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Optimization of Grid-Connected Solar Systems: A Dual-Stage Approach to Voltage Regulation and Harmonic Mitigation

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Abstract - This paper presents a comprehensive analysis of a dual-stage grid-connected photovoltaic (DS-PV) system, designed to enhance the reliability and stability of solar energy output under various operating conditions. The system operates through a two-stage topology, where the parallel converter functions as a sinusoidal voltage source and the series converter operates as a sinusoidal current source. The primary objective is to stabilize the output voltage and current at the point of common coupling (PCC) while compensating for reactive power and mitigating harmonic distortions.

The study evaluates the system under three distinct operational modes: (1) Ideal PV system under static resistive load, (2) Unbalanced RLC load, and (3) Dynamic loading. Each mode is simulated under different environmental and load conditions, including variable irradiance (600-1000 W/m²) and temperature (25-50°C), to analyze the system's performance in real-world scenarios. The simulation results demonstrate the effectiveness of the proposed system in maintaining synchronized output with the grid, ensuring voltage and current regulation, and providing reactive power compensation under unbalanced and dynamic loading conditions.

The proposed DS-PV system not only ensures efficient energy conversion but also addresses key power quality issues, including voltage fluctuations, harmonic distortion, and reactive power demand. This research highlights the system's potential to improve grid stability, enhance power quality, and support the integration of renewable energy sources into the grid. The findings validate the feasibility of deploying the dual-stage PV system in diverse applications, from residential to industrial sectors, to meet the increasing demand for clean and reliable energy.

Key Words: *Dual-stage photovoltaic system, grid-connected, power quality, reactive power compensation, harmonic mitigation, dynamic loading, unbalanced load, photovoltaic converter, solar energy integration, voltage regulation, maximum power point tracking (MPPT), simulation, energy stability, renewable energy.*

I. INTRODUCTION

This paper investigates cascaded H-bridge (CHB) inverters, crucial in modern power electronics for enhancing energy conversion efficiency, improving power quality, and integrating renewable energy sources.

There has been a groom in technological development of grid integration of renewable resources (RR). The two main causes for sudden increase of grid integration of RR, first scarcity in availability of conventional resources and another is that non-conventional resources are clean and green form of energy which can reduce the carbon traces. RR is a proven technology for environmentally friendly power generation system. The expanding weight on the need to heighten the support of cleaner types of energy to blend with the existing transformation frameworks, especially wind, small hydro and solar energy [1].

As a worldwide answer for beat the rising demand of power, sun oriented energy is turning into a promising alternative. Accessibility of sun energy around the earth and the advancements in sunlight based innovation had made a sun based energy system a dependable wellspring of vitality today. One more preferred standpoint that sunlight based energy has is that, it is a green and clean type of vitality that implies its carbon emanation is low as contrast with conventional source of power creation like thermal and so on. There carbon outflow is high and they contaminate nature.

There are number of overwhelming issues for the most part identified with control quality like power factor, responsive power quality, voltage flicker and harmonics in a PV framework associated with grid [2]. The general execution of the aggregate framework gets influenced and it turns into a genuine worry for the end clients. All in all, it diminishes the effectiveness and life of the gear and machines. The scientists constantly attempting to manage every one of these issues and to some degree a fruitful arrangement by planning appropriate control technique for inverter interfacing PV system to the grid, can be accomplished. Tremendous researches are available with enhance control and multi-functionality of PV inverters for power conditioning and application oriented [3].

II. LITERATURE SURVEY

The production of electricity from solar panels is categorized into two main systems: standalone and grid-connected. Standalone systems are prominent in applications like rural electrification, rooftop systems catering to local demand, and industrial operations where conventional electricity grids are inaccessible. Grid-connected systems, in contrast, feed power to the utility grid and can transition to islanded operation in the event of grid failure, ensuring reliable power supply to priority loads. This review focuses on the application of solar energy in grid-connected systems, emphasizing advancements in power quality (PQ) improvement, control strategies, and fault management.

