output voltage, output current, generated power, and maximum power point characteristics. The obtained results provide useful insights into the behaviour of photovoltaic systems under practical operating conditions and contribute to the optimization of high-efficiency solar energy conversion systems.[1][2]

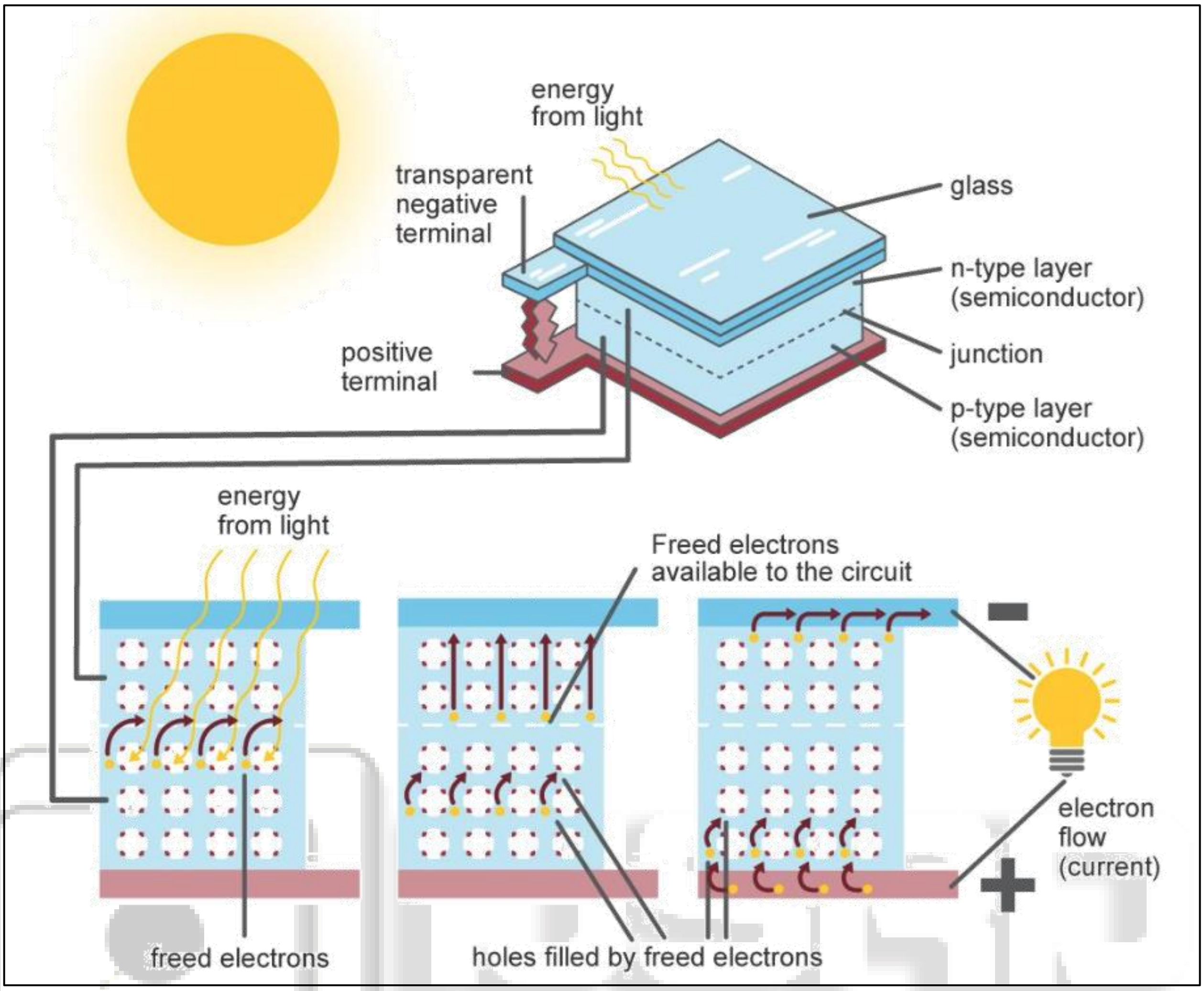

Fig. 1.1: working of solar pv

A. Absorption of Solar Radiation

The Solar PV array consists of multiple photovoltaic cells connected in series and parallel combinations. These cells are fabricated using semiconductor materials, primarily silicon. When sunlight falls on the surface of the PV cell, the incident photons are absorbed by the semiconductor material.

