Modeling and Simulation of a 4×4 Solar Photovoltaic Array under Partial Shading Conditions with Multiple P–V Curve Analysis Using MATLAB/Simulink

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Abstract — Solar photovoltaic (PV) technology has emerged as one of the most reliable and environmentally friendly renewable energy sources for sustainable electricity generation. The increasing demand for clean energy and the depletion of conventional fossil fuels have accelerated the deployment of photovoltaic systems in residential, commercial, and industrial applications. However, the performance of PV arrays is highly dependent on environmental conditions, particularly solar irradiance and temperature. Among various environmental factors, partial shading is one of the most critical issues affecting the efficiency and power generation capability of photovoltaic systems. Partial shading occurs due to clouds, nearby buildings, trees, dust accumulation, or other obstacles, causing non-uniform irradiance across the PV modules. This results in mismatch losses, reduction in output power, and the formation of multiple peaks in the Power–Voltage (P–V) characteristics, making efficient power extraction more challenging. The primary objective of this research is to develop and simulate a 4×4 solar photovoltaic array model under different partial shading conditions using MATLAB/Simulink and to investigate its electrical performance through multiple Power–Voltage (P–V) curve analysis. A mathematical model of the PV array is developed by interconnecting sixteen identical photovoltaic modules in a 4×4 configuration. Different irradiance levels are applied to individual modules to simulate realistic partial shading scenarios while maintaining a constant operating temperature. Initially, the PV array is analyzed under uniform irradiance conditions to establish its reference operating characteristics, followed by several partial shading patterns representing practical environmental conditions. The developed simulation model is used to evaluate important electrical parameters such as output voltage, output current, maximum output power, and the corresponding P–V and I–V characteristics. The simulation results clearly demonstrate that partial shading significantly influences the electrical behavior of the PV array by producing multiple local maximum power points (LMPPs) along with a single global maximum power point (GMPP). As the severity of shading increases, mismatch losses become more prominent, leading to considerable reductions in output power and overall system performance. Comparative analysis of different shading patterns provides a comprehensive understanding of the impact of non-uniform irradiance on photovoltaic array characteristics. The proposed MATLAB/Simulink model offers an effective platform for studying the behavior of photovoltaic arrays under realistic operating conditions without the need for complex experimental setups. The developed model can also be extended for the implementation and evaluation of advanced Maximum Power Point Tracking (MPPT) techniques, intelligent optimization algorithms, and PV array reconfiguration strategies to improve energy harvesting under partial shading conditions. The outcomes of this study provide valuable insights for researchers, engineers, and designers working towards the development of efficient, reliable, and high-performance solar photovoltaic systems.

Keywords: Solar Photovoltaic (PV) Array, Partial Shading Conditions, MATLAB/Simulink, 4×4 PV Array, Power–Voltage (P–V) Characteristics, Current–Voltage (I–V) Characteristics, Solar Irradiance, Maximum Power Point (MPP), Local Maximum Power Point (LMPP), Global Maximum Power Point (GMPP), Performance Analysis, Renewable Energy

I. Introduction

Solar energy has emerged as one of the most promising renewable energy sources due to the rapid depletion of conventional fossil fuels, increasing global energy demand, and growing environmental concerns. The extensive use of coal, petroleum, and natural gas has resulted in greenhouse gas emissions, climate change, and environmental degradation. Consequently, there is a worldwide shift towards clean, sustainable, and environmentally friendly energy resources. Among various renewable energy technologies, solar photovoltaic (PV) systems have gained significant attention because they directly convert sunlight into electrical energy without producing harmful emissions. Their modular structure, low maintenance requirements, long operational life, and continuous technological advancements have made photovoltaic systems suitable for residential, commercial, industrial, and utility-scale applications.