Grid-Connected Solar PV Systems and Power Quality Enhancement

1. **Single-Stage Grid-Tied Systems with Filtering Capabilities**
   Leonardo et al. [11] designed a dual-function single-stage grid-tied system that acts as both a power generator and a static compensator. This system features a feed-forward control loop to mitigate current harmonics and maintain voltage stability, even under fluctuating solar conditions.
2. **Universal Power Controllers** Devassy et al. [12] developed an integrated single-stage PV-fed power controller for three-phase systems with nonlinear loads. Using PI controllers and phase-locked loops (PLL), the system mitigates source voltage and current harmonics, ensures voltage regulation, and compensates for reactive power.
3. **Single vs. Dual-Stage PV Systems** Sandipan Patra et al. [13] compared single-stage and dual-stage PV systems. Single-stage systems, using one converter for both DC and AC conversion, are simpler but less efficient in power quality control. Dual-stage systems, with separate converters for DC and AC processes, achieve better harmonic mitigation and MPPT accuracy.
4. **Hybrid Microgrid Control** W. Libo et al. [14] investigated the integration of grid-connected solar PV systems in hybrid microgrids using coordinated control. The study highlighted the benefits of DC-based generation lines and energy exchange stations for simplifying AC coordination issues and improving grid stability.

Advanced Control Strategies for Grid-Tied Systems

1. **Sliding Mode Control** G. Ding et al. [15] and Sameer Rokade et al. [31] proposed sliding mode control strategies for robust disturbance rejection and simplified nonlinear system control. These methods provide precise control over the DC-link voltage and line currents, outperforming traditional proportional-integral (PI) control methods.
2. **Voltage and Current Regulation Techniques** Varshney et al. [16] presented a comprehensive modeling approach for grid-tied PV systems, using the Perturb and Observe (P&O) method for MPPT. The system includes DC-bus voltage regulation and harmonic compensation to enhance power quality.
3. **Neural Network-Based Controller Tuning** Surendran et al. [17] proposed a neural network-based approach for optimizing PI controller parameters, ensuring system stability and enhanced closed-loop performance.

Fault Management and Stability

1. **Fault Ride-Through Control** O. Vodyakho et al. [19] and P.-T. Cheng et al. [20] explored control schemes for maintaining system stability during grid faults. These studies emphasized adaptive voltage control and harmonic attenuation to ensure safe and efficient operation under low-voltage and unsymmetrical fault conditions.
2. **Z-Source Inverter-Based Systems** M. C. Cavalcanti et al. [18] compared power quality in single-stage and dual-stage PV systems using advanced inverters. Space Vector Pulse Width Modulation (SVPWM) control and sinusoidal pulse width modulation (SPWM) were evaluated for their effectiveness in transient conditions.

Custom Power Devices for Enhanced Performance

1. **FACTS and Custom Power Devices** N.G. Hingorani et al. [23] introduced Flexible AC Transmission Systems (FACTS) to enhance grid stability and power transfer capability. These devices, including SVC, STATCOM, and UPFC, mitigate disturbances by injecting voltage or current, improving grid performance.
2. **Dynamic Voltage Restorers (DVR)** Woodley et al. [25], Nielsen et al. [28], and Brito et al. [29] demonstrated the use of DVRs for voltage sag and swell compensation in PV systems. Advanced designs, such as high-voltage DVRs with multilevel inverters, provide cost-effective solutions with reduced harmonics and improved reliability.
3. **DC Storage in DVR Systems** H.P. Tiwari et al. [26] highlighted the impact of DC storage capacity on voltage sag compensation, demonstrating that higher storage ratings improve effectiveness under varying load conditions.

Experimental Validation and Simulation

Osama M. et al. [32] designed a single-stage grid-tied PV system with incremental conductance-based MPPT. Experimental results validated the system's ability to maintain high performance under fluctuating insolation levels, using advanced controllers to ensure safe and efficient operation.