The energy of an incident photon is given by

$$E = hf$$

where

E = Photon Energy (J)

h = Planck's Constant (6.626×10^{-34} J·s)

f = Frequency of Incident Light (Hz)

Only photons having energy greater than the semiconductor band-gap energy can generate electrical energy.

B. Generation of Electron–Hole Pairs

When the absorbed photon energy exceeds the band-gap energy of silicon, electrons gain sufficient energy to move from the valence band to the conduction band. This process creates electron-hole pairs inside the semiconductor material. These free charge carriers are responsible for electrical power generation.

C. Separation of Charge Carriers

The internal electric field developed across the P-N junction separates the generated charge carriers.

– Electrons move toward the N-type region.
– Holes move toward the P-type region.

This separation creates a potential difference across the solar cell terminals.

D. Generation of Electrical Power

When an external load is connected, electrons flow through the external circuit from the negative terminal to the positive terminal, producing direct current (DC).

The electrical output power of the PV array is expressed as

$$P = VI$$

where

P = Output Power (W)

V = Output Voltage (V)

I = Output Current (A)

The generated voltage and current continuously vary with changes in environmental conditions.

II. MAXIMUM POWER POINT TRACKING (MPPT)

Maximum Power Point Tracking (MPPT) is an essential control strategy employed in Solar Photovoltaic (PV) systems to ensure maximum utilization of the available solar energy. The electrical output of a PV array continuously changes with variations in solar irradiance and cell temperature, causing the operating point of the system to shift away from its optimum value. If the PV array does not operate at its Maximum Power

Point (MPP), a considerable amount of available solar energy remains unutilized, leading to reduced power generation and lower system efficiency. Therefore, MPPT techniques are widely implemented to maintain PV operation at the optimum operating point under varying environmental conditions.[3][4]

To achieve this objective, an MPPT controller is integrated with the photovoltaic system through a DC–DC converter. The controller continuously measures the output voltage and current of the PV array, determines the operating condition, and regulates the converter duty cycle so that the PV system operates close to the Maximum Power Point. As a result, the maximum available electrical power can be extracted even when environmental conditions change continuously.[7]

A. Need for MPPT

The electrical characteristics of a photovoltaic array are nonlinear and strongly influenced by environmental conditions. Both the Current–Voltage (I–V) and Power–Voltage (P–V) characteristics vary with changes in solar irradiance and cell temperature. During cloudy weather, seasonal variations, or temperature fluctuations, the location of the Maximum Power Point continuously shifts. Consequently, a fixed operating point cannot ensure maximum energy extraction under all operating conditions.

In the absence of an MPPT controller, the photovoltaic system may operate away from its optimum point, resulting in unnecessary power loss and reduced conversion efficiency. Therefore, an MPPT controller is indispensable for maintaining efficient operation under varying environmental conditions.

The major objectives of MPPT are:

– To maximize the extraction of available solar energy.
– To improve the overall efficiency of the photovoltaic system.
– To maintain the PV array at its optimum operating point under changing environmental conditions.
– To minimize power losses caused by irradiance and temperature variations.
– To enhance the reliability and operational performance of the Solar PV system.

1) Role of MPPT in the Proposed System

In the proposed MATLAB/Simulink model, the MPPT controller is incorporated to evaluate the performance of the Solar PV array under different environmental conditions. During simulation, the photovoltaic array is exposed to multiple irradiance levels and operating temperatures in order to investigate its electrical behaviour. Under each operating condition, the MPPT controller continuously tracks the Maximum Power Point and regulates the Boost DC–DC converter to ensure maximum power extraction from the PV array.

The performance of the proposed system is evaluated by analysing the following electrical parameters:

– Variation in PV output voltage.
– Variation in PV output current.
– Variation in output power.
– Maximum Power Point tracking capability.
– Overall efficiency of the photovoltaic system under different environmental conditions.

The simulation results demonstrate that the MPPT controller effectively maintains the PV array near its Maximum Power Point despite continuous variations in irradiance and temperature. Consequently, the proposed control strategy improves power extraction capability and enhances the overall performance and reliability of the photovoltaic system.

