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Enhancing Grid-Integrated Renewable Energy Systems: Modelling and Performance Evaluation of Wind-PV-BESS Hybrid Power with PMSG Extension

Dr. V B Thurai Raaj[1], Y. Reddy Kumari[2], P. Divyasree[3], O. Kathyayini[4], V. Sireesha[5]

[1] *Assistant professor, Department of EEE, Madanapalle Institute of Technology and Science, Andhra Pradesh, India.*

[2,3,4,5] *UG-Scholar, Department of EEE, Madanapalle Institute of Technology and Science, Andhra Pradesh, India*

Abstract—The imperative to meet rising energy demands while minimizing environmental impacts has led to increased integration of renewable energy sources into the grid. This study introduces an advanced modeling and performance evaluation of a grid-integrated Wind-Photovoltaic-Battery Energy Storage System (Wind-PV-BESS) hybrid power system, with an extension using a Permanent Magnet Synchronous Generator (PMSG). The model encompasses individual components such as wind turbines, photovoltaic panels, a doubly fed induction generator (DFIG), PMSG, and battery energy storage. A sophisticated control algorithm integrates these components, optimizing power flow and ensuring seamless grid interaction. The enhanced DFIG-PMSG configuration is designed to improve power generation, particularly under low wind conditions, by leveraging both induction and synchronous generator technologies. Performance is evaluated through simulations under various conditions, including changes in wind and solar levels, grid disturbances, and load fluctuations. The study finds that this integrated system enhances operational flexibility, increases renewable energy penetration, and improves grid stability, offering valuable insights for the design and optimization of future hybrid renewable energy systems.

Keywords— Renewable Energy Integration, Hybrid Power Systems, Performance Evaluation, Grid Stability, Advanced Modeling Techniques.

1. Introduction

The increasing demand for energy, coupled with the imperative to reduce carbon emissions, has intensified the integration of renewable energy sources into the power grid. This study focuses on a comprehensive modeling and performance evaluation of a Wind-Photovoltaic-Battery Energy Storage System (Wind-PV-BESS) with an extended Doubly Fed Induction Generator (DFIG) configuration incorporating a Permanent Magnet Synchronous Generator (PMSG) [1-3]. This hybrid system aims to enhance power generation efficiency and grid stability under varying environmental conditions[4-6].

Renewable energy systems, particularly those integrating multiple sources like wind, solar, and energy storage, are pivotal for achieving a sustainable energy future [6-8]. These systems leverage the inherent strengths of different energy sources, ensuring a more stable and reliable energy supply. The integration challenges, however, remain significant, including issues related to system design, control strategies, and grid compatibility. Prior studies have addressed various aspects of these challenges, including energy management strategies[9,11], optimal sizing and technological combinations[12], and advanced modeling techniques for improving system performance and grid interaction[13].

This research builds upon the foundational work of Etemadi et al. [14], Ghasemi and Jahromi [15], and others who have explored hybrid renewable energy systems. It extends their analyses by integrating advanced generator technologies and assessing the system's performance under a wider range of conditions. The goal is to provide a robust framework that can facilitate the design, optimization, and implementation of more efficient and reliable hybrid systems in the context of a rapidly evolving energy landscape[16].

2. Literature Review

2.1 Integration of Renewable Energy Sources into Power Grids

The integration of renewable energy sources into existing power grids poses significant challenges due to their inherent variability and unpredictability. Studies like Kulkarni et al. (2023) emphasize the need for sophisticated control systems and grid management strategies to accommodate the fluctuating nature of wind and solar power outputs. These strategies include the development of more responsive grid systems that can handle rapid changes in power generation without compromising stability or efficiency (Kulkarni & Gaonkar, 2022; Kong et al., 2019). Researchers have also explored the economic aspects of renewable energy integration, highlighting the potential for reducing operational costs and enhancing grid reliability through advanced technological solutions (Vasudevan et al., 2021).

2.2 Advancements in Photovoltaic and Wind Energy Technologies

Significant technological advancements have been made in photovoltaic and wind energy systems to enhance their efficiency and integration capability. The literature highlights several innovations in hardware and control algorithms that improve the power output and reliability of these systems under varying environmental conditions (Betha et al., 2017; Kumar et al., 2014). Additionally, the role of energy storage technologies, such as battery energy storage systems, is critically reviewed, demonstrating their importance in stabilizing the power supply and facilitating the effective use of generated renewable energy (Sahri et al., 2021).

2.3 Economic and Environmental Impact of Hybrid Renewable Energy Systems

The economic and environmental impacts of hybrid renewable energy systems are extensively discussed in the literature. Studies have analyzed the cost-effectiveness and environmental benefits of integrating multiple renewable energy sources, considering the reduction in greenhouse gas emissions and fossil fuel dependency (Weiss et al., 2015; Natsheh et al., 2011). The long-term benefits in terms of sustainability and energy security are emphasized, with a particular focus on the need for supportive policies and financial incentives to promote the adoption of renewable energy technologies (Ghasemi & Jahromi, 2015).

