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Design and Simulation of a Grid-Connected Solar-Wind Hybrid Power System with Inverter and Power Quality Enhancement in MATLAB

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ABSTRACT

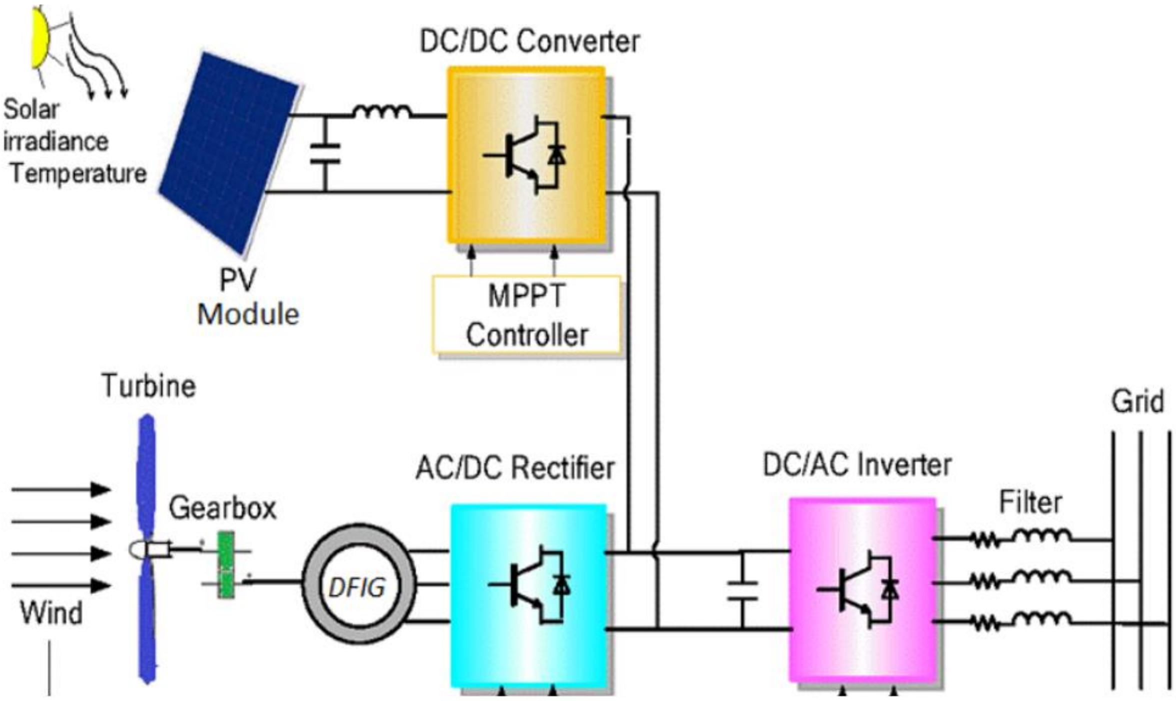
This paper presents a comprehensive design and simulation of a grid-connected hybrid power system integrating solar and wind energy, developed using MATLAB/Simulink. In contrast to conventional off-grid systems, this study focuses on a grid-connected configuration that combines the DC output from a solar power plant with the DC converted from wind power generation. The wind energy is initially captured by a wind power plant, where the AC output is converted into DC through a rectifier. The DC output is then coupled with the solar power system to create a hybrid energy source. A DC-DC converter is used to regulate the combined output, which is subsequently fed to an inverter. The inverter's output is connected to the grid through a filter to improve power quality. The system ensures optimal energy transfer and harmonics reduction, enhancing the stability and efficiency of the power supplied to the grid. This design provides a sustainable solution for renewable energy integration into the existing grid infrastructure. Furthermore, the paper highlights the importance of power quality enhancement techniques and the role of filters in reducing Total Harmonic Distortion (THD) to meet grid compliance standards. The MATLAB simulation results demonstrate the feasibility and efficiency of the proposed system in a real-world scenario. The study serves as an extension of off-grid hybrid systems, offering valuable insights for the development of on-grid renewable energy solutions in MATLAB-based simulations.