2.1. RESEARCH GAP

While significant advancements have been made in the grid integration of photovoltaic (PV) systems, maintaining Power Quality (PQ) remains a critical challenge. Power converters, essential for PV integration, are known to introduce harmonics that deteriorate the PQ of the system. This degradation leads to various PQ issues, such as voltage disturbances, interruptions, sag/swell, and other anomalies, which can severely impact system performance and potentially damage end-user equipment. Although numerous control techniques have been

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proposed for mitigating these issues, existing methods often fall short in addressing dynamic conditions, such as rapidly varying solar irradiance and load demands, or fail to achieve an optimal trade-off between harmonic reduction, voltage regulation, and system efficiency. Therefore, there is a pressing need to develop robust and adaptive control strategies for converters to effectively enhance PQ, ensuring stability, reliability, and protection of grid-connected PV systems under diverse operating conditions.

III. MODELING AND SIMULATION MODEL

The increasing global demand for electricity has positioned photovoltaic (PV) systems as a promising solution for sustainable energy generation. However, the reliability and robustness of PV panels remain a critical challenge. To address this, we propose a dual-stage PV converter system to stabilize the output of solar energy under various operating conditions.

The dual-stage topology incorporates two converters: a parallel converter and a series converter. The parallel converter is controlled to function as a sinusoidal voltage source, while the series converter operates as a sinusoidal current source. This architecture ensures optimal stability and robustness in the PV system's performance.

The control of the DC/AC converter is achieved using a Feed-Forward Current Loop (FFCL) methodology. This approach effectively suppresses load harmonic currents, compensates for reactive power, and delivers regulated, balanced, and harmonic-free output voltages to the load. The proposed system configuration is depicted in Fig. 1.

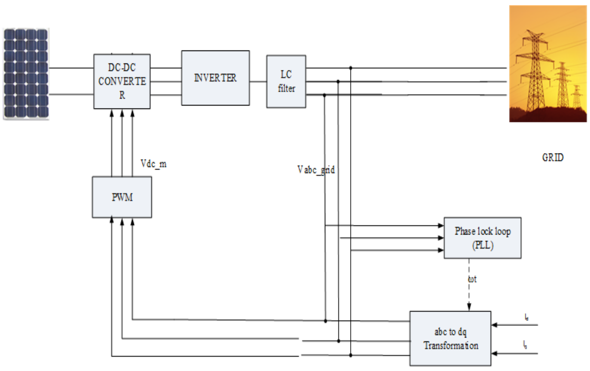

Fig. 1: Proposed System for Dual-Stage Grid-Tied PV System

In this study, we present a dual-stage (D-S) three-phase, four-wire (3P4W) grid-connected PV system, which integrates DC-DC regulation and DC-AC conversion with a power conditioning mechanism. The performance analysis of the proposed PV-connected grid system is conducted under the following operational modes:

1. **OPM-1:** Ideal PV system connected to the grid with a static resistive load.
2. **OPM-2:** PV system connected to the grid with an unbalanced RLC load.
3. **OPM-3:** PV system connected to the grid with dynamic loading.

Comparative results are provided for both single-stage and dual-stage grid-tied systems, highlighting the advantages of the proposed configuration in terms of stability and performance.

3.1 ROLES OF THE PV FRAMEWORK

PV frameworks serve multiple functions in modern energy systems, from powering local loads to integrating with distribution networks and operating as microgrids for localized power generation. The roles of the proposed PV framework include the following:

- **Regulated and Harmonic-Free Output:** The framework ensures the delivery of regulated, balanced, and harmonic-free output voltages, maintaining power quality under varying conditions.
- **Dynamic and Reactive Power Compensation:** The PV system can function as a dynamic compensator and reactive power compensator, improving grid stability.
- **Active Filtering:** The PV framework inherently generates active filtering capabilities, allowing it to operate as a Unified Power Quality Conditioner (UPQC).
- **System Stabilization:** A primary role of the PV framework is stabilizing system operation during periods of insolation shading or unavailability of solar power. Even under varying solar irradiance, the system maintains constant output voltage and current at the Point of Common Coupling (PCC), ensuring reliable power delivery.