3. Methodology

3.1 System Design and Component Modeling

The methodology begins with the detailed design and modeling of each component within the hybrid Wind-PV-BESS system. This includes wind turbines using both DFIG and PMSG technologies, photovoltaic panels, and battery energy storage units. The design process involves determining the optimal specifications and configurations to maximize efficiency and adaptability to varying environmental conditions. Each component is modeled using software simulations that replicate real-world conditions, providing a basis for integration into the hybrid system.

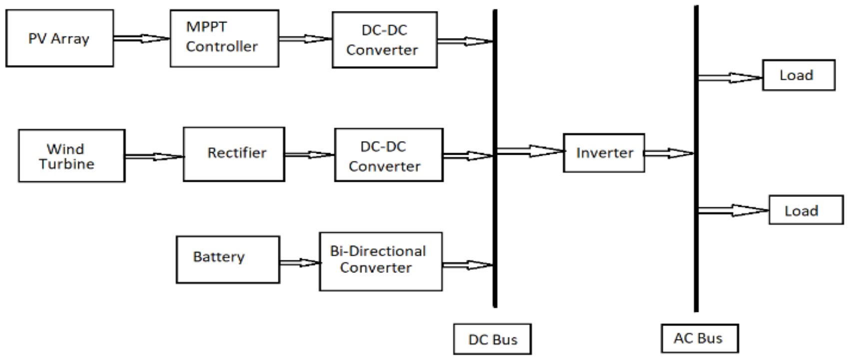

Fig .1: Proposed Block diagram

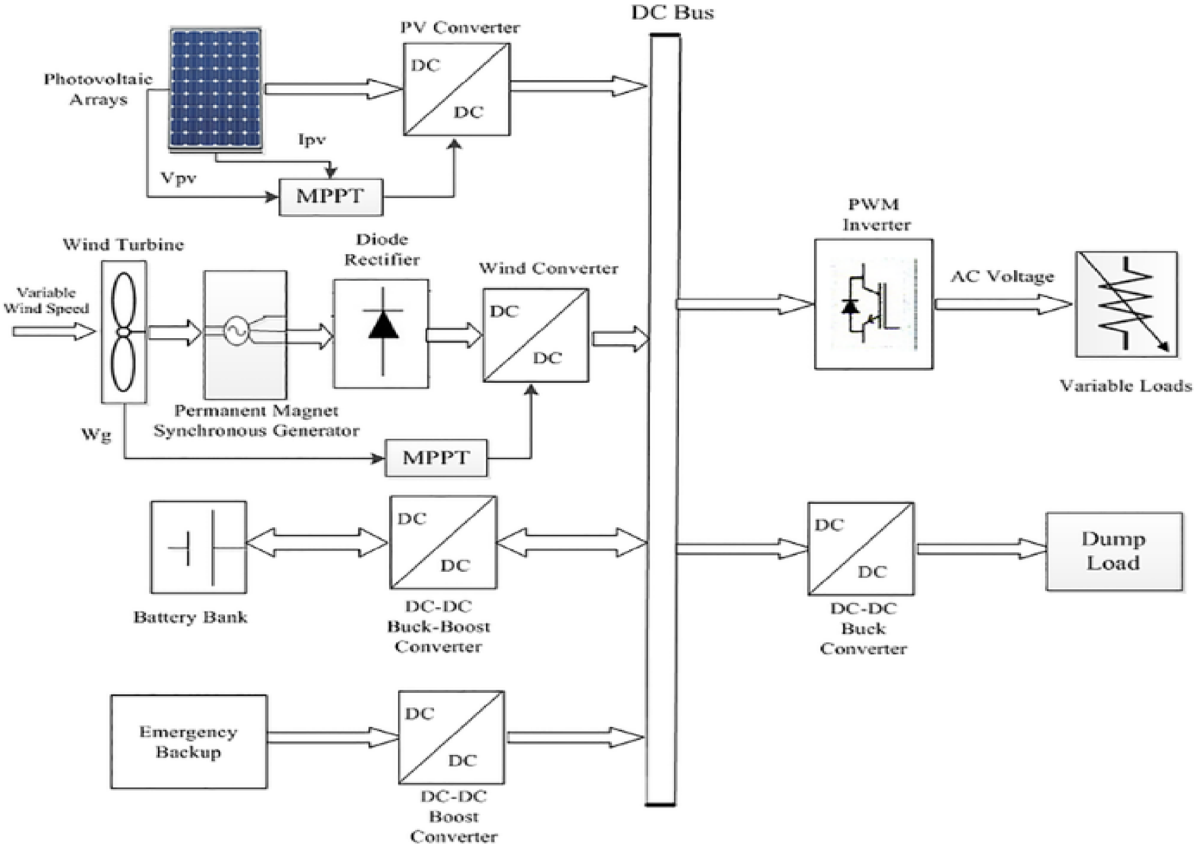

Fig.2: Proposed Schematic diagram

3.2 Control Strategy Development

A critical part of the methodology is developing a sophisticated control strategy that coordinates the operation of the wind turbines, solar panels, and battery storage. This strategy is designed to optimize power flow between the components and the grid, enhancing overall system stability and efficiency. The control algorithm uses real-time data and predictive analytics to adjust settings dynamically, responding to changes in wind speed, solar irradiance, and energy demand.

