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Simulation Based Performance Assessment of Solar System Using Mppt Controller In Renewable Energy Integration Of Grid

I. Mahmud[1], B.K. Ahmad[2]
Department of Electrical Engineering, Ahmadu Bello University, Zaria.
[1]imahmud@abu.edu.ng, [2] khalidbello93@gmail.com

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ABSTRACT

This study presents the simulation-based performance assessment of a solar photovoltaic (PV) system integrated with a Maximum Power Point Tracking (MPPT) controller, utilizing the Perturb and Observe (P&O) algorithm. The project aims to optimize the efficiency of solar energy conversion and its integration with the electrical grid. Two interconnected PV arrays, configured with different module specifications, were simulated using MATLAB, each employing a boost converter and an MPPT controller to maximize power output. The simulation results demonstrated a notable improvement in grid power output. Initially, a power level of 240 kW was achieved without the MPPT controller. However, with the integration of the MPPT controller, grid power increased to 270 kW, underscoring the controller's effectiveness in optimizing power delivery. Additionally, the voltage source converter (VSC) and accompanying filter played crucial roles in smoothing the output, contributing to enhanced stability and efficiency before connecting to the grid, ensuring stable energy supply. The results underscore the significance of enhanced power tracking, specifically through MPPT, as a response to the increasing demand for efficient, clean energy solutions. By demonstrating an increase from 240 kW to 270 kW with the MPPT controller, this study adds to the body of knowledge on grid-integrated solar systems by highlighting the quantifiable impact of optimized power delivery in renewable energy systems. This research provides actionable insights into how MPPT integration can lead to more stable, higher-performing solar power outputs, which is essential for advancing sustainable energy practices.

1. INTRODUCTION

The increasing demand for sustainable energy solutions has accelerated the development and integration of renewable energy systems into existing power grids [1, 2]. Among these, solar photovoltaic (PV) systems have gained significant attention due to their abundant and environmentally friendly energy source [3]. However, the efficiency of these systems can be significantly compromised by environmental factors such as temperature fluctuations, shading, and varying irradiance, which impact the overall energy yield and require optimization for consistent performance [4, 5]. To optimize the performance of solar PV systems, Maximum Power Point Tracking (MPPT) controllers have been extensively employed, with a variety of algorithms developed to ensure maximum energy extraction under diverse conditions [6][7].

MPPT controllers have become an essential component in enhancing solar PV system efficiency by dynamically adjusting the operating point of the solar panels to maximize output power. Several studies have highlighted the importance of MPPT in increasing the reliability and stability of solar PV systems, particularly when integrated into electrical grids [8][9]. A popular MPPT algorithm, the Perturb and Observe (P&O) technique, has been widely used due to its simplicity and effective real-time performance. According to [6], the P&O algorithm ensures that solar PV systems operate at their optimal power point by perturbing the operating voltage and observing the resulting changes in power output [10]. This method has been validated in several simulation and real-world studies, demonstrating its capacity to improve energy yields in varying environmental conditions [11][12].

The integration of renewable energy sources like solar PV into power grids requires the system to be stable and flexible to handle fluctuations in energy supply and demand. In [7], the study conducted performance comparisons between MPPT algorithms, including the P&O and Incremental Conductance methods, under different irradiance conditions [13]. Their work highlights how these algorithms help maintain grid stability by maximizing the power delivered from the PV array to the grid. This integration has been further explored in hybrid systems where solar energy is combined with other renewable sources, requiring advanced MPPT strategies for efficient energy management [14].

In addition to maximizing energy extraction, MPPT controllers play a crucial role in the voltage regulation and power quality of grid-connected PV systems. The inclusion of power electronics, such as voltage source converters (VSC) and boost converters, further enhances the performance of these systems. Studies by [8] emphasize the critical role of MPPT controllers in managing energy conversion, ensuring that power is delivered efficiently to the grid while maintaining voltage and current parameters within acceptable limits [15]. These studies have been corroborated by real-world applications where MPPT controllers have been shown to increase the overall energy output of solar PV systems by up to 20% [16].

In conclusion, the integration of MPPT controllers in solar PV systems represents a significant advancement in the field of renewable energy. By optimizing power output, ensuring grid stability, and improving energy management, MPPT technology plays a critical role in the transition towards a more sustainable and reliable energy future. Future work in this area could focus on developing more adaptive algorithms, enhancing the scalability of MPPT for large-scale solar installations, and integrating these systems with emerging technologies such as smart grids and energy storage solutions.