By addressing these roles, the proposed dual-stage PV framework offers a robust and efficient solution for grid-tied solar energy systems, contributing to sustainable and reliable energy generation.

IV. SIMULATION FOR OPM-1 WITH RESULTS

In this case, the system operates under a constant irradiance of **1000 W/m²** and a constant temperature of **25°C**. The solar panel is designed using a **single-diode model**, as depicted in **Fig. 2**. The inputs for temperature and irradiance are provided through a **signal builder** block.

The **DC-DC converter** boosts the PV output voltage from **77 V** to **127 V**, ensuring optimal operation. The inverter then converts the DC output of the PV system into a sinusoidal AC output. Under a linear resistive load, the output voltage remains **constant** and is **synchronized with the grid**, demonstrating stable operation and effective energy transfer.

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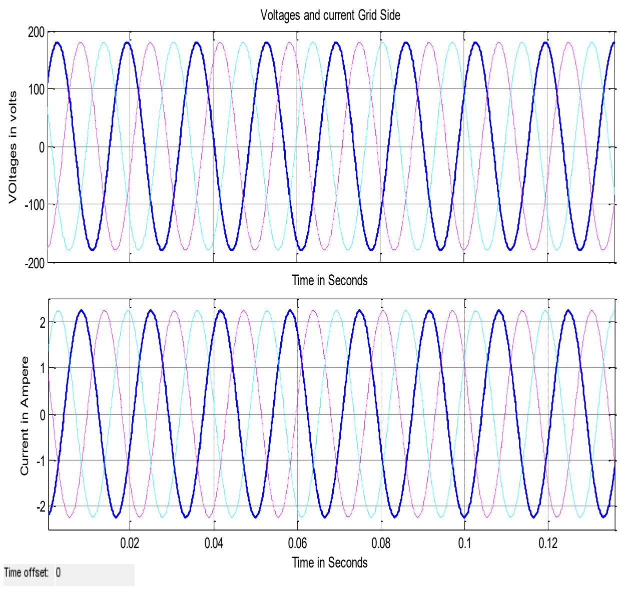

Figure 2: Output waveforms grid side Dual Stage Three-Phase Grid-Tied PV System with proposed topology

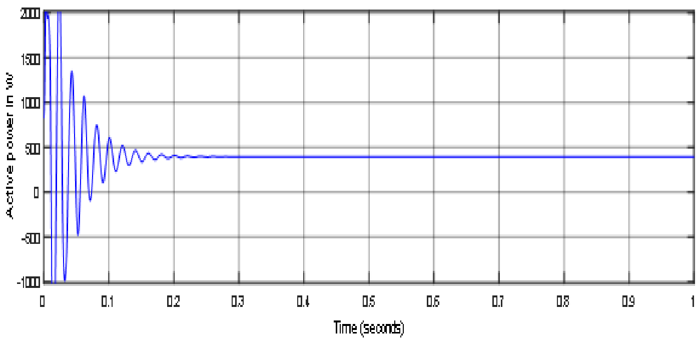

Fig. 3: Active power for OPM-1

The simulation results for the output waveforms at both the grid side and the load side are presented in Fig. 2 and Fig. 3, respectively.

The waveform at the grid side (Fig. 2) demonstrates that the output voltage and current are in perfect synchronization with the grid parameters. This synchronization ensures seamless integration of the PV system with the grid, minimizing disturbances and maintaining grid stability. The sinusoidal nature of the waveforms indicates that the grid-side output is free from significant harmonics, showcasing the effectiveness of the DC-AC inverter and the implemented control strategies.