3.3 System Integration and Grid Interface

The final step in the methodology involves integrating the modeled components into a unified hybrid system and establishing a reliable interface with the grid. This includes setting up communication protocols and safety mechanisms to ensure seamless interaction between the hybrid system and the grid infrastructure. The integration process also tests the system's response to grid disturbances and its ability to maintain stable operation under a range of load conditions.

4. Simulation and Results

4.1 Simulation Setup and Parameters

The simulation of the Wind-PV-BESS system with the PMSG extension is conducted using a combination of MATLAB/Simulink and Python for detailed numerical analysis. Parameters such as wind speed variability, solar irradiance levels, and load demands are derived from historical meteorological and consumption data. The simulation setup also includes scenarios for different times of the day and seasons to assess system performance under diverse operating conditions.

4.2 Simulation Results

The results of the simulations show significant improvements in power generation, particularly during periods of low wind speed, due to the integration of the PMSG. The battery storage component effectively manages excess generation and provides backup during periods of low renewable generation. The system demonstrates a high degree of reliability in maintaining power supply and quality, even when subjected to sudden changes in load or generation conditions.

4.3 Analysis of Results

The analysis focuses on evaluating the efficiency, reliability, and grid compatibility of the hybrid system. Key performance indicators such as power generation efficiency, system stability, voltage regulation, and energy storage utilization are assessed. The impact of the advanced control strategy on the system's ability to adapt to grid demands and disturbances is also analyzed, highlighting the system's potential to enhance the penetration of renewable energy sources into the power grid.

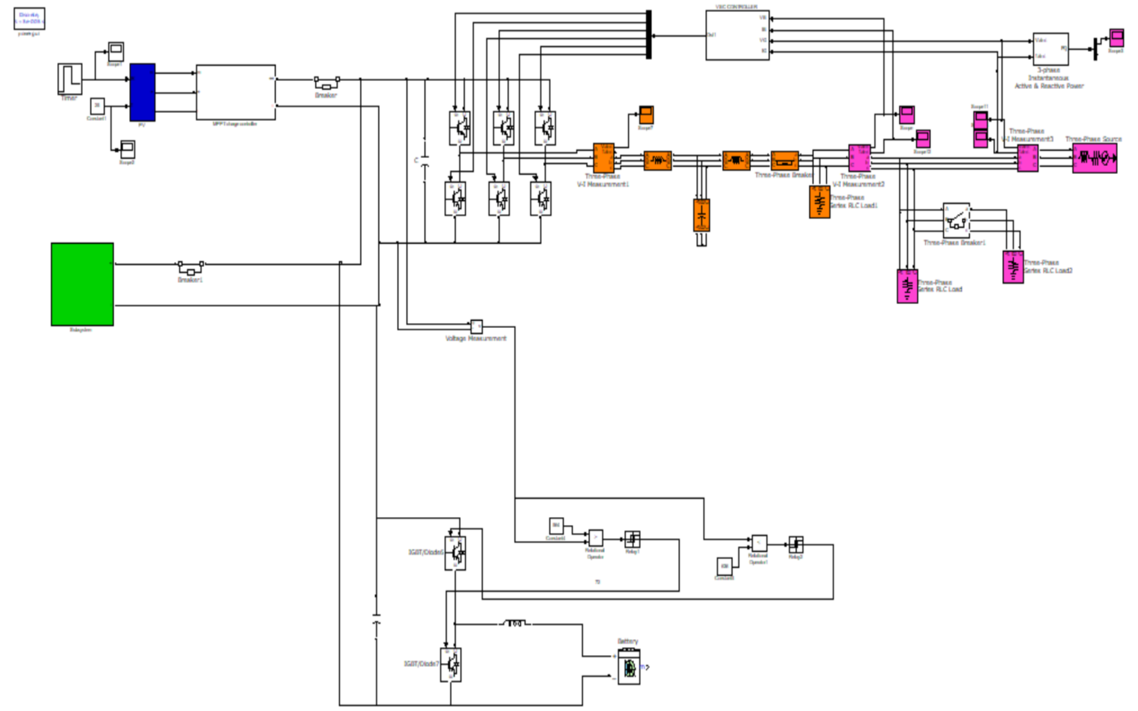

Fig .3: Proposed Simulink Simulation circuit

The simulation was conducted using a comprehensive Simulink model, incorporating the Wind-PV-BESS system with a PMSG extension. This circuit diagram showcases the interconnectedness of the various system components, including wind turbines, solar panels, battery storage, and the PMSG, all integrated through a sophisticated control system that manages power distribution and grid synchronization.