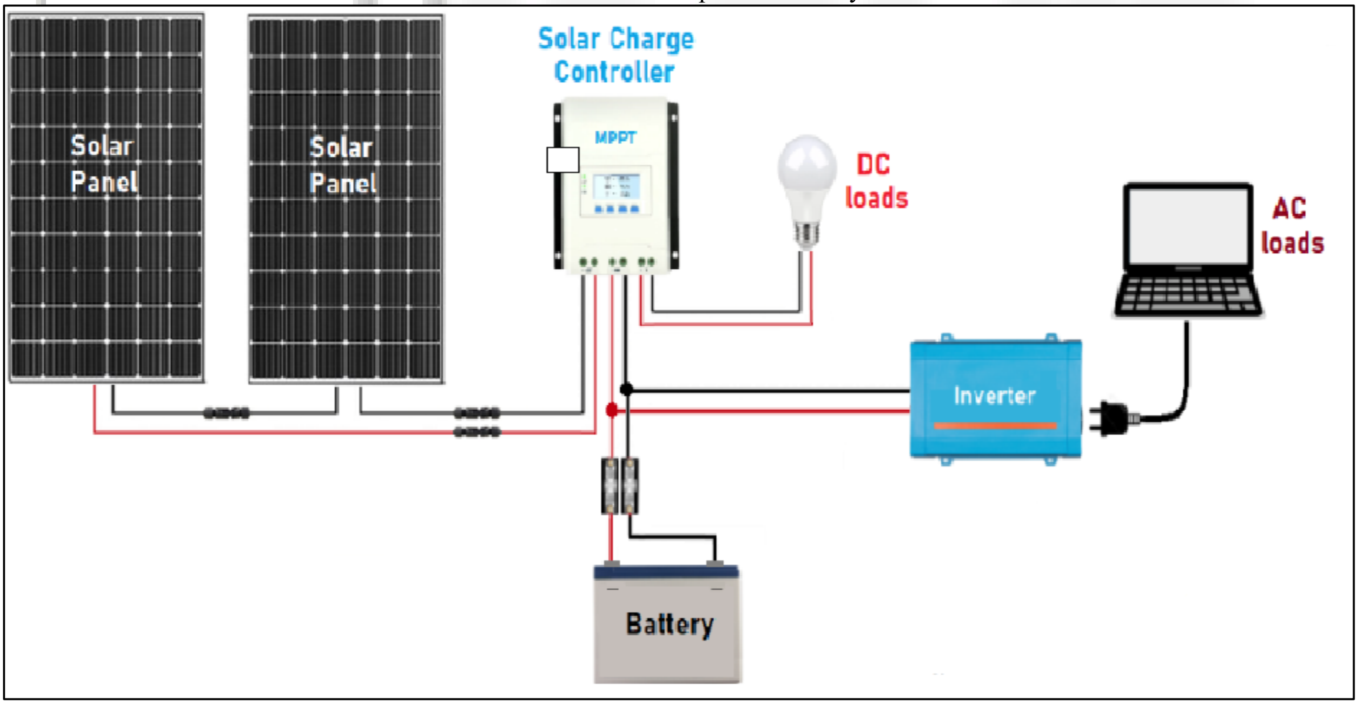

Fig. 1.2: MPPT connection and working

III. LITERATURE REVIEW

Several researchers investigated the influence of temperature on the performance of photovoltaic (PV) systems during the period 2012–2018. Their studies reported that an increase in PV cell temperature adversely affects the electrical characteristics of the module. Although the short-circuit current increases slightly with temperature, the open-circuit voltage decreases significantly, resulting in a reduction in maximum output power and overall conversion efficiency. These studies concluded that maintaining a lower operating temperature through proper ventilation or cooling techniques can improve the performance and lifespan of PV modules.[8]

A. Study on Partial Shading (2015–2020)

Various researchers examined the effect of partial shading on photovoltaic arrays between 2015 and 2020. Their findings showed that non-uniform irradiance caused by shading leads to the formation of multiple local maximum power points (LMPPs) on the power–voltage (P–V) characteristic curve. Under such conditions, conventional MPPT algorithms may converge to a local maximum instead of the global maximum, resulting in reduced energy extraction and lower system efficiency. The studies recommended the use of advanced MPPT techniques and suitable array configurations to minimize the adverse effects of partial shading. [9]