At the load side (Fig. 3), the waveform highlights the system's ability to provide regulated, balanced, and harmonic-free voltage and current to the connected load. This ensures that the load receives a consistent and reliable power supply, even under varying operating conditions. The smooth sinusoidal profile of the waveforms at the load side further validates the robustness of the dual-stage topology and its ability to handle reactive and harmonic compensation effectively.

These results confirm the successful operation of the proposed dual-stage PV system in maintaining power quality and delivering stable performance under the specified conditions.

V. SIMULATION FOR OPM-2 WITH RESULTS

In this case, the system operates under **variable irradiance** ranging from **600 W/m² to 1000 W/m²** and a **temperature range** of **25°C to 50°C**. The simulation model for this scenario is illustrated in **Fig. 4**, while the corresponding graphs for variable irradiance and temperature inputs are shown in **Fig. 5**. The **variable irradiance** represents the fluctuations in solar energy availability, while the **temperature variation** reflects the real-world operational conditions of the PV system. These inputs are dynamically provided using a **signal builder** block in the simulation.

The simulation model effectively demonstrates the system's ability to respond to changing environmental conditions. The **DC-DC converter** adjusts the PV voltage output to maintain consistent operation, while the **DC-AC inverter** ensures a stable sinusoidal output, synchronized with the grid, despite the variability in irradiance and temperature.

These results validate the proposed system's robustness and adaptability under dynamic environmental conditions, highlighting its capability to ensure stable power output and maintain grid synchronization.

An unbalanced three-phase load of 500 W with 50 VAr of both inductive and capacitive power demand is connected between the inverter and the Point of Common Coupling (PCC). This scenario represents a real-world condition where the load is unbalanced and has both reactive and active power requirements, simulating typical grid integration challenges.

The simulation results for the output waveforms at both the grid side and the load side are presented in Fig. 4. These waveforms demonstrate how the system compensates for the unbalanced load conditions. At the grid side, the output voltage and current remain synchronized with the grid, even in the presence of an unbalanced load, ensuring stable power transfer between the PV system and the grid. This synchronization is crucial for maintaining grid stability and avoiding power quality issues such as voltage flickers or current distortions.

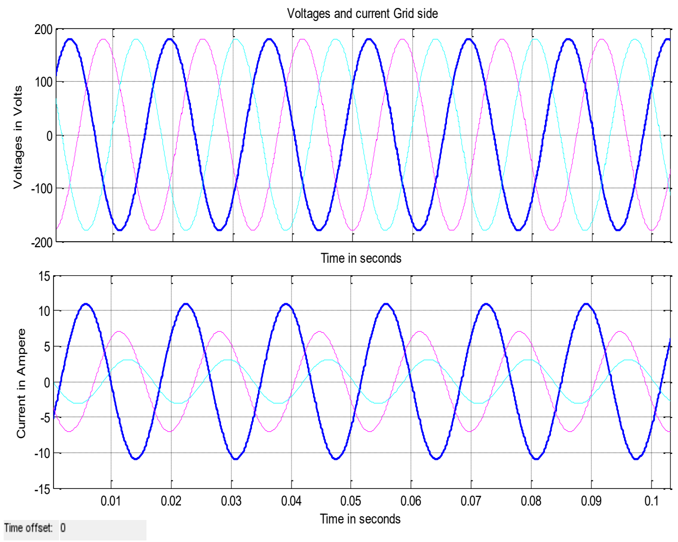

Fig - 4: Output voltage and current at load side (opm-2)

