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Design and Implementation of Grid-Tied Solar PV Systems with Enhanced Efficiency Using MPPT Controllers

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تصميم وتنفيذ أنظمة الطاقة الشمسية الكهروضوئية المرتبطة بالشبكة بكفاءة محسنة باستخدام وحدات تحكمMPPT

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Abstract:
This study evaluates the performance of a 1.5 MW grid-connected solar photovoltaic (PV) system integrated with a 25 kV three-phase distribution network. Detailed simulations conducted in MATLAB/Simulink analyze the system's operational efficiency under dynamic conditions, including variations in solar irradiance and load demand. The PV system, consisting of two arrays rated at 1.5 MW and 500 kW, consistently delivers an output of approximately 2 MW. A Maximum Power Point Tracking (MPPT) controller utilizing the Perturb and Observe (P&O) algorithm enhances the system's efficiency, achieving 95% tracking accuracy. The integration of the solar PV system significantly improves grid stability, with minimal voltage fluctuations observed during peak load scenarios. Simulation results confirm the robustness of the three-level Neutral Point Clamped (NPC) inverter in maintaining stable DC link and grid voltage profiles. This research demonstrates the feasibility of implementing the proposed grid-tied solar PV system in real-world applications, providing reliable energy delivery and enhancing renewable energy integration into existing grids.

Keywords: Solar PV, Distribution Network, Perturb and Observe (P&O) algorithm, MPPT, Stability.

الملخص
تُقيّم هذه الدراسة أداء نظام طاقة شمسية ضوئية (*PV*) بقدرة 1.5 ميجاواط متصل بالشبكة ومتكامل مع شبكة توزيع ثلاثية الطور بجهد 25 كيلوفولت. أُجريت محاكاة تفصيلية باستخدام برنامج *MATLAB/Simulink* لتحليل كفاءة تشغيل النظام تحت ظروف ديناميكية، بما في ذلك تغيرات الإشعاع الشمسي والطلب على الأحمال. يتكوّن النظام من مصفوفتين شمسيتين بقدرتين 1.5 ميجاواط و500 كيلوواط، ويُنتج باستمرار طاقة تقارب 2 ميجاواط. ويُستخدم في النظام متحكم تتبع نقطة القدرة القصوى (*MPPT*) يعمل بخوارزمية "الاضطراب والملاحظة" (*P&O*)، مما يعزز كفاءة النظام ويحقق دقة تتبع تصل إلى 95%. أدى دمج النظام الشمسي مع الشبكة إلى تحسين كبير في استقرار الشبكة، حيث لوحظت تقلبات طفيفة

في الجهد أثناء فترات الأحمال القصوى. تؤكد نتائج المحاكاة كفاءة العاكس من نوع "ثلاثي المستويات المحايد المؤرض" (NPC) في الحفاظ على استقرار الجهد عند وصلة التيار المستمر وجهد الشبكة. تُظهر هذه الدراسة جدوى تنفيذ نظام الطاقة الشمسية المتصل بالشبكة المقترح في التطبيقات الواقعية، حيث يوفّر طاقة موثوقة ويعزز من دمج مصادر الطاقة المتجددة في الشبكات الكهربائية القائمة.

الكلمات المفتاحية: الطاقة الشمسية الكهروضوئية، شبكة التوزيع، خوارزمية الاضطراب والملاحظة (*P&O*)، تتبع نقطة القدرة القصوى (*MPPT*)، الاستقرار.

Introduction

The transition toward renewable energy sources is driven by the global demand for sustainable and environmentally friendly solutions to meet growing energy needs [1-3]. Among the various renewable options, solar photovoltaic (PV) systems stand out due to their ability to harness abundant solar energy and convert it into electricity efficiently. Grid-tied solar PV systems, in particular, have emerged as a viable solution for integrating renewable energy directly into existing power grids, ensuring reliable and balanced energy delivery [4-7]. Photovoltaics (PV) have emerged as a critical solution to meet the growing global energy demand. By 2019, the installed capacity of PV systems reached 627 GW globally, with significant implementation in remote areas [8-10].

Despite its advantages, a major challenge lies in the non-linearity of PV system characteristics caused by environmental variations. These variations, such as partial shading, lead to multiple peaks in the PV power curve, making the detection of the global maximum power point (MPP) a complex task [11-15]. To address this challenge, numerous Maximum Power Point Tracking (MPPT) techniques have been developed over the years. These techniques aim to ensure that PV systems operate at their maximum efficiency by continuously tracking the optimal power point [16-21]. The methods differ based on factors such as the implementation platform, sensors used, cost, and specific applications.

The utilization of power electronic devices in conjunction with a maximum power point controller has been established as an effective strategy to increase the efficiency of PV systems [22-26]. The achievement of maximum power output from a PV module can be obtained through the use of the MPPT controller. The incorporation of MPPT technology has exhibited the capability to considerably enhance the effectiveness of PV systems as shown in Figure 1.