B. Study on Environmental Comparison (2020–2025)

Recent studies conducted between 2020 and 2025 have focused on the comparative performance evaluation of photovoltaic systems under different environmental conditions. Researchers analyzed the combined effects of solar irradiance, temperature, humidity, dust, and wind speed using both experimental setups and MATLAB/Simulink models. The results consistently showed that higher solar irradiance increases the output current and generated power, whereas higher operating temperatures reduce the output voltage and overall efficiency of PV modules. These comparative investigations provide valuable insights for selecting appropriate operating conditions and improving the design and performance of photovoltaic systems. [10]

Several researchers have investigated the influence of environmental conditions on the performance of solar photovoltaic (PV) systems. Previous studies have reported that the electrical output of PV modules is primarily affected by solar irradiance and operating temperature. An increase in solar irradiance generally improves the output current and generated power, whereas higher operating temperatures reduce the open-circuit voltage and overall conversion efficiency of the PV system. These findings highlight the importance of analysing PV system behaviour under different environmental conditions to achieve optimum energy conversion.[8]

IV. METHODOLOGY

A. Problem Identification

The performance of a Solar Photovoltaic (PV) system is highly influenced by environmental conditions, particularly solar irradiance and operating temperature. In practical applications, these parameters continuously vary due to weather changes, cloud movement, seasonal variations, and atmospheric conditions. Such variations directly affect the electrical characteristics of the PV array, including output voltage, current, and generated power.

A decrease in solar irradiance leads to a significant reduction in output current and power generation, whereas an increase in cell temperature mainly reduces the output voltage and overall conversion efficiency. Consequently, the operating point of the PV array shifts away from its Maximum Power Point (MPP), resulting in lower energy extraction and reduced system performance. Therefore, analysing the behaviour of photovoltaic systems under different environmental conditions is essential for improving their operational efficiency and reliability.

B. Research Gap

A review of the existing literature indicates that numerous researchers have analysed the performance of photovoltaic systems under varying environmental conditions. Most of the reported studies have primarily focused on the effect of solar irradiance or temperature as individual parameters. Although these investigations provide valuable insights into PV system behaviour, only limited research has presented a comprehensive comparative analysis considering multiple irradiance levels together with temperature variations using a MATLAB/Simulink-based simulation model.

Furthermore, there is still a need for a systematic evaluation of photovoltaic performance under different environmental scenarios to understand the combined influence of irradiance and temperature on the electrical characteristics of PV arrays. Addressing this gap can provide useful information for improving system design, performance assessment, and energy harvesting capability.

C. Aim of the Study

The primary aim of this research is to develop a MATLAB/Simulink model of a Solar Photovoltaic (PV) system and perform a comparative performance evaluation under different environmental conditions. The study investigates the influence of varying solar irradiance and operating temperature on the electrical characteristics of the PV array, including output voltage, output current, output power, and Maximum Power Point (MPP). The analysis also evaluates the effectiveness of the implemented Perturb and Observe (P&O) based MPPT controller in maintaining maximum power extraction under different operating conditions.

V. SIMULATION

Figure 4.1 shows the control panel of the proposed MATLAB/Simulink model used for evaluating the performance of the Solar Photovoltaic (PV) system under different environmental conditions. The model consists of a PV Control subsystem that receives the measured PV voltage (Vpv), PV current (Ipv), output voltage (Vo), and load current (IL) as input signals. Based on these measured parameters, the controller generates the appropriate gate pulse (Gpv) for the DC–DC Boost converter to regulate the operating point of the photovoltaic system.

The simulation model includes an interactive Solar Irradiance control knob, which allows the irradiance level to be varied from approximately 250 W/m² to 1000 W/m² during simulation. This feature is used to investigate the influence of changing solar radiation on the output voltage, current, and power of the PV system.

A Load Power control knob is also provided to modify the load demand during simulation. By changing the load conditions, the dynamic response and stability of the PV system can be analysed under different operating scenarios. The model further provides a PV Mode selector with two operating modes:

- MPPT Mode: The Perturb and Observe (P&O) algorithm continuously tracks the Maximum Power Point (MPP) to maximize the extracted solar power under varying environmental conditions.
- Voltage Control Mode: The PV array operates at a fixed voltage reference instead of continuously tracking the MPP. This mode is generally used when the required load power is lower than the maximum available PV power.