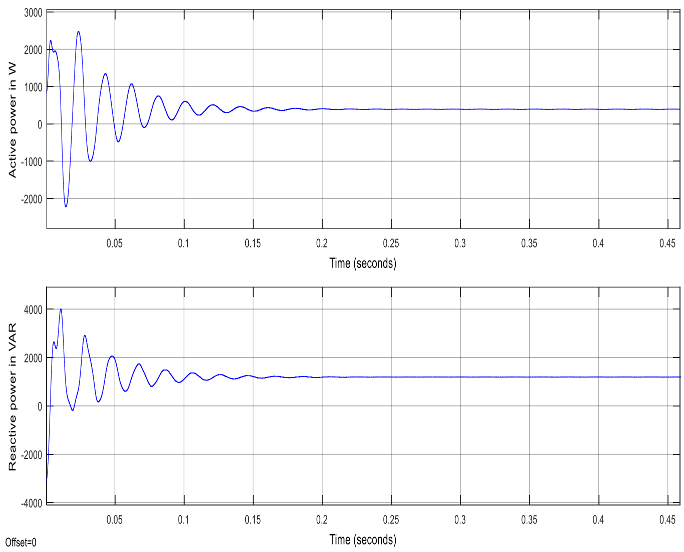

Figure 5: Active and Reactive power at load side for unbalance loading (opm-2)

At the load side, the simulation results (shown in Fig. 4) demonstrate how the system maintains stable and balanced voltage despite the unbalanced load. The DC-AC inverter performs harmonic filtering and reactive power compensation to ensure that the voltage supplied to the load is regulated, balanced, and free from significant distortions, despite the varying power demand.

VI. SIMULATION FOR OPM-3 WITH RESULTS

In this case, a **dynamic type of loading** is connected to the system. Unlike static loads, **dynamic loading** causes both **active** and **reactive power** to vary continuously over time. This type of loading is crucial for understanding the behavior of the **Dual-Stage PV (DS-PV) system** when integrated with the grid under **variable load patterns**. The dynamic load simulates real-world conditions where the demand fluctuates over time due to varying consumption by the connected appliances or systems.

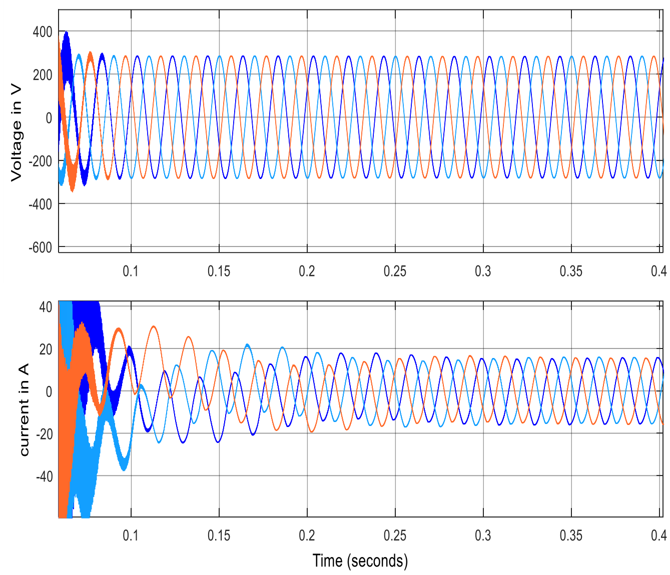

Figure 6: Output waveforms of OPM -3 load side

The **simulation results** for the output waveforms at the **grid side** and the **load side** are presented in **Fig. 6**, respectively. These waveforms illustrate how the system responds to the time-varying load conditions. On the **grid side**, the waveforms show the synchronization of the output voltage and current with the grid, even as the load changes dynamically. This synchronization is important for maintaining grid stability and ensuring smooth power transfer between the PV system and the grid, despite the fluctuations in demand.

On the **load side**, the output waveforms presented in **Fig. 6** show how the system adapts to the dynamic loading, ensuring that the load receives stable and balanced power, free from significant fluctuations or distortions. The **DC-AC inverter** effectively handles the variations in both active and reactive power demand, while compensating for the dynamic nature of the load. The system uses advanced control strategies to maintain the voltage quality, and prevent any disruption in power delivery to the load.