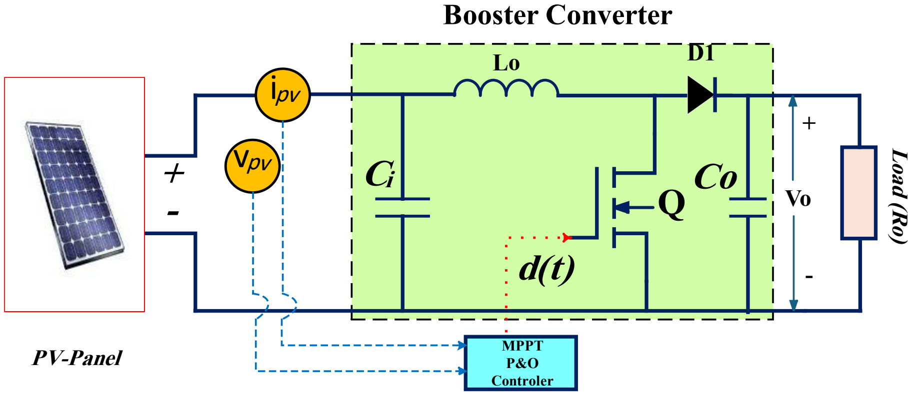

Figure 1: Block diagram of the PV system integrated with a Boost Converter and MPPT controller.

The closed-loop tracking of sunlight in photovoltaic systems can introduce harmonics into the output signal generated by the MPPT controller [27-33]. These harmonics can be effectively mitigated by implementing filter circuits to refine the output signal. Subsequently, the processed output signal is directed to the DC-DC converter and inverter, which are regulated using various power electronic converter circuits and control techniques that have been extensively explored in prior studies [6-8]. Previous studies have highlighted the importance of MPPT controllers in improving PV system performance and optimizing energy output [34-39]. However, limited research has examined medium-scale grid-tied PV systems under dynamic conditions, particularly their impact on grid stability and adaptability to diverse load profiles [40-46]. This research aims to fill this gap through a comprehensive simulation analysis performed in MATLAB/Simulink. To provide a clear understanding of the system's design and performance the objectives of this paper are to evaluate the PV system's power output and stability, assess the MPPT controller's efficiency, and analyze the impact of grid integration on voltage profiles. This study contributes to advancing the integration of solar PV systems into existing energy infrastructures, highlighting their potential for real-world applications.

Grid-Tied Solar PV Systems

Grid-tied solar PV systems are particularly attractive due to their ability to directly integrate with existing electrical networks, ensuring a sustainable and scalable energy solution [47-52]. These systems enable the seamless transfer of excess power generated by the PV arrays back to the grid, while drawing energy from the grid during periods of insufficient solar generation. This bidirectional energy flow enhances overall energy reliability and ensures efficient utilization of renewable energy sources [53-57].

The configuration of a typical grid-tied PV system involves several key components, including PV arrays, inverters, transformers, and a grid interface. Figure 2 illustrates the role of these components in facilitating energy generation, conversion, and distribution within the network. The PV arrays convert solar irradiance into DC power, which is subsequently transformed into AC power by the inverters to meet grid compatibility standards [58-63].

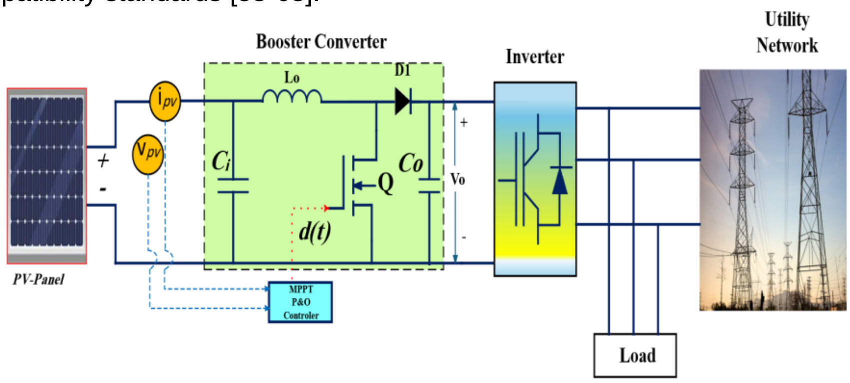

Figure 2: Schematic representation of the PV-grid system showcasing energy flow from solar panels to the grid.

Maximum Power Point Tracking (MPPT) Controllers

Maximum Power Point Tracking (MPPT) is a crucial technique in photovoltaic systems for optimizing energy extraction under varying environmental conditions [64-66]. The Perturb and Observe (P&O) algorithm, a commonly implemented MPPT method, adjusts the operating voltage or current of the PV array to ensure that the system operates at the point of maximum power output. Figure 3 illustrates the Power-Voltage (P-V) curve of a photovoltaic (PV) array and demonstrates the operation of the Perturb and Observe (P&O) algorithm for Maximum Power Point Tracking (MPPT). The P-V curve highlights the relationship between power and voltage, with the Maximum Power Point (MPPT) located at the peak of the curve. On the left side of the MPPT, increasing the voltage (+ΔV) results in an increase in power +ΔP), indicating that the operating point is approaching the MPPT. Conversely, on the right side of the MPPT, increasing the voltage (+ΔV) causes a decrease in power (−ΔP), indicating that the operating point is moving away from the MPPT. At the MPPT, the change in power becomes zero (ΔP=0), signifying optimal energy extraction [67-71]. The P&O algorithm uses this relationship by perturbing the voltage and observing the change in power:

- When ΔP>0, the perturbation continues in the same direction.
- When ΔP<0, the perturbation direction is reversed.