Keywords: *Grid-connected system, Solar-Wind hybrid, MATLAB/Simulink, Power quality enhancement, Inverter, DC-DC converter, Total Harmonic Distortion (THD).*

1. INTRODUCTION

Renewable energy sources have gained significant attention in recent years due to the growing concerns over environmental sustainability, fossil fuel depletion, and the increasing demand for electricity. Among various renewable energy sources, solar and wind energy are considered the most promising due to their abundance and sustainability. However, the intermittent nature of these energy sources poses a challenge to their reliable integration into the power grid. Hybrid power systems, which combine different renewable sources, offer a viable solution to this issue. This paper presents the design and simulation of a grid-connected solar-wind hybrid power system using MATLAB/Simulink. By integrating wind and solar energy, the system ensures continuous power supply while improving overall efficiency and reliability. Unlike conventional off-grid systems, which require extensive energy storage solutions, the proposed grid-connected system directly supplies generated power to the grid, reducing dependency on battery storage and improving system economics.

A solar-wind hybrid system leverages the complementary nature of solar and wind energy. Solar power is abundant during the day, while wind energy can be available at any time, depending on geographical and meteorological conditions. The hybrid approach ensures a more stable and continuous energy supply, addressing the intermittent nature of individual renewable sources. In the proposed system, the AC power generated from the wind turbine is first converted to DC through a rectifier. This DC power is then combined with the DC output of the solar photovoltaic (PV) system. A DC-DC converter is employed to regulate the voltage and optimize power flow. The combined DC power is then fed into an inverter, which converts it back to AC before supplying it to the grid. A filter is used to minimize harmonics and improve power quality, ensuring compliance with grid regulations.



Proposed system configuration

One of the primary objectives of this research is to enhance power quality and system efficiency. The integration of renewable energy sources into the grid introduces challenges such as voltage fluctuations, frequency variations, and harmonic distortions. These issues can impact the stability of the power system and the performance of connected loads. The use of inverters with advanced control strategies and filters helps mitigate these challenges. In this study, a Total Harmonic Distortion (THD) analysis is conducted to assess the effectiveness of the filter in maintaining grid power quality. Additionally, power flow management strategies are implemented to ensure optimal utilization of the available renewable energy resources, thereby improving overall system performance and reliability.

MATLAB/Simulink is chosen as the simulation platform due to its advanced modeling capabilities and wide acceptance in power system studies. The platform enables detailed modeling of power electronic converters, control strategies, and grid integration aspects. The simulation results validate the effectiveness of the proposed system by demonstrating stable voltage levels, reduced harmonics, and improved efficiency. The study provides insights into the practical implementation of grid-connected hybrid systems and serves as a foundation for future research in renewable energy integration. Furthermore, the findings emphasize the role of hybrid renewable energy systems in achieving sustainable energy goals and reducing dependence on conventional fossil fuels.

In conclusion, this research highlights the significance of integrating solar and wind energy in a grid-connected configuration to enhance power system stability and efficiency. By addressing the limitations of individual renewable sources and implementing power quality enhancement techniques, the proposed system offers a feasible solution for large-scale renewable energy integration. The simulation results confirm the viability of the designed system, providing valuable contributions to the field of renewable energy research. Future work may focus on optimizing control algorithms, incorporating energy storage solutions, and expanding the system to accommodate additional renewable sources for further improvements in performance and reliability.

2. LITERATURE SURVEY

The integration of renewable energy sources into power systems has been widely studied in the literature. Various research efforts have focused on the optimization, control, and performance improvement of hybrid renewable energy systems. Solar and wind hybrid systems are considered one of the most effective solutions to address the intermittency of renewable energy sources. Several studies have investigated the feasibility of integrating these systems into the power grid. For instance, researchers have explored different power electronic converters and control strategies to enhance energy transfer efficiency and grid stability. Advanced power electronics and smart grid technologies have further facilitated the seamless integration of renewable energy sources into the existing power infrastructure.

Hybrid renewable energy systems have been examined extensively for their ability to provide a stable and continuous power supply. Studies indicate that combining solar and wind energy can significantly reduce dependency on fossil fuels and contribute to a cleaner and more sustainable energy mix. The literature highlights various modeling approaches, including MATLAB/Simulink-based simulations, to evaluate the performance of hybrid systems. Additionally, research has been conducted to assess the impact of different DC-DC converter topologies and inverter control techniques on overall system efficiency. Various filtering techniques have been proposed to minimize harmonics and improve power quality, ensuring compliance with grid regulations and reducing total harmonic distortion.