The performance of a photovoltaic system mainly depends on the amount of solar irradiance received by the PV modules and the operating temperature. Under ideal operating conditions, all PV modules receive uniform solar radiation and operate at their maximum power point, thereby achieving maximum energy conversion efficiency. However, in practical installations, PV arrays are frequently subjected to non-uniform environmental conditions due to moving clouds, nearby buildings, trees, utility poles, dust accumulation, bird droppings, and other surrounding obstacles. These conditions create partial shading, where different modules in the same array receive different levels of solar irradiance. Partial shading causes electrical mismatch among the modules, resulting in significant power loss, reduction in system efficiency, and the formation of multiple peaks in the Power–Voltage (P–V) characteristics.

The occurrence of multiple power peaks under partial shading makes the operation of photovoltaic systems considerably more complex. Unlike uniform irradiance conditions, where only one maximum power point exists, partial shading introduces several local maximum power points (LMPPs) and one global maximum power point (GMPP). Conventional control strategies may fail to identify the global maximum power point, thereby reducing the overall energy harvested from the PV array. Therefore, understanding the electrical behavior of photovoltaic arrays under different shading conditions has become an important area of research in modern renewable energy systems.

MATLAB/Simulink provides a flexible and efficient simulation platform for analyzing the performance of photovoltaic systems under various operating conditions. The software enables accurate mathematical modeling of PV cells, PV modules, and complete PV arrays while allowing researchers to modify irradiance, temperature, and electrical parameters without the need for expensive experimental setups. Simulation-based analysis significantly reduces development time and provides valuable insights into the behavior of photovoltaic systems before practical implementation.

In this research, a 4×4 solar photovoltaic array consisting of sixteen identical PV modules is developed using MATLAB/Simulink. Various partial shading patterns are applied by assigning different irradiance levels to individual PV modules, thereby replicating realistic environmental conditions. The electrical performance of the PV array is evaluated through output voltage, output current, output power, and multiple Power–Voltage (P–V) characteristic curves. Comparative analysis between uniform irradiance and different partial shading conditions is carried out to investigate the influence of shading on photovoltaic system performance.

The results obtained from the developed simulation model provide a clear understanding of mismatch losses, reduction in output power, and changes in the electrical characteristics of the PV array under partial shading conditions. The study also establishes a simulation framework that can be extended for future implementation of advanced Maximum Power Point Tracking (MPPT) algorithms, intelligent optimization techniques, and PV array reconfiguration methods aimed at improving the efficiency and reliability of photovoltaic systems operating under non-uniform environmental conditions.

Overall, this research contributes to the analysis of photovoltaic array behavior under practical operating environments and demonstrates the effectiveness of MATLAB/Simulink as a powerful tool for the modeling and performance evaluation of solar photovoltaic systems. The outcomes of this work are expected to support future research in the design and optimization of high-efficiency photovoltaic power generation systems.[1]

A. Renewable Energy Sources

Renewable energy refers to energy obtained from naturally replenishing resources that are continuously available in the environment and can be utilized without permanent depletion. Unlike conventional fossil fuels such as coal, petroleum, and natural gas, renewable energy sources are sustainable, environmentally friendly, and capable of meeting long-term energy demands. These resources are naturally regenerated through processes such as sunlight, wind circulation, the water cycle, geothermal heat, and biological growth. Due to their inexhaustible nature, renewable energy sources play a significant role in achieving sustainable development and reducing dependence on non-renewable energy resources.[4]

The increasing global demand for electricity, rapid industrialization, population growth, and the depletion of fossil fuel reserves have created a serious need for alternative energy resources. Moreover, excessive consumption of fossil fuels has resulted in greenhouse gas emissions, global warming, climate change, and environmental pollution. These challenges have encouraged governments and researchers worldwide to promote renewable energy technologies as an effective solution for clean and sustainable power generation. Renewable energy not only reduces carbon emissions but also improves energy security, decreases fuel dependency, and supports economic development.