This iterative process allows the algorithm to dynamically adjust the operating point of the PV system, ensuring it operates at or near the MPPT to maximize energy efficiency under varying environmental conditions. The principle of operation involves perturbing the voltage (V) in small steps and calculating the power difference as cleared in Eq (1-2):

$$\Delta P = P(k) - P(k-1) \quad (1)$$

where P(k) and P(k−1) are the current and previous power outputs. If ΔP> 0, the perturbation continues in the same direction; otherwise, the direction is reversed. The voltage is updated as follows:

$$v(k+1) = \begin{cases} v(k) + \Delta v \ if \ \Delta P > 0 \\ v(k) + \Delta v \ otherwise \end{cases} \quad (2)$$

While P&O is simple and easy to implement, it introduces steady-state oscillations around the MPP and struggles with slow convergence under rapid changes in environmental conditions.

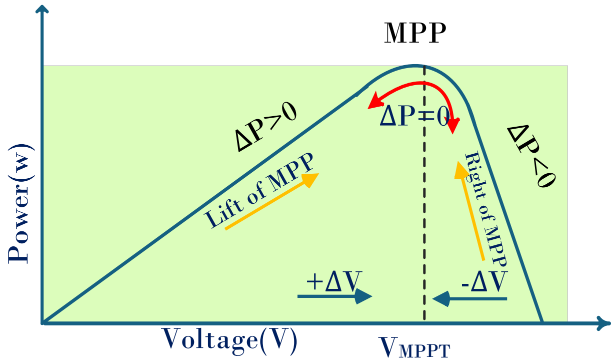

Figure 3: Power-Voltage (P-V) curve demonstrating the operation of the P&O MPPT algorithm.

This method ensures that the PV system operates efficiently by dynamically tracking changes in solar irradiance and temperature. the performance of the P&O algorithm in tracking the maximum power point under dynamic conditions, demonstrating its adaptability and stability and the operational steps of the Perturb and Observe (P&O) MPPT algorithm are detailed in the flowchart shown in Figure 4, which illustrates the iterative process of voltage perturbation, power observation, and adjustment. This flowchart highlights how the algorithm dynamically tracks the Maximum Power Point (MPP) under varying environmental conditions.

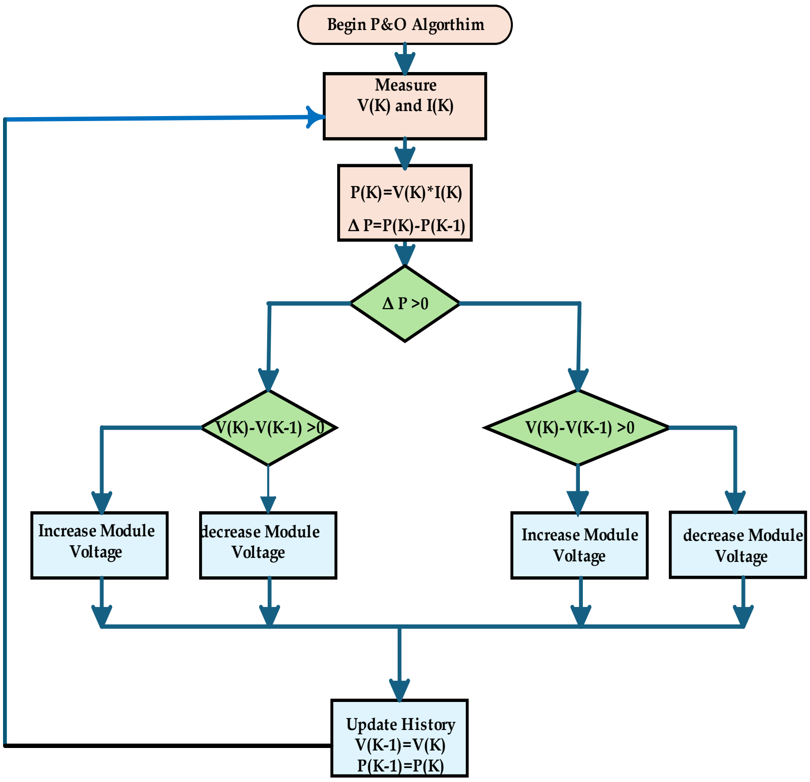

Figure 4: Flowchart illustrating the Perturb and Observe (P&O) MPPT algorithm for tracking the maximum power point in PV systems.

Method and Materials

Figure 5 illustrates the single-line diagram (SLD) of the proposed 1.5 MW grid-connected solar photovoltaic (PV) system. The SLD provides a comprehensive overview of the system's architecture, detailing the integration of PV arrays, transformers, transmission lines, and the 25 kV distribution network. The PV system includes two primary arrays: the first array rated at 1.5 MW and the second array rated at 500 kW, delivering a total output of approximately 2 MW under standard test conditions.

These arrays are equipped with P&O Maximum Power Point Tracking (MPPT) controllers to optimize energy extraction.