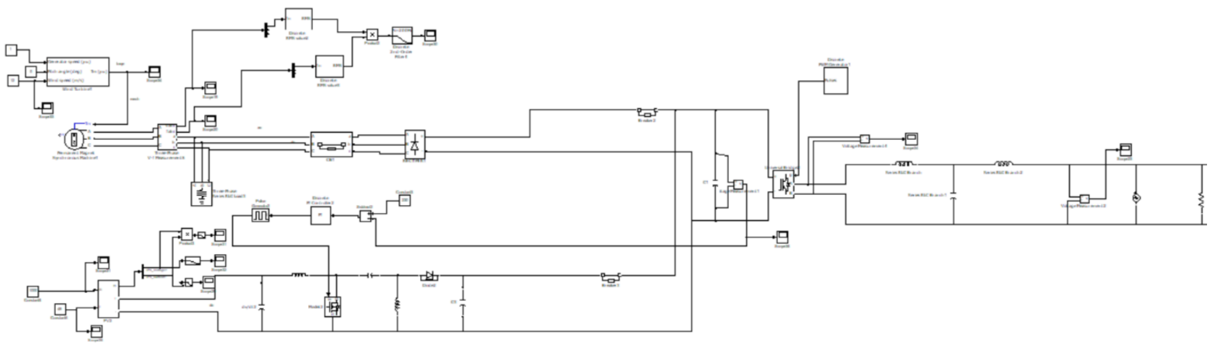
Recent studies emphasize the importance of power management strategies in hybrid energy systems. Researchers have developed and tested different maximum power point tracking (MPPT) algorithms to optimize the power extraction from solar panels and wind turbines. These algorithms play a crucial role in enhancing the efficiency of hybrid power systems by dynamically adjusting operating points based on environmental conditions. Additionally, intelligent control methods, such as fuzzy logic and artificial neural networks, have been explored to improve the stability and reliability of grid-connected hybrid energy systems. The literature further suggests that integrating energy storage solutions, such as batteries or supercapacitors, can enhance the system's ability to manage fluctuations in power generation and demand.

The role of grid-connected hybrid systems in modern power networks has been a topic of extensive research. Various studies have analyzed the economic and environmental benefits of integrating solar-wind hybrid systems into the grid. These systems have been shown to reduce greenhouse gas emissions, decrease reliance on non-renewable energy sources, and provide cost-effective solutions for electricity generation. The literature also discusses the challenges associated with grid integration, such as voltage regulation, frequency stability, and grid synchronization. Advanced inverter control strategies, such as vector control and droop control, have been proposed to address these challenges and ensure smooth operation of hybrid systems in grid-connected mode.

Overall, the literature provides valuable insights into the development, optimization, and control of grid-connected solar-wind hybrid systems. The research findings support the feasibility and effectiveness of integrating hybrid renewable energy sources into the power grid. Future studies may focus on further enhancing the efficiency of hybrid systems through advanced machine learning algorithms, real-time monitoring systems, and improved grid interaction strategies. Additionally, research on hybrid systems with multi-energy integration, including hydrogen storage and bioenergy, may contribute to the evolution of more sustainable and resilient power networks.

3. EXISTING SYSTEM

Off-grid photovoltaic (PV) and wind energy systems are standalone power generation solutions that operate independently of the conventional electricity grid. These systems are designed to provide electricity in remote areas where grid access is limited or unavailable. The primary advantage of an off-grid hybrid system is its ability to harness energy from multiple renewable sources, ensuring a more stable and reliable power supply. Solar PV panels generate electricity during daylight hours, while wind turbines produce energy when sufficient wind speeds are available. By integrating both sources, the system can compensate for the intermittency of each individual energy source, enhancing overall energy reliability.



Existing system simulation circuit

A key component of an off-grid PV-wind system is the energy storage unit, typically consisting of batteries. Since renewable energy generation is highly dependent on weather conditions, energy storage plays a crucial role in maintaining power availability during periods of low solar irradiance or insufficient wind speeds. Battery storage systems allow excess energy generated during peak conditions to be stored and used when needed, thereby reducing dependency on real-time generation. Additionally, charge controllers are used to manage the charging and discharging of batteries, preventing overcharging and deep discharging, which can reduce battery lifespan.

The power generated from PV panels is in direct current (DC) form, while wind turbines often produce alternating current (AC), which must be converted into DC using rectifiers before integration. A DC bus is used to combine power from both sources before it is directed to an inverter, which converts the DC power to AC for use by standard electrical appliances. The choice of inverter technology is critical in off-grid systems, as it determines the quality and efficiency of the power supplied to the load. Modified sine wave and pure sine wave inverters are commonly used, with the latter offering superior power quality and efficiency, albeit at a higher cost.