Renewable energy resources can be classified into six major categories: solar energy, wind energy, hydropower, biomass energy, geothermal energy, and ocean energy. Each renewable energy source has unique characteristics, advantages, and application areas depending on the availability of natural resources and geographical conditions.

Among these resources, solar energy is the most abundant and widely available source of renewable energy. Solar photovoltaic (PV) technology directly converts sunlight into electrical energy using semiconductor devices called photovoltaic cells. Solar energy is clean, noiseless, requires minimal maintenance, and can be installed in residential, commercial, industrial, and utility-scale applications.

Wind energy converts the kinetic energy of moving air into electrical energy using wind turbines. It is one of the fastest-growing renewable energy technologies and is particularly suitable for regions with high wind speeds. Wind power generation is environmentally friendly but depends on wind availability and seasonal variations.

Hydropower utilizes the energy of flowing or stored water to generate electricity through hydraulic turbines. It is one of the oldest and most reliable renewable energy technologies and provides stable power generation. However, large hydropower projects require significant investment and may have environmental impacts on aquatic ecosystems.

Biomass energy is generated from organic materials such as agricultural residues, forestry waste, municipal solid waste, and animal waste. Biomass can be converted into electricity, heat, or biofuels through different conversion processes. It contributes to waste management while providing an alternative source of renewable energy.

Geothermal energy utilizes the heat stored beneath the Earth's surface for electricity generation and heating applications. This energy source provides continuous power generation with low environmental pollution but is limited to regions having suitable geothermal resources.

Ocean energy, including tidal energy, wave energy, and ocean thermal energy, represents another promising renewable energy resource. Although it possesses enormous energy potential, its commercial implementation is still limited due to technological and economic challenges.

Among all renewable energy technologies, solar photovoltaic energy has gained the greatest attention because of its high availability, modular design, low operating cost, long service life, and environmental sustainability. Continuous improvements in photovoltaic materials, power electronic converters, and simulation software have significantly enhanced the performance and economic viability of solar PV systems. Consequently, photovoltaic technology has become one of the fastest-growing renewable energy sectors across the world.[2][3]

Energy Source	Main Resource	Major Application	Advantages	Limitations
Solar Energy	Sunlight	Electricity, Heating	Clean, abundant, low maintenance	Weather dependent
Wind Energy	Wind	Electricity Generation	No fuel cost, clean	Variable wind speed
Hydropower	Water	Electricity Generation	High efficiency, reliable	High initial cost
Biomass	Organic Matter	Heat, Electricity, Biofuel	Waste utilization	Emissions during combustion
Geothermal	Earth's Heat	Electricity, Heating	Continuous power generation	Limited geographical availability
Ocean Energy	Waves, Tides	Electricity Generation	Huge energy potential	High installation cost

Table 1.1:

B. *Solar Energy*

Solar energy is the radiant energy emitted by the Sun in the form of electromagnetic radiation. It is one of the most abundant, clean, and sustainable renewable energy sources available on Earth. Every day, the Sun releases an enormous amount of energy, a small fraction of which reaches the Earth's surface and is sufficient to meet global energy requirements. Unlike conventional fossil fuels, solar energy is naturally replenished, environmentally friendly, and does not produce harmful greenhouse gas emissions during electricity generation. Owing to its unlimited availability and eco-friendly nature, solar energy has become one of the fastest-growing renewable energy resources worldwide.

The increasing demand for electricity, rapid industrialization, and growing environmental concerns have accelerated the adoption of solar energy technologies. The extensive use of fossil fuels has resulted in air pollution, global warming, and depletion of natural resources. Consequently, governments and research organizations are encouraging the use of solar energy to achieve sustainable development and reduce carbon emissions. Technological advancements, decreasing installation costs, and supportive government policies have further enhanced the economic feasibility of solar energy systems.