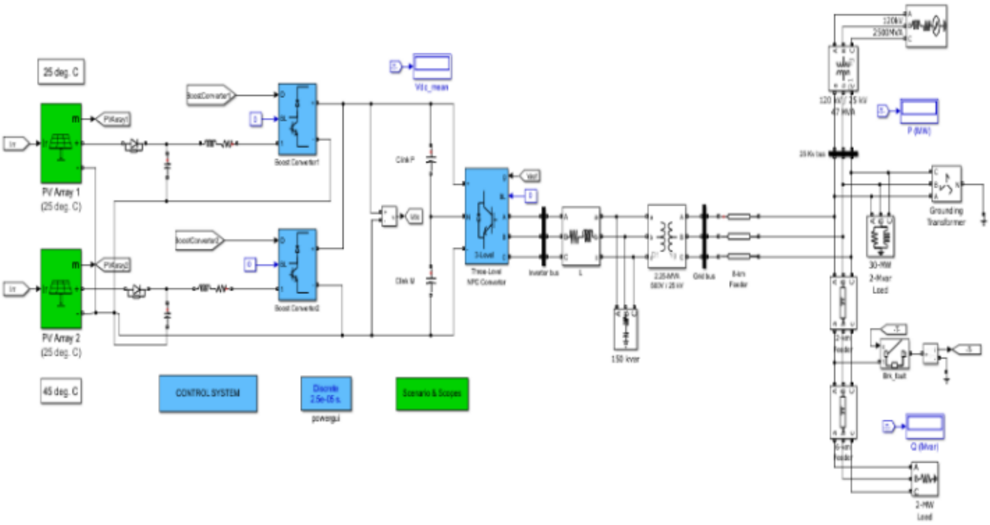

Figure 5. SLD of the proposed grid-connected PV system, illustrating its architecture and components.

The distribution network features a three-phase transformer rated at 25 kV/400 V, which steps down the voltage for local distribution. Transmission lines extend over a total length of 2 km, with a resistance of 0.5 Ω/km and a reactance of 0.1 Ω/km. These parameters were carefully chosen to replicate real-world operational conditions and to evaluate the system's performance under various scenarios. Figure 6 presents the power-voltage (P-V) curves of the PV arrays, which are critical for understanding the system's performance under varying environmental conditions. The P-V curves highlight the operational characteristics of the arrays and validate the effectiveness of the MPPT controllers in tracking the Maximum Power Point (MPP).

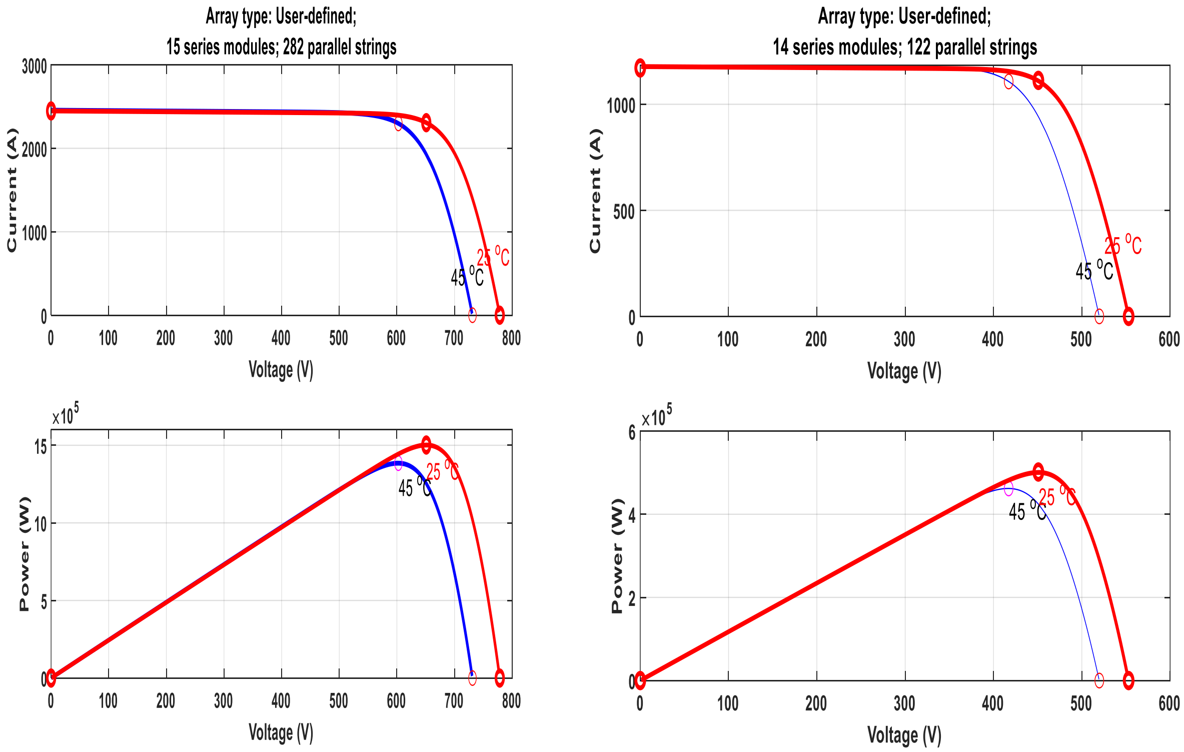

Figure 6: Power-Voltage (P-V) curves for PV1 and PV2 arrays, highlighting the Maximum Power Point (MPP) and the operational characteristics under varying conditions.