2. SOLAR PV ARRAY

Solar PV arrays are an essential component in renewable energy systems, converting sunlight directly into electricity. Understanding the characteristics of PV arrays, such as their current-voltage (I-V) and power-voltage (P-V) curves, is crucial for optimizing their performance under varying environmental conditions. These characteristics are influenced by factors like irradiance, temperature, and load conditions, which ultimately determine the system's efficiency. At maximum power point (MPP), the PV array operates at its most efficient level, where the product of voltage and current yields the highest power output. However, due to the nonlinear nature of PV array characteristics, achieving and maintaining MPP under fluctuating environmental conditions becomes challenging. As shown in Fig 1, the I-V and P-V curves of a PV array change significantly with irradiance and temperature levels [17][18] This demonstrates the importance of maximum power point tracking (MPPT) controllers, which continuously adjust the operating voltage to ensure that the system extracts the maximum possible power from the PV array under any given conditions [19].

MPPT controllers are particularly vital in renewable energy systems where efficiency must be maximized to meet energy demands. The perturb and observe (P&O) algorithm is one of the most widely used MPPT techniques due to its simplicity and effectiveness. It iteratively perturbs the operating point of the PV array and observes the resulting change in power. If the power increases, the algorithm continues in the same direction; if the power decreases, it reverses the perturbation direction [20].

The impact of temperature and irradiance on PV array performance highlights the critical role of MPPT. As temperature increases, the open-circuit voltage of the PV array decreases, reducing overall efficiency. On the other hand, higher irradiance levels increase the short-circuit current, which can improve performance but requires the MPPT to adapt to prevent losses from mismatches between the array and the load [21]. Figure 2 illustrates how an MPPT controller adjusts the operating point of the PV array to maintain maximum power output across different environmental conditions [22].

In addition, the integration of MPPT controllers helps in reducing energy losses during partial shading conditions, a common issue in PV arrays installed in urban or irregular terrains. When part of a PV array is shaded, the I-V characteristics shift, causing significant power losses. An MPPT controller minimizes these losses by quickly finding the new MPP under the altered conditions**.**

3. PROPOSED SIMULATION MODEL

This section outlines the design of the PV system, the MPPT controller implementation, and the simulation setup.

3.1 PV Array Configuration

Two different PV arrays were simulated. The first system comprises 54-cell modules, 6 series-connected modules per string, and 61 parallel strings. The second system consists of 96-cell modules, 5 series-connected modules per string, and 66 parallel strings. Each system is connected to an MPPT controller.

3.2 MPPT Controller Design

The MPPT controller employs the P&O algorithm, which adjusts the operating voltage and monitors the power output. If the power increases, the controller continues adjusting the voltage in the same direction. If the power decreases, the direction of adjustment is reversed to maintain operation at the maximum power point.