Solar energy can be utilized in two primary forms: solar thermal energy and solar photovoltaic (PV) energy. Solar thermal systems convert solar radiation into heat energy, which is used for water heating, space heating, industrial processes, and electricity generation through steam turbines. In contrast, photovoltaic systems directly convert sunlight into electrical energy using semiconductor devices known as photovoltaic cells. Among these technologies, photovoltaic power generation has gained widespread acceptance because of its simplicity, modular design, low maintenance requirements, and ability to generate electricity without moving mechanical components.

The amount of solar energy received at any location depends on several environmental factors, including geographical position, seasonal variation, time of day, atmospheric conditions, cloud cover, and ambient temperature. Solar irradiance, usually measured in watts per square meter (W/m²), represents the intensity of solar radiation incident on a unit surface area. Under Standard Test Conditions (STC), the irradiance is considered 1000 W/m², with a cell temperature of 25°C and an air mass (AM) of 1.5. These standard conditions are widely used for evaluating and comparing the performance of photovoltaic modules.

Solar energy offers several advantages over conventional energy sources. It is clean, renewable, silent in operation, and requires minimal maintenance after installation. Solar photovoltaic systems have a long operational life, typically exceeding 25 years, and can be deployed in both grid-connected and standalone applications. Furthermore, solar energy reduces dependence on fossil fuels, minimizes greenhouse gas emissions, and contributes to sustainable economic development. However, the performance of solar energy systems is highly dependent on environmental conditions such as solar irradiance, temperature, dust accumulation, and partial shading. These factors significantly influence the electrical output and overall efficiency of photovoltaic systems.

Today, solar energy is widely utilized in residential buildings, commercial establishments, industries, agricultural irrigation systems, street lighting, telecommunication stations, water pumping systems, electric vehicle charging stations, and large-scale solar power plants. Continuous improvements in photovoltaic materials, power electronic converters, and energy storage technologies have further expanded the applications of solar energy in modern electrical power systems.

In the present research, solar energy is utilized through a 4×4 photovoltaic array developed in MATLAB/Simulink to investigate the effect of different partial shading conditions on the electrical characteristics of the PV system. Since solar irradiance is the primary energy source for photovoltaic power generation, understanding the fundamentals of solar energy is essential for analyzing the performance of PV arrays under both uniform and non-uniform operating conditions.[6] [7]

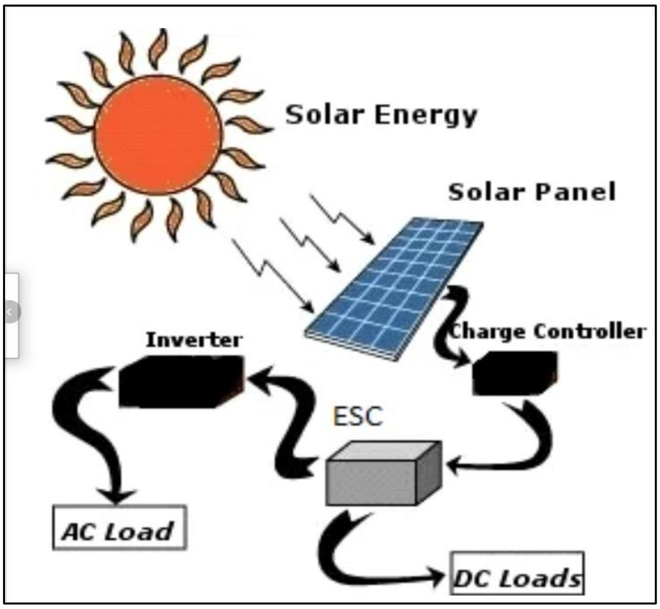

Fig. 1: working of solar system

II. Literature Review

A. *Solar Photovoltaic Array Modelling*

The modelling of photovoltaic (PV) arrays has become an important research area because simulation enables researchers to analyse system behaviour before practical implementation. Mathematical models developed using MATLAB/Simulink accurately represent the nonlinear electrical characteristics of PV modules under different operating conditions. These models predict the current–voltage (I–V) and power–voltage (P–V) characteristics while considering variations in solar irradiance and cell temperature. Simulation-based modelling also reduces experimental cost, improves design accuracy, and provides a flexible platform for evaluating different PV configurations and control techniques.[8]