The simulation outputs are continuously monitored through the monitoring block and stored in the MATLAB workspace for further analysis. The recorded voltage, current, and power values are used to generate the comparative performance graphs presented in the subsequent sections.

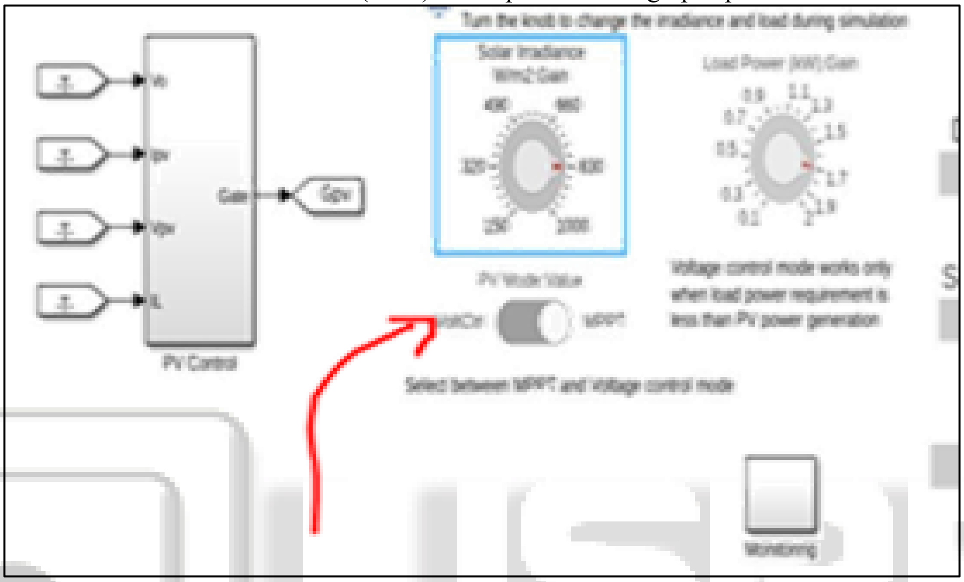

Fig. 4.1: MATLAB/Simulink control panel showing PV Control block, Solar Irradiance adjustment.

VI. Results and Discussion

A. MATLAB/Simulink Model of the Proposed Solar PV System

Figure 5.1 illustrates the complete MATLAB/Simulink model developed for the performance evaluation of the proposed Solar Photovoltaic (PV) system under variable environmental conditions. The model consists of a Solar PV array, Boost DC–DC converter, PV Control subsystem, measurement blocks, and monitoring units.

The Solar PV array converts solar irradiance into electrical energy, while the Boost converter regulates the output voltage and maintains an appropriate DC bus voltage. The PV Control subsystem receives the measured PV voltage (Vpv), PV current (Ipv), output voltage (Vo), and load current (IL) as feedback signals. Based on these measured values, the controller generates the gate pulse (Gpv) required for switching the Boost converter.

The simulation model also includes an adjustable Solar Irradiance control knob, allowing the irradiance level to be varied from approximately 250 W/m² to 1000 W/m² during simulation. Similarly, the Load Power control enables different loading conditions to be applied for performance analysis. A PV operating mode selector is provided to switch between Maximum Power Point Tracking (MPPT) mode and Voltage Control mode according to the operating requirements.

The measured output parameters, including DC bus voltage, PV voltage, PV current, and solar power, are continuously displayed and simultaneously stored in the MATLAB workspace for detailed analysis. This simulation model provides a flexible platform for evaluating the effect of changing environmental conditions on the electrical performance of the photovoltaic system.