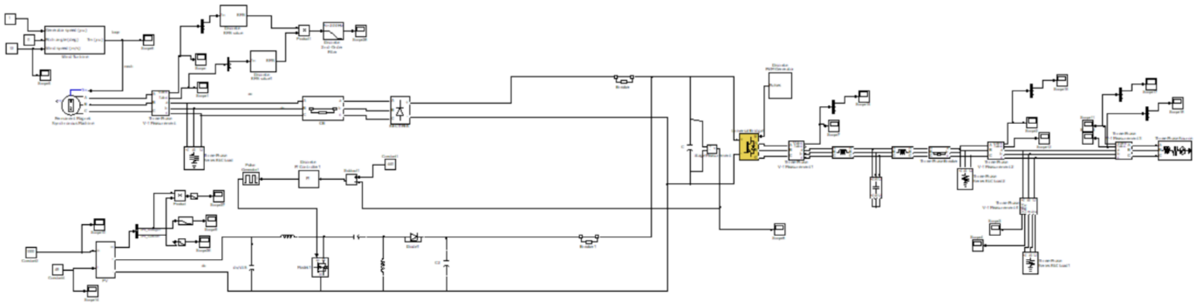
Despite their advantages, off-grid PV-wind systems face several challenges. One of the main issues is the high initial investment cost, including the expenses for solar panels, wind turbines, battery storage, inverters, and charge controllers. Additionally, the system requires regular maintenance to ensure optimal performance, particularly for wind turbines, which have moving parts that are susceptible to wear and tear. Moreover, battery storage systems degrade over time, necessitating periodic replacement, which adds to the long-term cost of operation. The efficiency of off-grid systems is also affected by environmental factors such as seasonal variations in sunlight and wind speed, making proper system sizing and load management crucial for sustained performance.

The development of advanced energy management techniques and hybrid optimization strategies has improved the performance and feasibility of off-grid PV-wind systems. Recent advancements include the use of smart controllers, artificial intelligence-based load forecasting, and hybrid energy storage solutions such as supercapacitors and hydrogen fuel cells. These innovations help enhance energy utilization, minimize storage dependency, and improve system efficiency. By addressing existing challenges, off-grid PV-wind hybrid systems continue to evolve as a viable solution for sustainable energy generation, particularly in rural and remote areas where grid connectivity remains a challenge.

4. PROPOSED SYSTEM

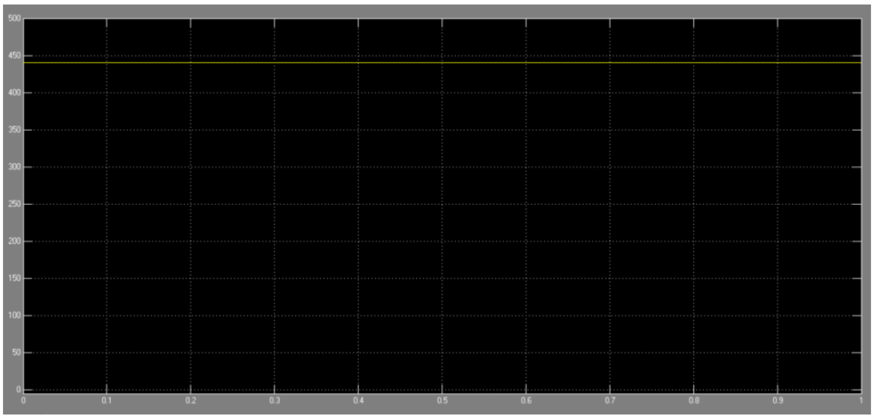
The proposed system focuses on a grid-connected solar-wind hybrid power generation model developed in MATLAB/Simulink. This system aims to optimize the integration of renewable energy sources into the power grid while ensuring power quality enhancement. The core idea behind this hybrid system is to utilize solar photovoltaic (PV) panels and wind turbines as complementary energy sources, addressing the intermittency issues associated with each. The wind energy conversion system (WECS) generates alternating current (AC), which is converted into direct current (DC) using a rectifier. Simultaneously, solar PV panels generate DC power, which is combined with the rectified wind energy to create a unified DC link. This DC power is then processed through a DC-DC converter, which regulates voltage levels and optimizes power flow. The final output is fed to an inverter, which converts the DC power into AC and synchronizes it with the grid through a power quality enhancement filter.