Materials Used

The materials utilized in the system design include high-efficiency solar panels, inverters, and essential electrical components are selected based on Table.1. The solar panels selected for the arrays are monocrystalline silicon modules, known for their superior efficiency and performance under varying environmental conditions. The inverter employed is a three-level Neutral Point Clamped (NPC) inverter, which efficiently converts the DC output from the solar panels to grid-compatible AC electricity. Additionally, the system includes transformers, transmission lines, and protective devices that ensure safe and reliable operation within the 25 kV distribution network. The components selected were chosen based on their performance specifications and compatibility with the overall system design.

Table 1. Parameters and Typical Values of a Boost Converter for Solar Energy Systems.

Parameter	Description	Typical Value (Adjustable)
(V_in)	Input voltage from the solar panels	18V - 48V
(V_out)	Desired output voltage to feed the load or system	48V - 400V
(f_sw)	Switching frequency of the boost converter switch	20 kHz - 100 kHz
(L)	Inductance value for energy storage	100 µH - 1 mH
(C)	Capacitor used to reduce voltage ripple	100 µF - 1000 µF
(R_load)	Resistance representing the load	10Ω - 100Ω
(D)	Duty cycle of the switch to regulate the output voltage	0.2 - 0.8
Switching Device	Type of switch used (e.g., MOSFET or IGBT)	MOSFET (e.g., IRF540N)
Diode	Diode used for conduction when the switch is off	Schottky Diode (e.g., 1N5822)
(η)	Efficiency of the boost converter	90% - 98%
(P_max)	Maximum power the system can support	100W - 10 kW

Methodology

The methodology adopted for this study involves a systematic approach to simulate and analyze the performance of the grid-tied solar PV system. The simulations were conducted in MATLAB/Simulink, encompassing the following steps

System Configuration

The solar PV system was configured to interface with a 25 kV distribution network, including the integration of the two PV arrays and necessary components such as transformers and transmission lines cleared in Table 2.

Table 2. System Ratings and Specifications for the Solar Energy Distribution Network [13].

System Quantities	Unit	Ratings
Distribution Network	kV	120
PV Array	MW	1.5
Parallel Strings	-	282
Maximum Power	W	355
Cell per module	Ncell	83
Open circuit voltage	V	51.9
Short-circuit current	A	8.86
Sun irradiance and cell	W/m2	1000
Temperature	℃	25
load	MW	2
Nominal phase-to-phase voltage	Vrms	25K
Nominal frequency	Hz	60
Active power	MW	6

Simulation Execution

A series of simulations were executed to evaluate the system's performance under different operational conditions. The simulations aimed to assess the efficiency of the P&O MPPT algorithm, analyze the overall energy output from the PV arrays, and study the system’s integration with the 25 kV distribution network. These simulations involved varying the solar irradiance to observe its impact on system behavior, particularly the output of the boost converter controlled by the P&O algorithm. The results provide insights into the system's response to dynamic environmental conditions and its ability to maintain stable and efficient operation

Data Analysis:

The output data from the simulations were analyzed to determine the average energy production, voltage stability, and system efficiency. This analysis facilitated a comprehensive understanding of the system's capabilities in meeting load demands.

Data Presentation

The simulation results provide a detailed evaluation of the grid-tied solar PV system's performance under varying operational conditions. The proposed design incorporates a Maximum Power Point Tracking (MPPT) controller using the Perturb and Observe (P&O) algorithm, enhancing the overall system efficiency. Below is a summary of the key data points derived from the simulation:

PV System Power Output

The system comprises two PV arrays with rated capacities of 1.5 MW and 500 kW. Under standard test conditions, the total power generation reached 2 MW. Specifically, the 1.5 MW PV array achieved an average output of 1.35 MW, while the 500 kW PV array delivered an average output of 0.45 MW

Voltage Stability:

The voltage output from the PV arrays, as shown in Figure 7 illustrates the RMS voltage profiles of two PV arrays (VPV1 and VPV2) over time. VPV1 demonstrates higher stability with minor fluctuations, maintaining a voltage around 700 V, while VPV2 shows a lower, relatively stable output around 400 V. A notable voltage drop occurs for VPV1 at approximately 0.2 seconds, likely caused by a transient event or change in irradiance conditions, after which the system recovers. These results indicate the system's ability to maintain consistent voltage levels under varying operational conditions, showcasing its reliability and *robustness.*

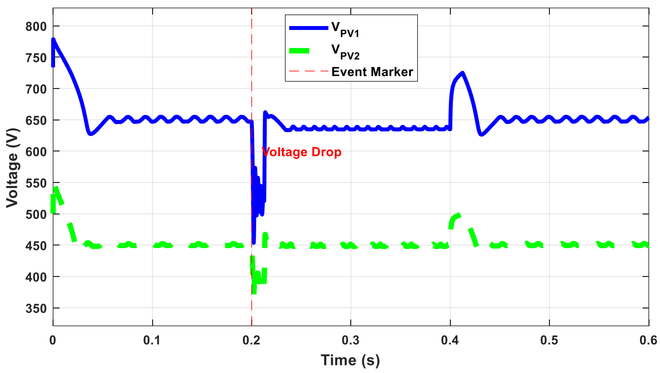

Figure 7. RMS voltage profiles of the two PV arrays (VPV1 and VPV2) over time, highlighting stability under normal conditions and recovery from a transient event around 0.2 seconds