B. *Effect of Partial Shading on Photovoltaic Arrays*

Partial shading is one of the most significant factors responsible for reducing the performance of photovoltaic arrays. Under practical operating conditions, different PV modules receive different levels of solar irradiance because of clouds, nearby buildings, trees, dust, or other obstructions. This non-uniform irradiance creates mismatch losses among interconnected modules and causes multiple local maximum power points (LMPPs) to appear on the power–voltage (P–V) curve. As a result, the overall output power and efficiency of the PV array decrease considerably. Researchers have analysed different shading patterns, including row, column, diagonal, and random shading, to understand their impact on photovoltaic system performance.[9]

C. *Photovoltaic Array Configurations under Partial Shading*

Different interconnection schemes have been proposed to minimise mismatch losses under partial shading conditions. Conventional Series–Parallel (SP) arrays are simple to implement but experience considerable power loss during non-uniform irradiance. To improve energy extraction, researchers have investigated Total Cross-Tied (TCT), Bridge-Linked (BL), Honeycomb (HC), and Sudoku-based array configurations. Comparative studies indicate that the TCT configuration provides better current sharing among PV modules and improves power generation under partial shading compared with conventional Series–Parallel arrays.[10]

D. *MATLAB/Simulink-Based Analysis of Partial Shading*

MATLAB/Simulink has become one of the most widely adopted simulation platforms for analysing photovoltaic systems because of its accurate modelling capability and user-friendly graphical environment. Researchers have successfully implemented PV arrays, DC–DC converters, MPPT controllers, and load models using MATLAB/Simulink to investigate electrical performance under different irradiance conditions. The software allows detailed analysis of I–V and P–V characteristics, output voltage, current, generated power, and multiple power peaks produced during partial shading. Simulation results obtained from MATLAB/Simulink closely match practical observations and are therefore widely accepted for photovoltaic system design and optimisation.[11]

III. Research Methodology

A. *Introduction*

This chapter presents the methodology adopted for modelling and simulating a 4×4 Solar Photovoltaic (PV) array under different partial shading conditions using MATLAB/Simulink. The proposed methodology includes the development of the PV array model, implementation of different shading patterns, execution of simulations, and analysis of the resulting Current–Voltage (I–V) and Power–Voltage (P–V) characteristics. The chapter also describes the simulation parameters and performance indices used to evaluate the behaviour of the PV array.

B. *Problem Identification*

Photovoltaic systems are highly dependent on solar irradiance. Under practical operating conditions, PV arrays are frequently exposed to partial shading due to clouds, nearby buildings, trees, dust accumulation, or other environmental obstacles. Partial shading causes different PV modules within the same array to receive unequal irradiance levels, creating electrical mismatch among the modules. As a result, the output power decreases significantly and multiple peaks appear in the Power–Voltage (P–V) characteristics. These effects reduce the efficiency and reliability of photovoltaic systems, making it essential to investigate PV array behaviour under various shading conditions.

C. *Research Gap*

Numerous studies have analysed photovoltaic arrays under partial shading conditions using different MPPT techniques and array configurations. However, most published research mainly focuses on improving MPPT algorithms or comparing different electrical interconnections of PV modules. Comparatively fewer studies provide a comprehensive MATLAB/Simulink-based modelling and simulation of a 4×4 photovoltaic array with detailed analysis of multiple P–V curves under different partial shading patterns. Therefore, a systematic comparative investigation is required to understand the occurrence of local and global maximum power points under various shading scenarios.