A key feature of this system is the inclusion of an advanced DC-DC converter to enhance voltage regulation. The converter is designed to improve efficiency and minimize losses during the power conversion process. The integration of maximum power point tracking (MPPT) techniques ensures that the solar panels and wind turbines operate at their highest efficiency points. The hybrid energy is fed to a voltage source inverter (VSI), which converts it back into AC before transmitting it to the grid. The inverter is equipped with pulse width modulation (PWM) control to enhance the quality of the output waveform, reducing harmonic distortions. To further improve power quality, an LC filter is used to smoothen the output waveform and ensure compliance with grid standards.



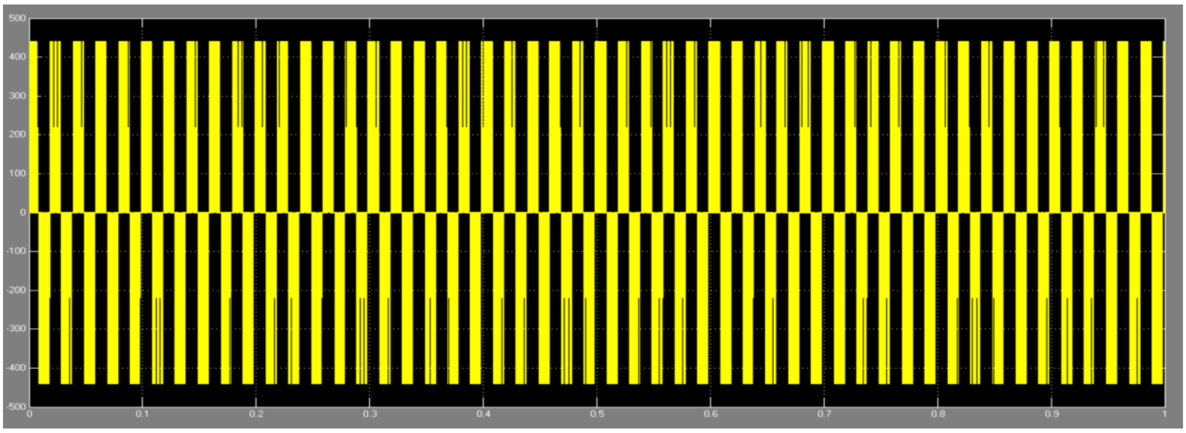
Proposed system simulation configuration

The proposed hybrid power system incorporates a smart energy management system (EMS) that dynamically allocates power to the grid based on real-time conditions. The EMS ensures optimal utilization of available resources, balancing the power contribution from solar and wind sources. The system is also designed with a fault tolerance mechanism, allowing it to adjust power output based on grid fluctuations and environmental conditions. The synchronization mechanism between the hybrid system and the grid plays a crucial role in maintaining a stable power supply. The inverter synchronizes the output voltage and frequency with the grid parameters, ensuring seamless power integration. Moreover, reactive power compensation is implemented to improve power factor and minimize grid disturbances.