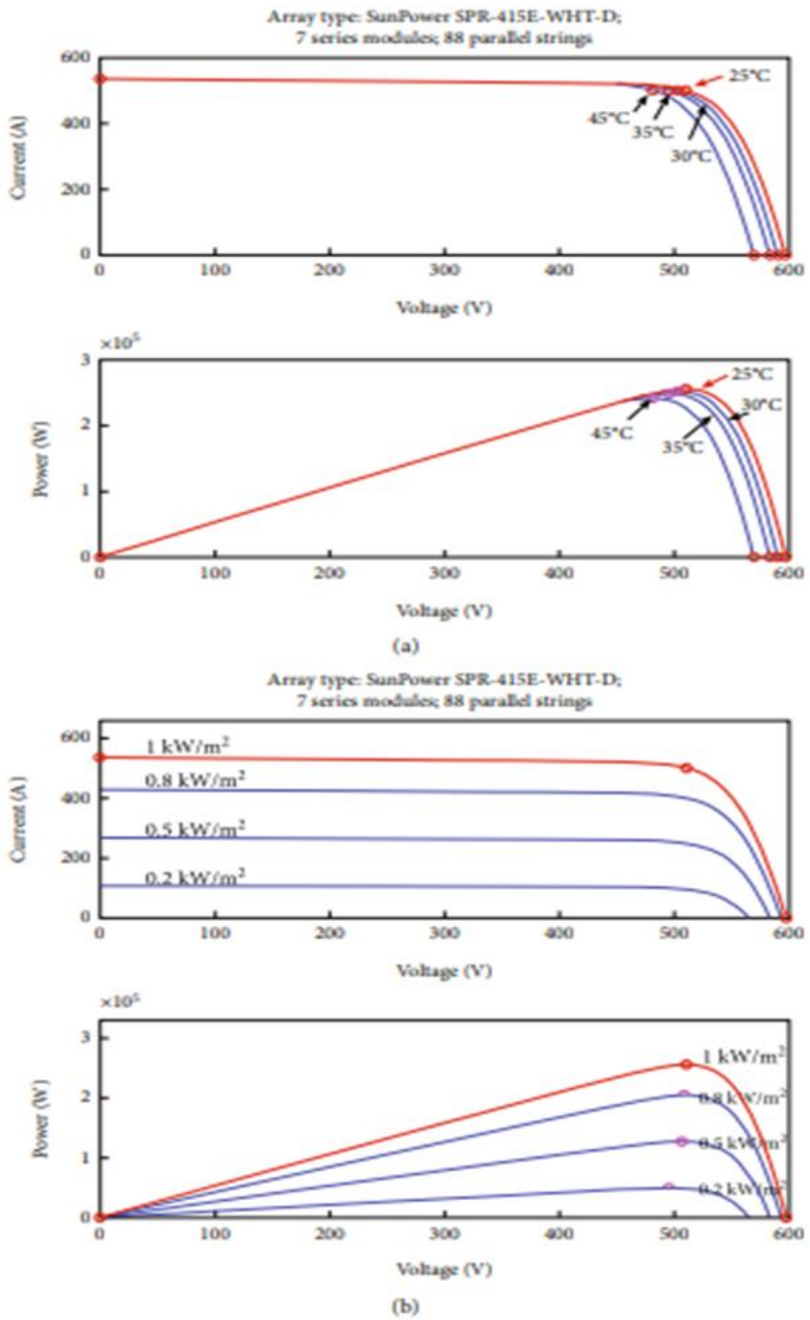

Fig 1: PV array characteristics: (a) I-V and P-V curves at STC irradiation and variable temperature and (b) I-V and P-V curves at STC temperature and variable irradiation

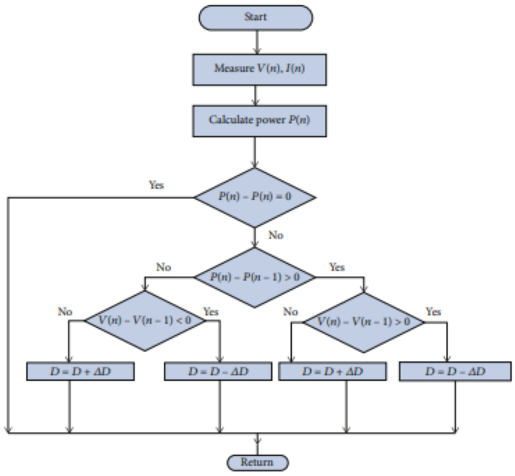

Fig 2: Flowchart of the P&O algorithm

The Perturb and Observe (P&O) algorithm in Fig 2 works by slightly perturbing the operating voltage or current of a photovoltaic (PV) system and observing the resulting change in power P(n). Initially, the algorithm measures the PV array's voltage V(n) and current I(n) to compute power. A small perturbation (ΔD) is then applied to the system.

If the power increases, the perturbation (D) continues in the same direction. If the power decreases, the direction of perturbation is reversed. This continuous process allows the algorithm to track the maximum power point (MPP) of the PV array. The cycle repeats until the system stabilizes near the MPP, where small oscillations may still occur, but the system operates at its maximum efficiency.

The P&O algorithm is simple and effective but can struggle under rapidly changing environmental conditions, as it may fail to track the MPP accurately during such fluctuations [23]. The flowchart typically visualizes these steps by showing the initialization, perturbation, power comparison, and direction adjustment processes in a loop, ensuring continuous optimization of power output.

3.3 Simulation Setup

In the simulation setup, MATLAB/Simulink was employed to model a solar photovoltaic (PV) system connected to the grid as shown in fig 3.

The methodology for this study involved simulating a photovoltaic (PV) system connected to the grid to assess its performance with and without a Maximum Power Point Tracking (MPPT) controller, a technique widely discussed in PV optimization research due to its capacity to maximize energy capture [24]. The system was designed in MATLAB/Simulink with two distinct PV arrays connected independently, each integrated with its own MPPT controller using the Perturb and Observe (P&O) algorithm. These arrays had unique configurations: the first array used modules with 54 cells, arranged with six modules in series and 61 parallel strings, while the second used 96-cell modules arranged in five series-connected modules and 66 parallel strings. These configurations allowed for realistic operational testing and a comparative analysis of various module designs in enhancing power output.

This process optimizes performance but may struggle to track the MPP in rapidly fluctuating irradiance conditions, which can impede power capture [23]. In the non-MPPT scenario, a standard duty cycle of 0.5 and irradiance of 1000 W/m² were assumed, aligning with industry standards to facilitate comparison between scenarios with and without MPPT control [25]. A toggle switch was introduced in the simulation to enable quick switching between MPPT-enabled and disabled states, providing a dynamic assessment of MPPT's impact on energy output.