D. Aim of the Study

The primary aim of this research is to develop a 4×4 Solar Photovoltaic array model using MATLAB/Simulink and evaluate its performance under different partial shading conditions. The study investigates the electrical behaviour of the PV array by analysing its Current–Voltage (I–V) and Power–Voltage (P–V) characteristics, identifying Local Maximum Power Points (LMPPs) and the Global Maximum Power Point (GMPP), and comparing the performance under different shading patterns.

E. Objectives of the Study

The objectives of the proposed work are:

- To develop a MATLAB/Simulink model of a 4×4 Solar PV array.
- To simulate different partial shading conditions by applying different irradiance levels to individual PV modules.
- To analyse the Current–Voltage (I–V) characteristics under different shading patterns.
- To analyse the Power–Voltage (P–V) characteristics and identify multiple power peaks.
- To determine the Local Maximum Power Points (LMPPs) and Global Maximum Power Point (GMPP).
- To compare the electrical performance of the PV array under different shading scenarios.
- To evaluate the influence of partial shading on overall PV system efficiency.

F. Proposed Methodology

The proposed methodology begins with the development of a 4×4 photovoltaic array in the MATLAB/Simulink environment. Initially, all sixteen PV modules are operated under uniform irradiance to establish the reference performance of the system. Different partial shading conditions are then introduced by assigning different irradiance levels to selected PV modules. The output voltage, current, and power are measured for each shading pattern. Finally, the corresponding I–V and P–V characteristics are generated to analyse the electrical behaviour of the PV array and identify the local and global maximum power points.

G. Development of the 4×4 PV Array Model

A 4×4 photovoltaic array, consisting of sixteen identical solar modules, is developed using MATLAB/Simulink. Each PV module is provided with an independent irradiance input so that different shading conditions can be simulated accurately. Voltage and current measurement blocks are connected to the array for continuous monitoring of electrical output parameters. The simulation data are stored in the MATLAB workspace and later used for generating I–V curves, P–V curves, and comparative performance plots.

IV. SIMULATION

A. Development of 4×4 PV Array Model in MATLAB/Simulink

A 4×4 solar photovoltaic (PV) array model was developed in the MATLAB/Simulink environment to investigate the performance of the PV system under different operating conditions. The complete model consists of sixteen identical PV modules connected in a predefined array configuration. Each PV module is provided with independent irradiance and temperature inputs, allowing different partial shading conditions to be simulated by assigning different irradiance values to individual modules. This approach enables accurate analysis of the electrical behavior of the PV array under both uniform and non-uniform solar irradiance.

The PV array model includes measurement blocks for voltage and current, enabling the calculation of output power and the generation of current–voltage (I–V) and power–voltage (P–V) characteristics. The simulation parameters are configured to record all output variables in the MATLAB workspace, facilitating further analysis and graphical representation of the system performance.