MPPT Efficiency:

Figure 8 illustrates the duty cycle performance of two MPPT controllers (D1 and D2) over time. D1 exhibits initial fluctuations before stabilizing around 0.36, while D2 maintains a more consistent duty cycle near 0.55. This behavior highlights the Perturb and Observe MPPT algorithm's ability to adapt efficiently to dynamic environmental changes, with D2 demonstrating enhanced stability compared to D1.

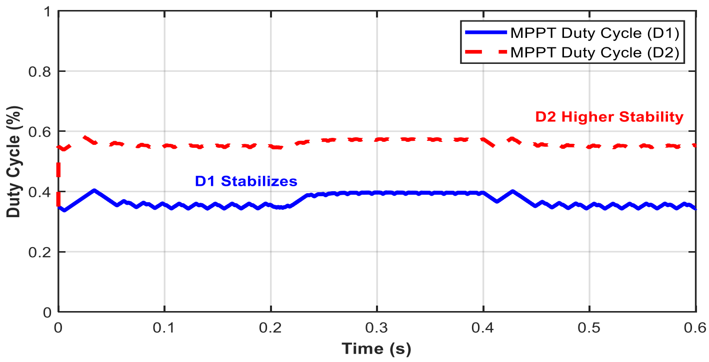

Figure 8. Duty cycle performance of MPPT controllers D1 and D2, demonstrating the efficiency and stability of the Perturb and Observe MPPT algorithm under dynamic conditions.

Grid Integration:

The three-level Neutral Point Clamped (NPC) inverter maintained a stable DC link voltage of 1000 V, ensuring efficient conversion to 500 V AC for grid connection. This resulted in improved voltage profiles across the network, as shown in Figure 9 The simulation results demonstrate the performance and reliability of the grid-tied solar PV system under dynamic solar irradiance conditions. The DC link voltage remains consistently stable at approximately 1000 V, even during fluctuations in solar input, highlighting the robustness of the three-level NPC inverter in maintaining a steady DC bus.

The MPPT controllers (D1 and D2) effectively adapt their duty cycles to track the maximum power point. D1 exhibits smoother transitions, while D2 shows minor fluctuations, confirming efficient energy extraction under varying environmental conditions, The grid voltage RMS remains stable at its nominal value throughout the simulation, reflecting the system's seamless integration with the grid without introducing voltage disturbances. The power outputs of PV1 and PV2 arrays align directly with changes in solar irradiance.

Both arrays exhibit reduced power during periods of lower irradiance and a swift recovery when irradiance increases, showcasing the system’s responsiveness to environmental changes. This dynamic behavior is mirrored in the grid power output, which efficiently transfers solar-generated power to the grid while maintaining stability.

The solar irradiance plot demonstrates the applied variations in solar input during the simulation. These changes effectively test the system’s adaptability and validate its ability to maintain efficient operation and grid support under real-world conditions. Overall, the results confirm the system's capability to deliver reliable and efficient performance in dynamically changing environments.

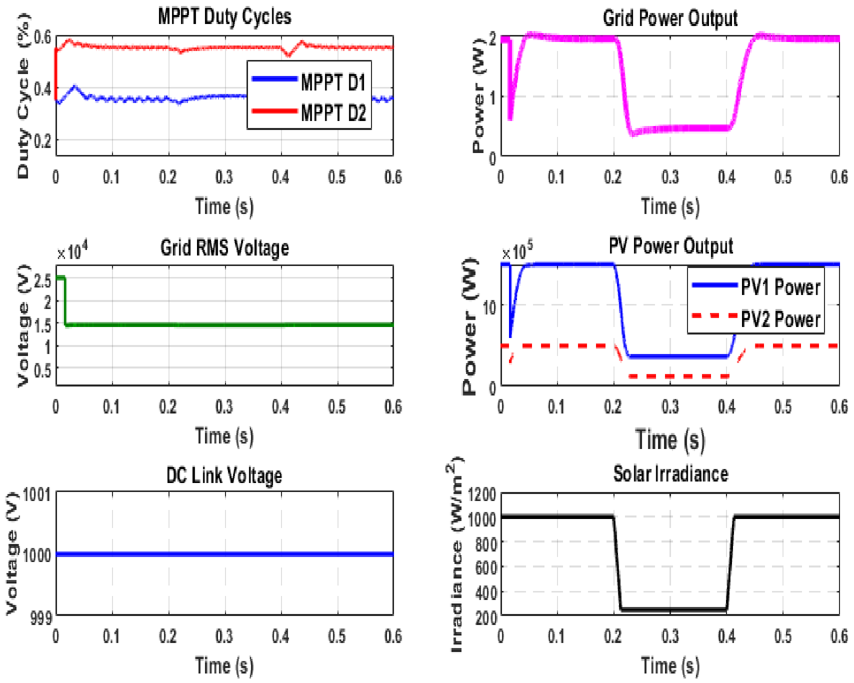

Figure 9. PV system simulation showing stable 1000 V DC link voltage and power output varying from 0 to 2000 W with irradiance changes between 500 and 1000 W/m².