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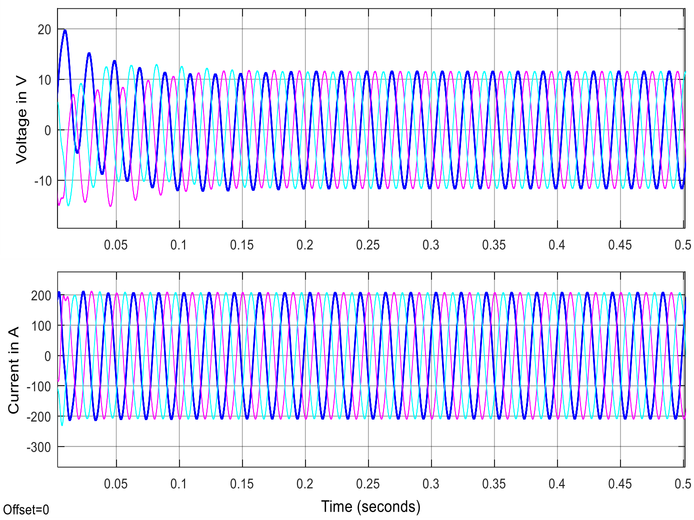

Figure 7: Output waveforms of OPM -3 grid side.

Additionally, the **power flow** at the **load side** under dynamic loading conditions is presented in **Fig. 7**. This figure demonstrates how the power is delivered to the load, with both active and reactive power continuously adjusted in response to the changing load. The simulation results confirm the **dual-stage PV system's** capability to effectively manage dynamic load conditions, providing stable and high-quality power while compensating for fluctuations in demand.

These results are critical for evaluating the performance of the DS-PV system under real-world, dynamic load conditions and provide valuable insights into its behavior when integrated with the grid. The system's ability to maintain grid synchronization, voltage regulation, and compensation for varying power demands highlights its robustness and suitability for practical deployment in variable load scenarios.

VII. CONCLUSION

This research presents a detailed investigation into the operation and performance of a dual-stage grid-connected photovoltaic (DS-PV) system, particularly focusing on its ability to stabilize output under varying load conditions. Through a series of simulation models and results, we have examined the system's behavior under three distinct operational modes: static resistive load, unbalanced RLC load, and dynamic load.

In OPM-1, the system was evaluated under constant irradiance and temperature, demonstrating the DS-PV system's ability to convert solar power efficiently, with the inverter ensuring a constant, synchronized AC output to the grid, under linear resistive load. The results confirmed the system's capability to maintain a steady and reliable power supply to both the grid and the load.

In OPM-2, we explored the system under variable irradiance and temperature, which highlighted the DS-PV system's dynamic response to changing environmental conditions. The inclusion of an unbalanced three-phase load with inductive and capacitive power demands further demonstrated the system's robustness in maintaining voltage and current stability, even under unbalanced conditions. The results showcased the dual-stage converter's ability to provide both reactive power compensation and harmonic suppression, ensuring balanced and high-quality power output.

Finally, OPM-3 focused on dynamic loading, where both active and reactive power continuously varied over time. This simulation provided insights into how the DS-PV system manages fluctuating load patterns, adjusting to real-time changes in power demand. The system's response was evaluated based on power flow, grid synchronization, and its ability to stabilize voltage and current under variable load conditions. The findings confirmed the system's capability to handle real-world dynamic loading effectively, ensuring the continuity of stable power delivery.

Overall, the proposed dual-stage PV system has proven to be a highly adaptable and reliable solution for integrating solar power into the grid, particularly in scenarios with variable, unbalanced, or dynamic loads. The system not only ensures efficient conversion of solar energy but also provides reactive power compensation, harmonic filtering, and voltage regulation, making it a valuable tool for improving power quality in grid-connected applications. The simulation results across different operational modes emphasize the system's potential for widespread implementation, offering a stable and sustainable energy source that can address the growing demand for reliable and high-quality power in various real-world applications.

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