The energy from each array was routed through a boost converter, allowing for voltage optimization before being directed to a three-phase Voltage Source Converter (VSC), modeled with three bridge arms functioning as an inverter. The VSC allowed for DC-to-AC conversion, necessary for grid integration, and was followed by a basic RLC filter to smooth the output and reduce harmonics in the AC signal, a vital step for ensuring compatibility with grid standards. After filtering, the AC power was stepped up to grid level using a 33 kV/415 V transformer, supplying a 15 kW load and interfacing with the 33 kV grid, simulating an authentic grid-tied renewable energy system. This setup facilitated an examination of the renewable energy system's contribution to grid power delivery, with simulation results showing an increase in grid power from 240 kW without MPPT to 270 kW with MPPT.

Graphical results from the simulation include plots illustrating the relationship between input parameters like irradiance and the corresponding power output. These graphs highlight the system's response and confirm the effectiveness of the MPPT algorithm in optimizing power output.

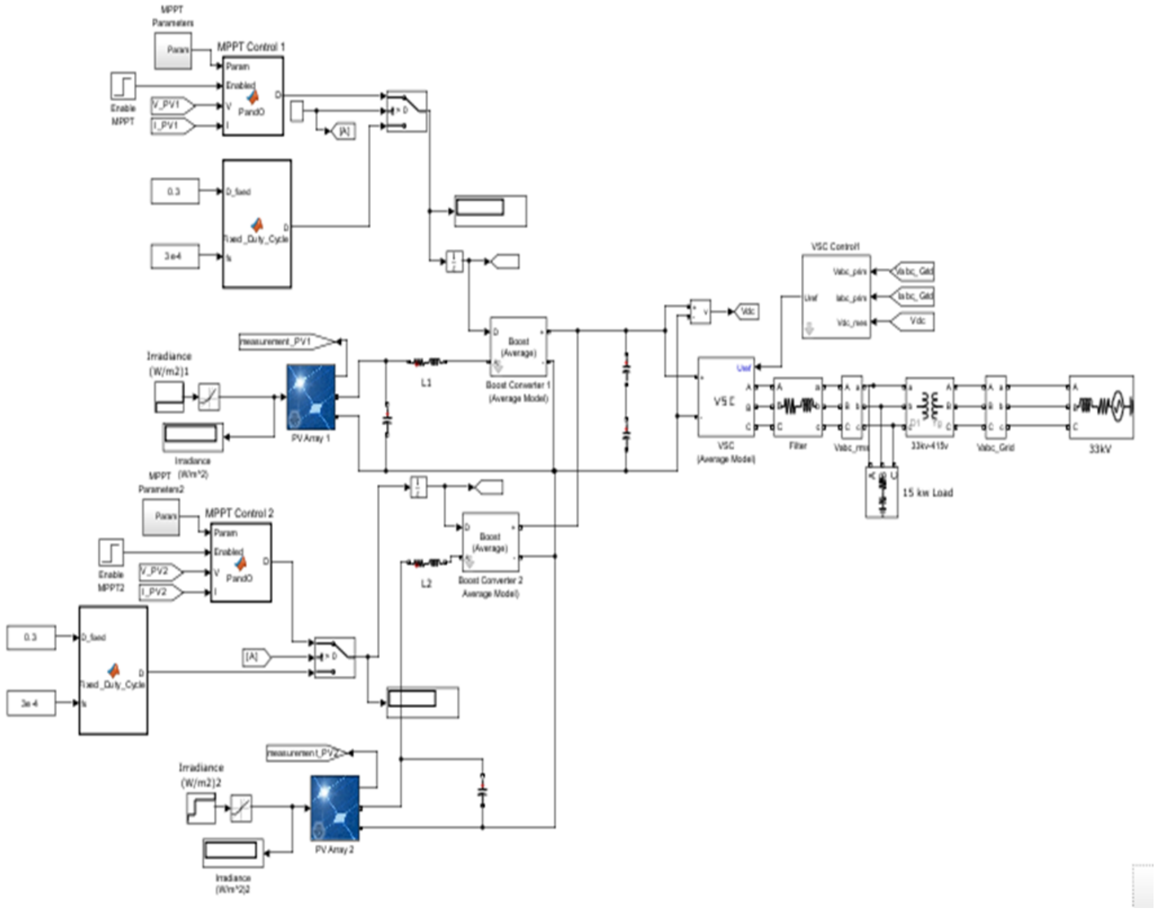

Fig 3: Simulaton Setup Block Model

4. RESULT AND DISCUSSION

The simulation results indicate a significant improvement in grid power when using the MPPT controller. The power generated by the PV arrays increased from 240 kW to 270 kW, demonstrating the effectiveness of the MPPT controller in optimizing the energy output of the solar PV systems.