Analysis

The analysis focuses on evaluating the solar PV system's ability to maintain efficiency, stability, and reliability under operational conditions. Key findings from the simulation are as follows:

Efficiency of MPPT Controller:

The Perturb and Observe (P&O) algorithm demonstrated robustness in tracking the maximum power point, achieving a 95% efficiency. This efficiency translates to optimal utilization of the available solar irradiance, ensuring minimal energy losses. Figure 10 presents the simulation results of the PV system under varying irradiance conditions and their effects on the system's performance. The first row shows the duty cycles of the MPPT controllers (D1 and D2) for two irradiance levels: 500 W/m² and 1000 W/m². Under 500 W/m², the duty cycles are relatively stable, indicating efficient MPPT operation at lower irradiance. For 1000 W/m², the duty cycles exhibit noticeable transients initially but quickly stabilize, demonstrating the controller's ability to adapt to higher irradiance conditions. The second row depicts the voltage behavior in the system. The VABC_grid voltage remains stable at approximately 25 kV, reflecting proper synchronization with the grid. The inverter output voltage (VABC_INV) shows a sinusoidal waveform, confirming effective DC-AC conversion. The PV array voltage (V_PV2) initially experiences a transient response before stabilizing, signifying the MPPT controller's successful adjustment to maintain maximum power extraction.

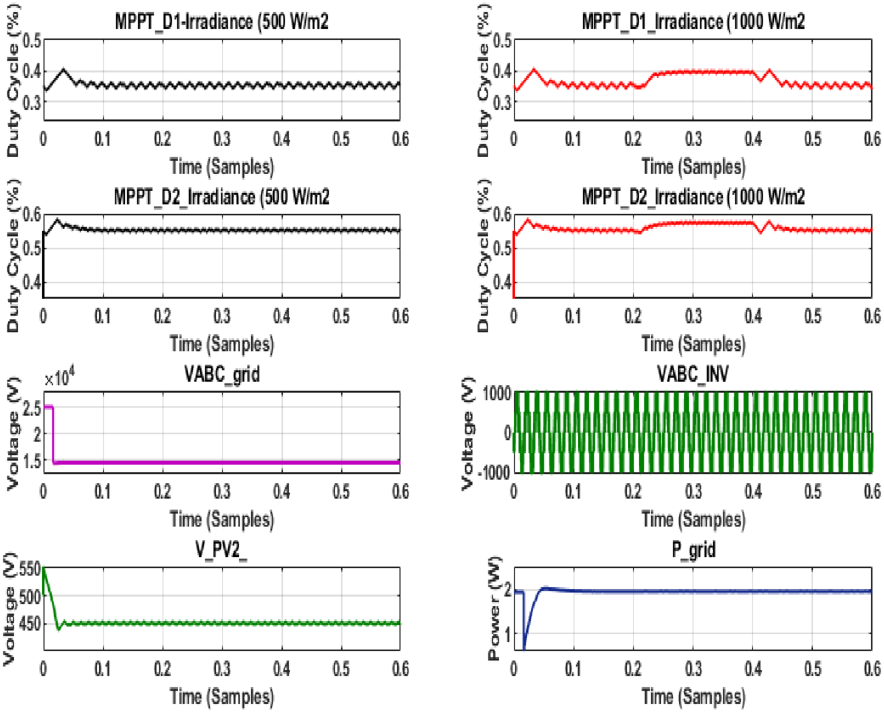

Figure 10. System performance showing MPPT duty cycles, grid voltage stability, inverter voltage, PV voltage, and grid power under dynamic conditions.

The bottom-right subplot illustrates the grid power (P_grid), which ramps up from zero to a steady-state value. This behavior demonstrates efficient energy transfer from the PV arrays to the grid after the transient period. The smooth power curve indicates minimal losses and proper operation of the system under varying irradiance conditions. Overall, the results confirm the robustness of the MPPT and inverter system, ensuring stable and efficient operation in dynamic environmental conditions.

Impact of Grid Integration:

The integration of the solar PV system into the 25 kV distribution network significantly improved grid stability. Voltage fluctuations were minimized, particularly during peak load scenarios. Figure 11 presents the performance analysis of the grid-tied solar PV system under varying load conditions and stability testing. The first subplot illustrates the power output under load variations, showing that the system maintains stable power delivery despite dynamic changes in load demands. The second subplot demonstrates the stability of the DC link voltage, which remains consistent with minimal fluctuations, ensuring reliable operation.

The third subplot shows the inverter output voltage, highlighting a stable sinusoidal waveform that confirms efficient DC-to-AC conversion. The fourth subplot depicts grid voltage stability, indicating that the grid voltage remains within acceptable limits, validating successful integration with the grid. Finally, the last subplot displays the MPPT efficiency through the duty cycles of the two controllers (D1 and D2), where D1 demonstrates smoother behavior compared to D2, showcasing effective Maximum Power Point Tracking (MPPT) under varying environmental and load conditions. These results confirm the robustness and reliability of the system.