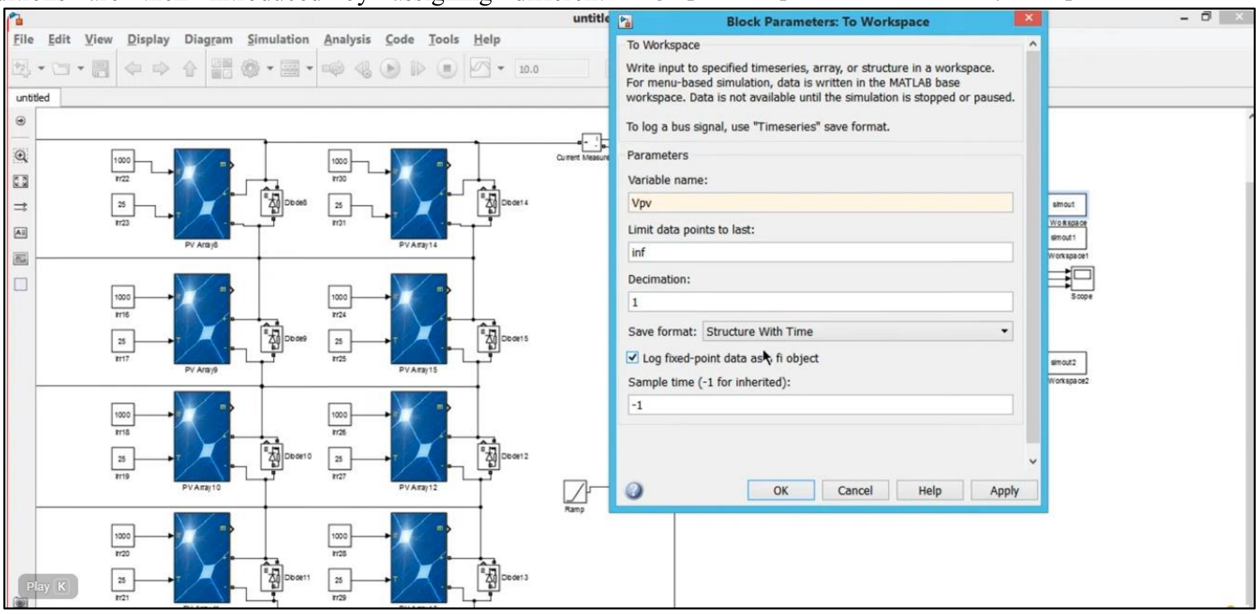

Fig. 4.1: MATLAB/Simulink model of the 4×4 solar photovoltaic array with To Workspace block configuration for storing simulation data.

V. RESULTS AND DISCUSSION

A. Simulation Results and Discussion

The developed 4×4 solar photovoltaic (PV) array model was simulated in MATLAB/Simulink to evaluate its electrical characteristics under the specified operating conditions. During the simulation, the PV array voltage was gradually varied using a controlled voltage source while the corresponding output current and power were continuously measured. The measured data were transferred to the MATLAB workspace using the To Workspace blocks for further analysis and graphical representation.

The simulation outputs include the variation of array voltage, current, and output power with respect to time. These results provide a clear understanding of the operating characteristics of the PV array and help identify the maximum power point (MPP). The generated P–V characteristics also demonstrate the electrical behavior of the PV array, which serves as the reference case before applying different partial shading patterns.

The simulation is carried out under different environmental conditions.

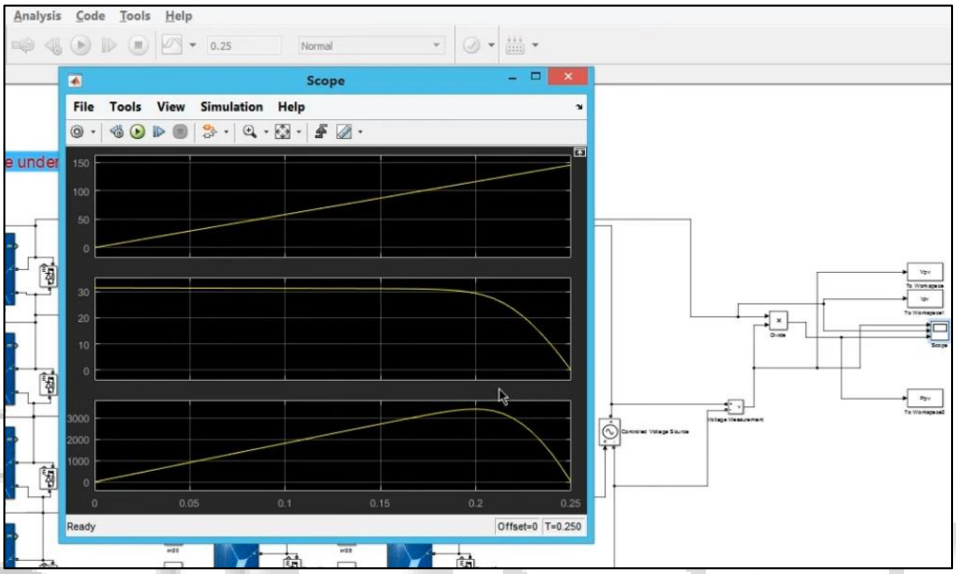

Fig. 5.1: Scope output illustrating the voltage, current, and power characteristics of the 4×4 solar PV array.