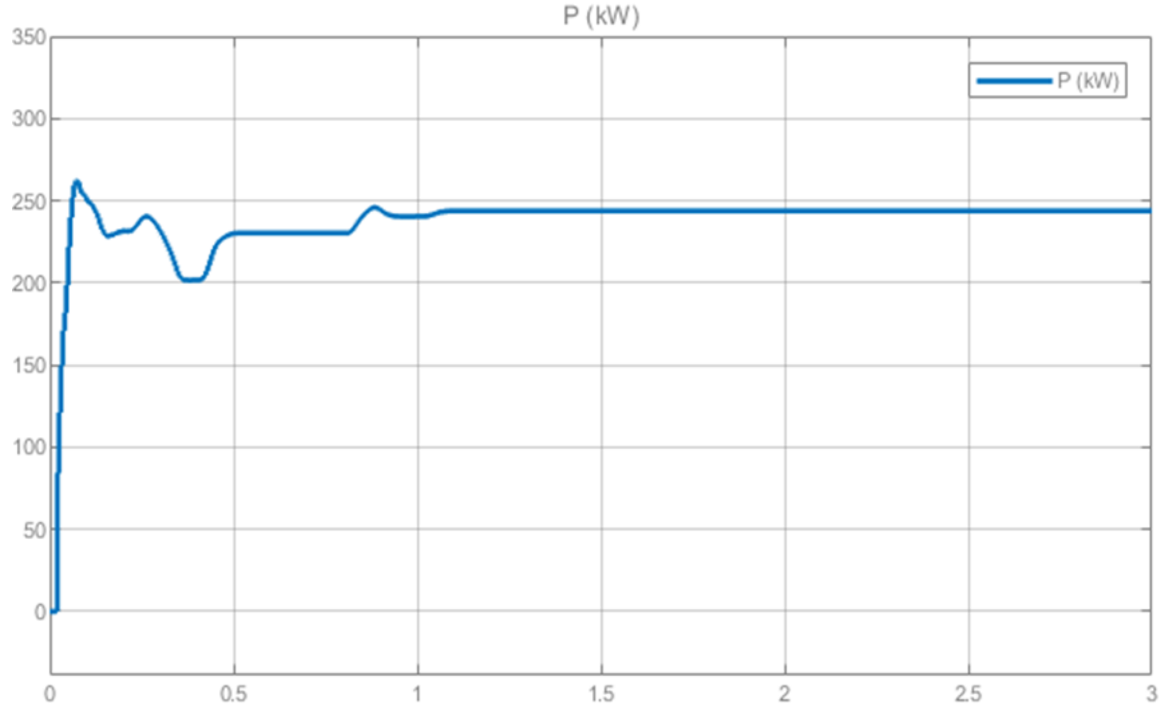

Fig 4: Grid power perfomance without MPPT Controller

4.1 Performance assessment of Grid Power

Figures 4 and 5 illustrate the impact of using an MPPT controller on grid power delivery over time, providing a comparative analysis between systems operating with and without MPPT control.

In Figure 4, which shows the power output without the MPPT controller, the Y-axis represents grid power in kilowatts (kW), while the X-axis represents time in seconds (s). The graph indicates that, in the absence of MPPT, the grid power stabilizes around 240 kW. This power level aligns with typical output expectations under standard conditions without optimization. However, without an active tracking mechanism, the system cannot adjust dynamically to fluctuating irradiance, which can limit the overall energy harvested and delivered to the grid.

In contrast, Figure 5 presents the power output with the MPPT controller activated. Similarly, the Y-axis denotes power in kW, and the X-axis denotes time in seconds. The graph clearly shows an increase in power output, with the grid power consistently reaching around 270 kW. This increase of approximately 30 kW demonstrates the MPPT controller's effectiveness in maximizing power delivery by continuously adjusting the operating point to the maximum power point of the PV system. The MPPT controller's real-time adjustments allow the system to respond to varying environmental conditions, optimizing energy conversion even under fluctuating irradiance.

The comparison between Figures 4 and 5 underscores the critical role of MPPT in renewable energy applications, highlighting that, with MPPT control, grid power output can be significantly improved, thus enhancing the overall efficiency and effectiveness of PV systems integrated into the grid. This finding supports the growing use of MPPT controllers in solar PV systems to meet increasing demands for reliable and optimized clean energy sources.