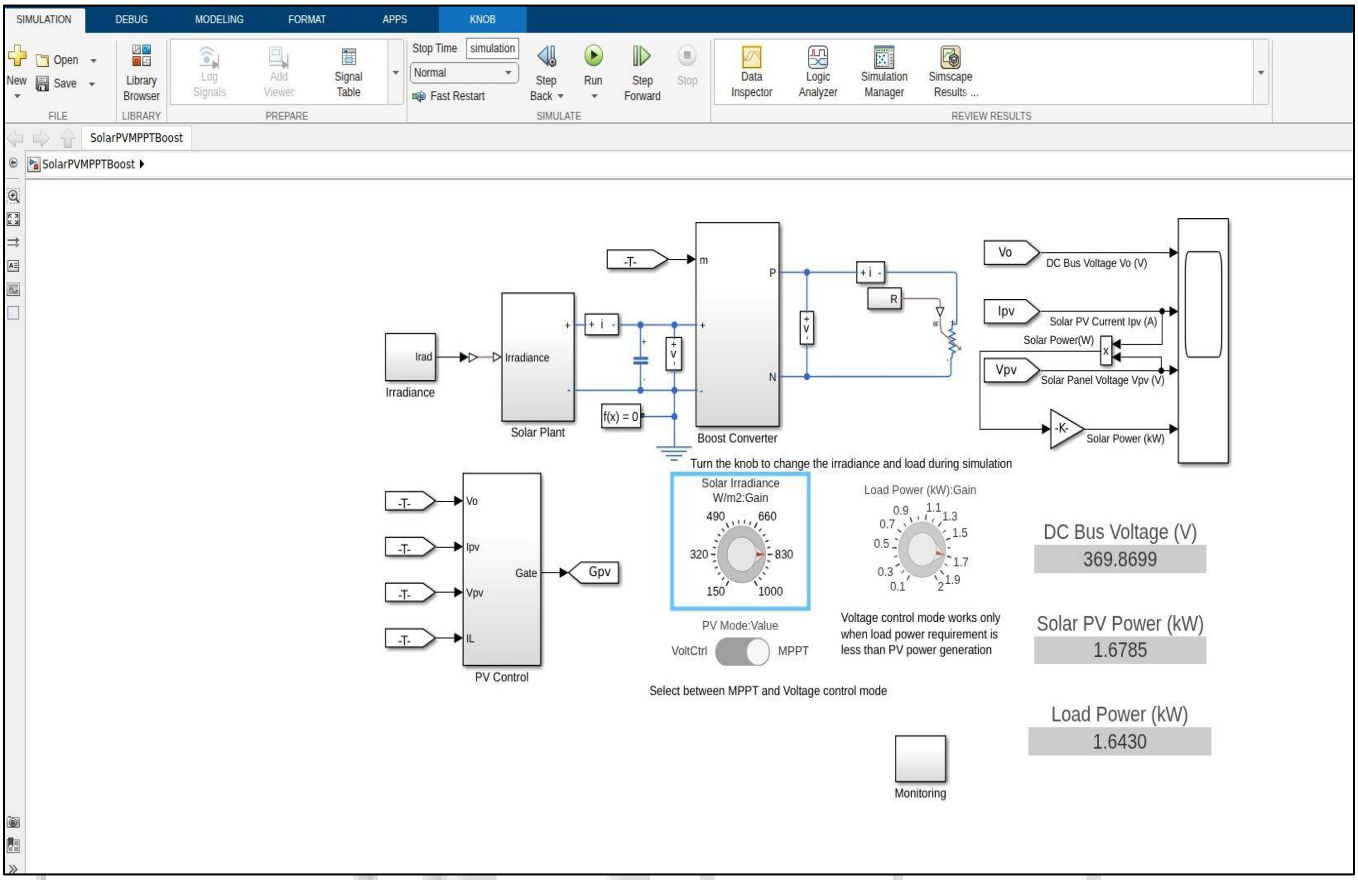

Fig. 5.1: MATLAB/Simulink model of the proposed Solar Photovoltaic system used for performance evaluation under variable environmental conditions.

B. *Output Waveforms of the Proposed PV System*

Figure 5.2 presents the simulation output waveforms obtained from the MATLAB/Simulink model. The figure displays the variations of DC bus voltage, PV output current, PV output voltage, and solar output power during the simulation period. The first waveform represents the DC bus voltage, which initially rises from its starting value and gradually reaches a stable operating level. This behavior indicates the proper operation of the Boost converter and the stable regulation of the DC bus.

The second waveform illustrates the PV output current. The current increases rapidly during the initial transient period and then stabilizes at a nearly constant value, indicating that the photovoltaic array is operating under steady environmental conditions.

The third waveform shows the PV output voltage. After a short transient response, the voltage reaches a stable operating point with only minor fluctuations. This confirms that the PV system operates close to its desired voltage under the implemented control strategy.