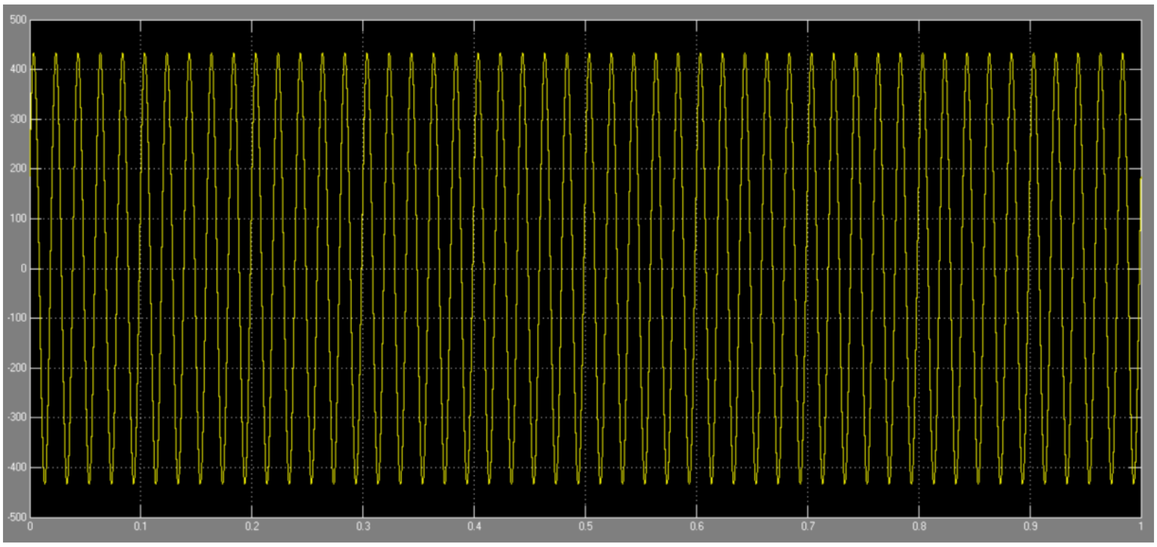


Dc link voltage vs time

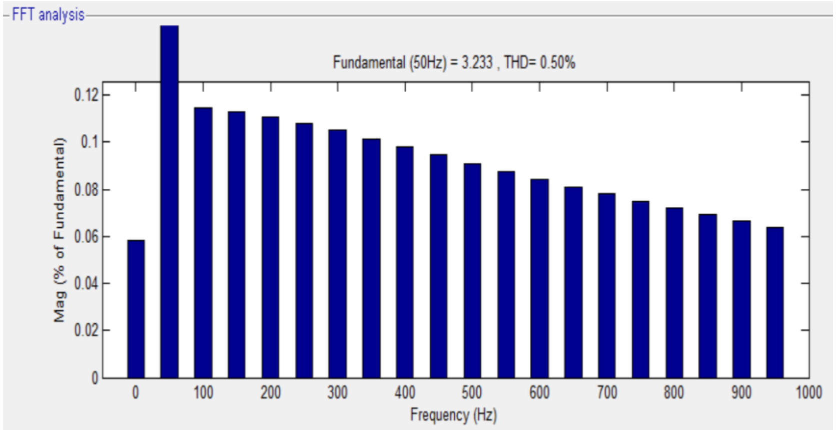
The simulation of the proposed system in MATLAB/Simulink provides valuable insights into its operational feasibility. The results demonstrate improved power quality with reduced Total Harmonic Distortion (THD), meeting industry standards for grid compliance. The hybrid system effectively mitigates fluctuations in energy generation by leveraging both solar and wind resources, ensuring a steady power supply. The LC filter significantly reduces high-frequency harmonics, leading to improved grid stability. Additionally, the system's response to varying environmental conditions is analyzed, showcasing its ability to sustain performance under different scenarios. The impact of different control strategies, including MPPT and reactive power compensation, is evaluated to highlight their effectiveness in enhancing system performance.



Inverter voltage without filter



Inverter voltage (Grid) with filter



Proposed system THD

In summary, the proposed system offers a sustainable and efficient solution for renewable energy integration into the power grid. The combination of solar and wind energy sources, coupled with power quality enhancement techniques, ensures a reliable and high-performance energy system. The findings of this study contribute to the advancement of grid-connected hybrid renewable energy solutions, offering practical insights for future implementations. Further research can focus on incorporating battery storage systems for enhanced energy reliability and exploring advanced machine learning-based control strategies for real-time optimization.

CONCLUSION

The design and simulation of a grid-connected solar-wind hybrid power system in MATLAB/Simulink offer a significant contribution to renewable energy integration. By combining solar and wind energy sources, the proposed system effectively addresses the intermittency issues associated with standalone renewable energy generation. The use of a DC-DC converter, inverter, and power quality enhancement filter ensures efficient energy conversion and delivery to the grid. The system's ability to reduce Total Harmonic Distortion (THD) and optimize power factor demonstrates its feasibility for real-world applications. The simulation results highlight the system's robustness in maintaining stable power output under varying environmental conditions. The smart energy management system enhances operational efficiency by dynamically adjusting power flow based on real-time conditions. The implementation of Maximum Power Point Tracking (MPPT) ensures that solar and wind energy sources operate at optimal efficiency, further improving overall system performance. The study also underscores the importance of integrating fault tolerance mechanisms to enhance grid stability and prevent disruptions. Future research can focus on expanding the system's capabilities by incorporating energy storage solutions such as battery banks or supercapacitors. This would enhance energy reliability and allow surplus power to be stored for later use. Additionally, the application of artificial intelligence and machine learning algorithms for predictive control and real-time optimization could further improve system efficiency. Overall, this study lays the foundation for future advancements in grid-connected hybrid renewable energy systems, contributing to a more sustainable and efficient power infrastructure.

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