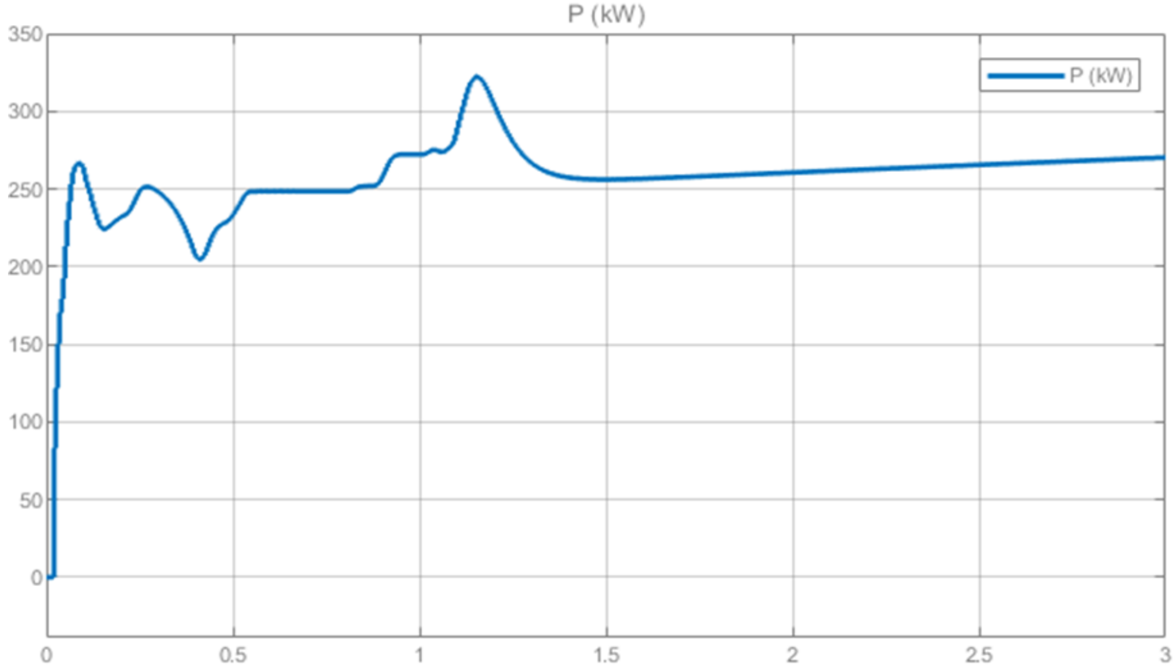

Fig 5: Grid power perfomance with MPPT Controller

4.2 PV Array Performance (With and Without MPPT)

Figures 6 and 7 provide a detailed comparison of photovoltaic (PV) array performance under conditions with and without MPPT control, highlighting three critical sections: irradiance, PV power output, and PV voltage along with duty cycle.

In both Figures 6 (without MPPT) and 7 (with MPPT), the irradiance levels for PV arrays 1 and 2 remain constant throughout the duration, with PV array 1 receiving an irradiance of 1000 W/m² and PV array 2 receiving 800 W/m². These consistent irradiance levels create a stable environment to observe the specific impact of the MPPT controller on the other parameters—namely, power output, voltage, and duty cycle.

In Figure 6, which displays the system without MPPT control, the PV power output for array 1 stabilizes around 70 kW, while array 2 reaches approximately 25 kW. This steady but suboptimal power level indicates that, without MPPT, the PV arrays are unable to dynamically adjust to maximize power output, potentially underutilizing the available irradiance. This is a common limitation in PV systems lacking MPPT, where environmental and operational conditions remain unchanged, and the system cannot adjust to capture the optimal energy from the PV arrays.

Conversely, in Figure 7, with the MPPT controller activated, PV power output shows a notable improvement, with array 1 achieving approximately 100 kW and array 2 reaching around 65 kW. This increase demonstrates the MPPT controller’s effectiveness in actively adjusting the operating point to maintain maximum power extraction, even under fluctuating environmental conditions. The result is a significant improvement in power delivery, underscoring the MPPT’s role in enhancing energy capture from solar PV systems.

The PV voltage and duty cycle in both figures offer further insights into the MPPT’s impact. In

Figure 6, without MPPT, the duty cycle remains constant at 0.5, which aligns with standard assumptions when the controller is inactive. However, in Figure 7, the duty cycle fluctuates as the MPPT continuously adjusts to track the maximum power point (MPP). This dynamic adjustment, visible in the DC voltage fluctuation, is a direct result of the MPPT algorithm working to optimize power output. By constantly adjusting the duty cycle, the MPPT controller ensures that the PV arrays operate close to their optimal power points, leading to the observed improvements in power output.