The fourth waveform represents the solar output power generated by the photovoltaic system. The output power increases during the initial stage of simulation and finally settles at a constant value after the Maximum Power Point is reached. The stable power output demonstrates the effective operation of the Perturb and Observe (P&O) MPPT algorithm, which continuously adjusts the operating point of the PV array to maximize power extraction under the selected environmental conditions.

Overall, the simulation results indicate that the proposed MATLAB/Simulink model achieves stable operation with fast transient response, efficient power conversion, and reliable maximum power tracking. The obtained waveforms validate the effectiveness of the developed PV system under the specified operating conditions.

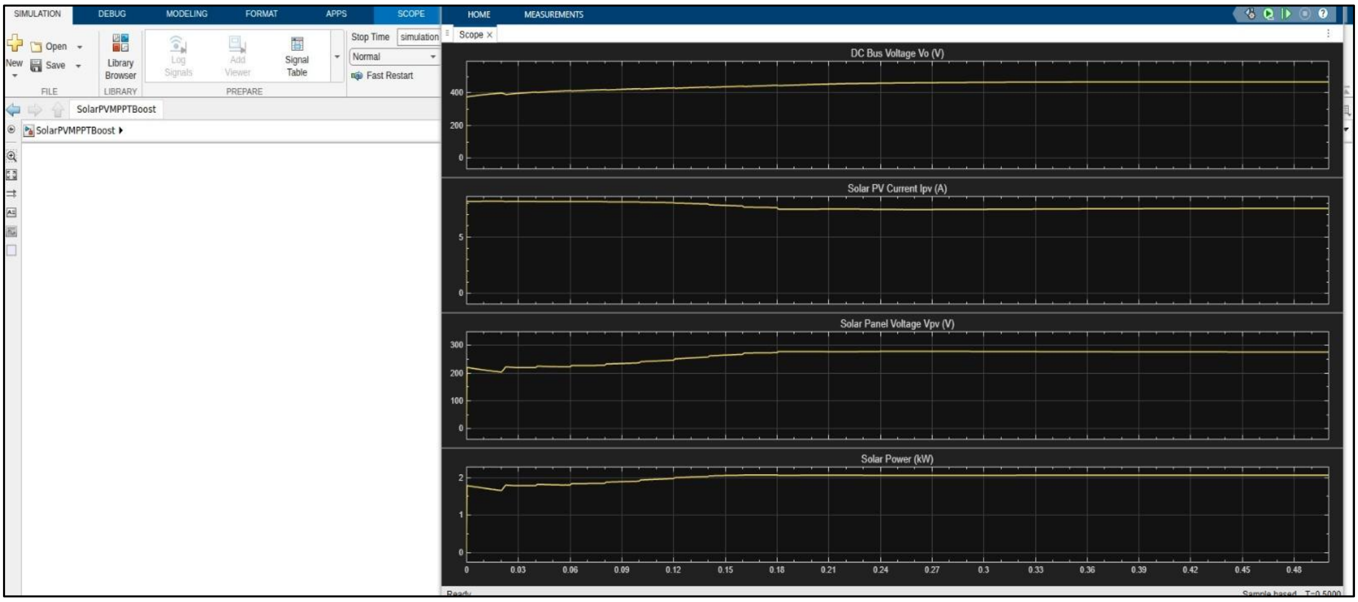

Fig. 5.2: Simulation output waveforms showing PV output voltage, and solar output power

VII. CONCLUSION

A comparative performance evaluation of the Solar PV array under different environmental conditions has been successfully carried out using MATLAB/Simulink. The developed model effectively demonstrates the influence of solar irradiance and temperature on PV voltage, current, output power, and overall efficiency.

The obtained results indicate that increasing solar irradiance enhances power generation, whereas increasing operating temperature reduces the output voltage and system efficiency. The MPPT controller effectively tracks the Maximum Power Point under all environmental conditions, thereby improving the overall performance of the Solar PV system.

VIII. FUTURE SCOPE

Future work may include:

- Comparison of different MPPT techniques.
- Partial shading analysis.
- Grid-connected Solar PV systems.
- Battery Energy Storage System integration.
- AI-based MPPT algorithms.
- IoT-enabled remote monitoring of Solar PV systems.

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