B. Scope Output Analysis

The Scope window shown in Figure 4.X displays three important electrical parameters obtained during the simulation.

- The first waveform represents the PV array output voltage, which increases linearly with simulation time due to the controlled voltage sweep.
- The second waveform shows the output current of the PV array. Initially, the current remains nearly constant, indicating normal operation of the PV modules. As the operating voltage approaches the open-circuit voltage (Voc), the current decreases rapidly and finally becomes zero.
- The third waveform represents the output power of the PV array. The output power increases with voltage, reaches a maximum value corresponding to the Maximum Power Point (MPP), and then decreases sharply as the operating voltage approaches the open-circuit condition.

These waveforms confirm the expected electrical characteristics of a photovoltaic array and validate the developed MATLAB/Simulink model.

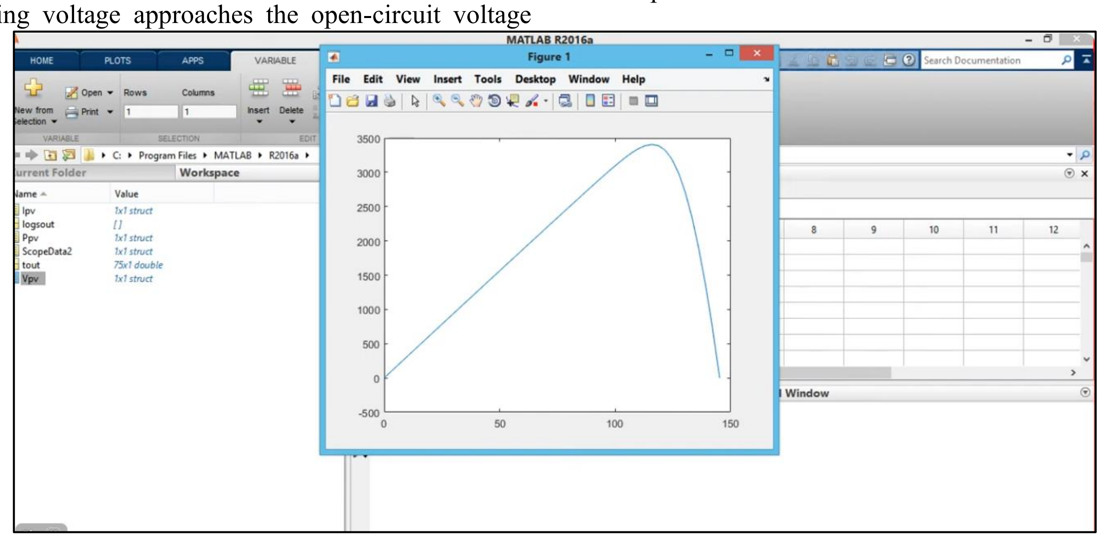

Fig. 5.2: Power–Voltage (P–V) characteristic of the 4×4 solar PV array under standard test conditions (1000 W/m², 25°C).

C. Comparative Performance Analysis

The simulation results demonstrate that solar irradiance has a direct impact on the electrical performance of the photovoltaic array. As the irradiance decreases, the output current and generated power decrease proportionally. On the other hand, increasing temperature mainly affects the PV output voltage and reduces the overall efficiency of the system.

The comparative analysis confirms that maximum power generation is achieved under high irradiance and low temperature conditions. Furthermore, the MPPT controller continuously tracks the maximum power point and ensures efficient utilization of the available solar energy under varying environmental conditions.

VI. 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.

VII. 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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