This comparison between Figures 6 and 7 highlights the critical role of MPPT in PV systems. By actively tracking and adjusting to the MPP, the MPPT controller maximizes power extraction, making it a

valuable component in solar energy systems, particularly in settings where efficiency and optimization are paramount. The findings reinforce the importance of MPPT technology in renewable energy integration, contributing to increased efficiency and more reliable clean energy generation.

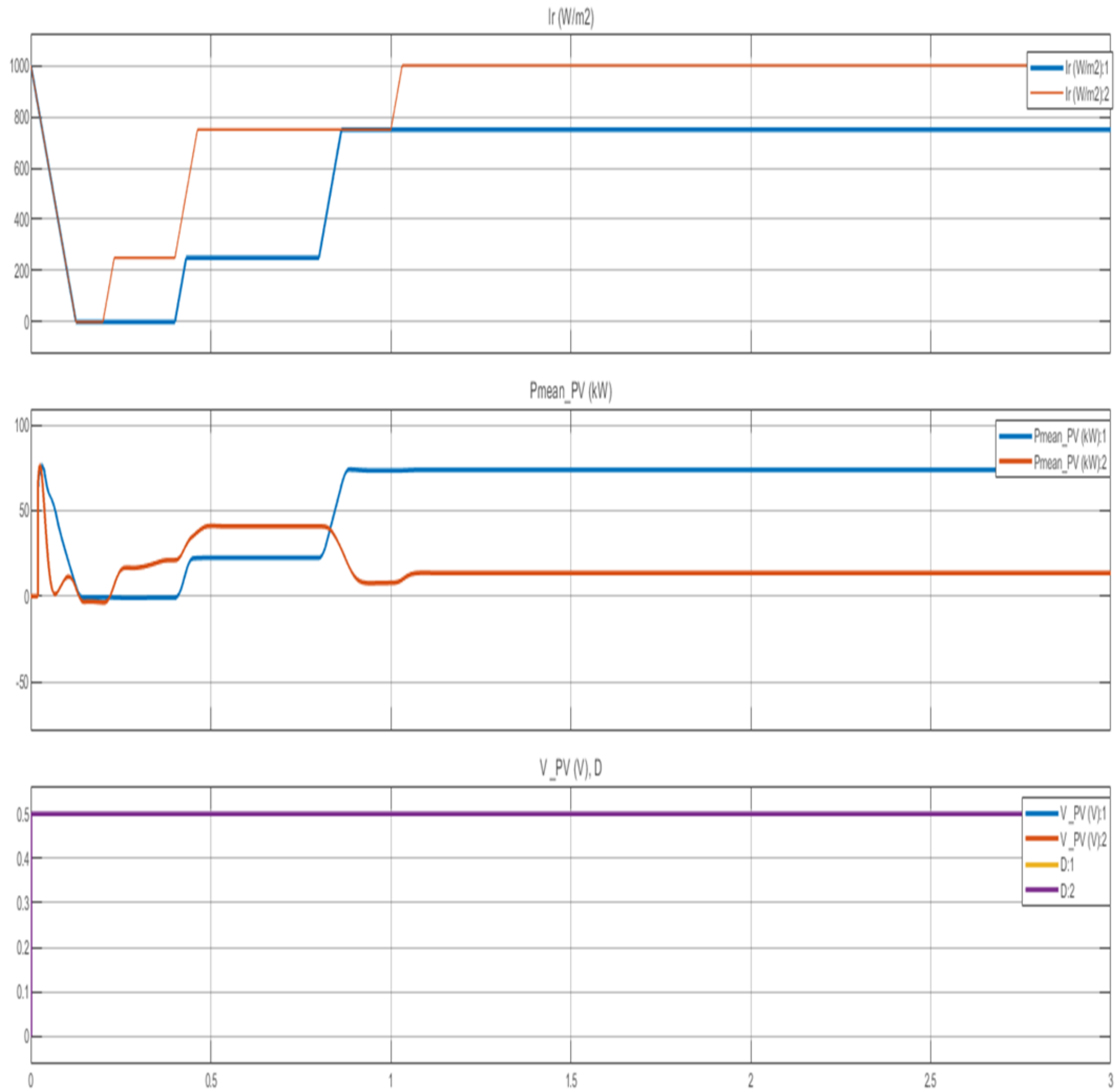

Fig 6: PV Array perfomance without MPPT Controller

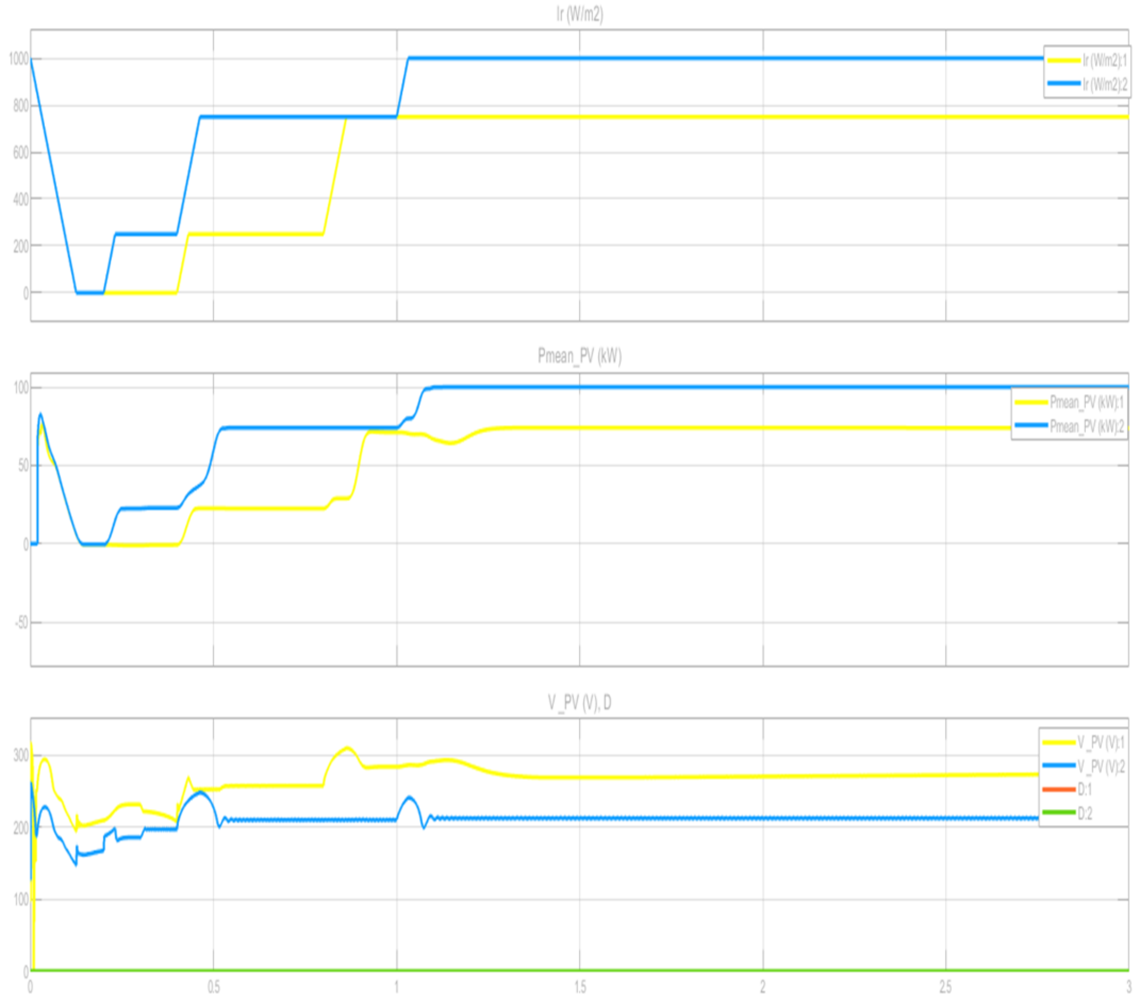

Fig 7: PV Array perfomance with MPPT Controller

5. CONCLUSION

This paper has presented a simulation-based performance assessment of a grid-connected solar PV system using an MPPT controller based on the P&O algorithm. The results demonstrate that the MPPT controller significantly increased the grid power from 240 kW to 270 kW, highlighting its effectiveness in optimizing energy conversion and maintaining grid stability.

The findings of this study are consistent with previous research, which has shown that MPPT controllers play a crucial role in enhancing the efficiency and reliability of solar PV systems. The use of the P&O algorithm ensures that the PV arrays operate at their maximum power point, reducing power losses and improving overall system performance.

Future work could focus on further optimizing the MPPT algorithm to reduce oscillations around the maximum power point and improve performance under rapidly changing environmental conditions. Additionally, the integration of advanced MPPT algorithms, such as those based on machine learning, could further enhance the performance of grid-connected solar PV systems.

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