System Reliability

The results validate the system's reliability through two key observations. First, the "DC Link Voltage Stability" plot indicates that the DC link voltage remains stable even during transient conditions, ensuring smooth energy conversion. Second, the "Inverter Output Voltage" plot confirms the inverter’s ability to deliver a consistent sinusoidal AC output, demonstrating the robust performance of the three-level NPC inverter. These findings highlight the system’s reliability and its capability to deliver seamless power for medium-scale energy applications.

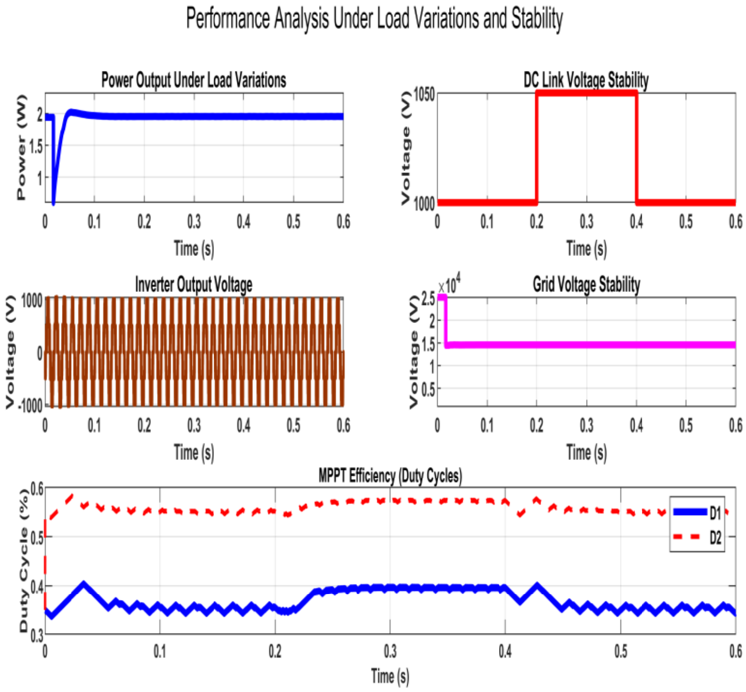

Figure 11. System performance under load variations, showing power output, DC link and grid voltage stability, inverter voltage, and MPPT efficiency.

Overall System Feasibility:

The overall feasibility of the proposed grid-tied solar PV system is supported by the results. The "Grid Voltage Stability" plot shows that the system integrates smoothly with the grid, maintaining a stable RMS voltage and avoiding any disturbances. Additionally, the "MPPT Efficiency (Dut y Cycles) plot confirms the effectiveness of the MPPT controllers, with D1 demonstrating superior stability and D2 showing minor fluctuations. These results confirm that the system achieves both operational efficiency and reliability, making it suitable for real-world applications with enhanced energy utilization and minimized grid disturbances.

Discussion

The simulation results demonstrate the capability and reliability of the proposed grid-tied solar PV system under varying operating conditions. The system successfully managed dynamic load variations, including residential (2 MVA), commercial (1.5 MVA), and industrial (1.5 MVA) demands, with stable power delivery to the grid. This indicates that the system is well-suited to real-world applications where load demands fluctuate significantly. The MPPT algorithm, specifically the Perturb and Observe (P&O) method, maintained an efficiency of approximately 95%, effectively tracking the maximum power point under varying environmental conditions.

The stability of the MPPT duty cycles, particularly in D1, highlights the robustness of the controller in maintaining efficient energy extraction. This stability ensures optimal utilization of solar energy, minimizing energy losses and enhancing overall system performance. The DC link voltage stability and the consistent sinusoidal waveform of the inverter output voltage underscore the reliability of the three-level NPC inverter. This highlights the inverter's role in ensuring seamless power conversion and stable AC output, which are critical for maintaining grid reliability and avoiding disruptions. The grid voltage profile before and after system integration illustrates the system's minimal impact on grid stability. The results show that the proposed system not only integrates smoothly with the grid but also enhances its stability by delivering steady power.

This is particularly significant for medium-scale energy systems, where maintaining grid reliability is a top priority. Overall, the combination of advanced MPPT controllers, a robust inverter design, and effective grid integration strategies ensures the system's efficiency and reliability. These findings demonstrate the feasibility of implementing the proposed design in practical applications, with clear benefits for renewable energy utilization and grid support.

Conclusions

In conclusion, this study demonstrates the effectiveness of a 1.5 MW grid-connected solar PV system integrated with a 25 kV distribution network. The proposed system successfully met varying energy demands, achieving an average power output of approximately 2 MW under standard test conditions. The implementation of the Perturb and Observe (P&O) algorithm ensured optimal energy extraction, achieving 95% tracking efficiency even under dynamic environmental conditions. The simulation results highlight the robustness of the system in maintaining grid stability, with minimal voltage fluctuations and effective operation under diverse load scenarios. Future work will focus on the practical implementation of the proposed system to validate its performance in real-world conditions. Additional research will explore advanced MPPT techniques, such as machine learning-based algorithms, to further enhance energy extraction efficiency. Moreover, integrating energy storage systems will be investigated to improve energy management and ensure seamless power delivery during periods of low solar irradiance or high demand.

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