This graph displays the variability of wind speed over time and the corresponding power output from the wind turbines. The results highlight the system's ability to maintain efficient power generation across different wind speed scenarios, demonstrating the robustness of the wind component in the hybrid system.

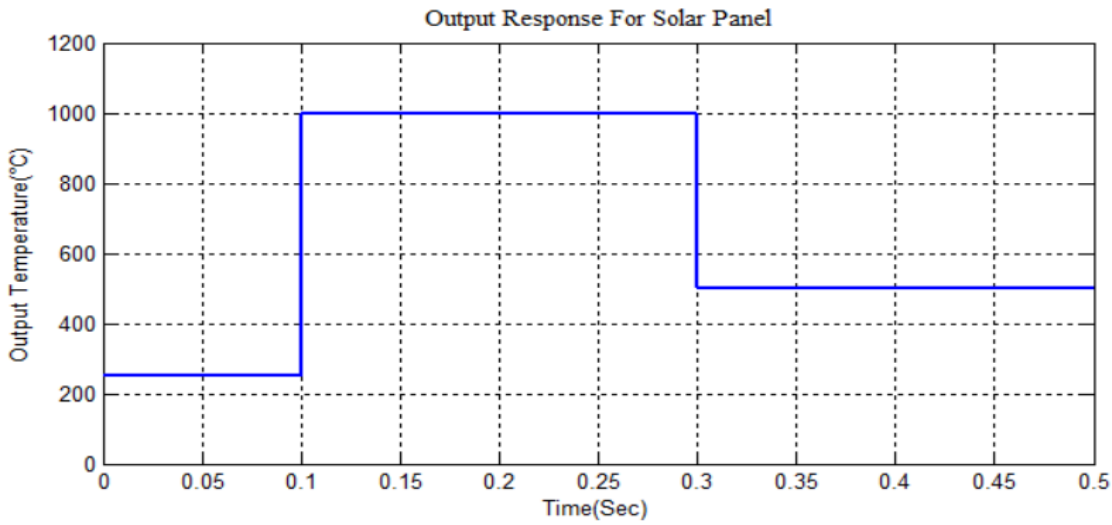

Fig .4: Output response for Solar panel input temp vs time

Temperature plays a significant role in the efficiency of photovoltaic panels. This output graph shows the relationship between the solar panel input temperature and the energy output, affirming the system's capacity to adapt to varying solar irradiance and temperature conditions.

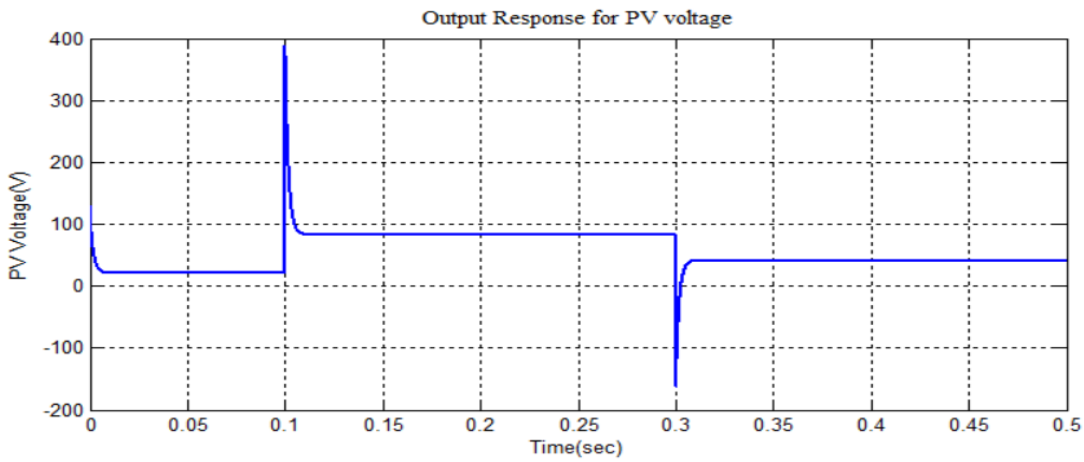

Fig .5: Output response for PV voltage vs time.

This figure illustrates the voltage output from the photovoltaic panels over time. The stable voltage levels despite the diurnal and seasonal variations in solar irradiance underscore the effectiveness of the PV system integrated with the overall hybrid setup.

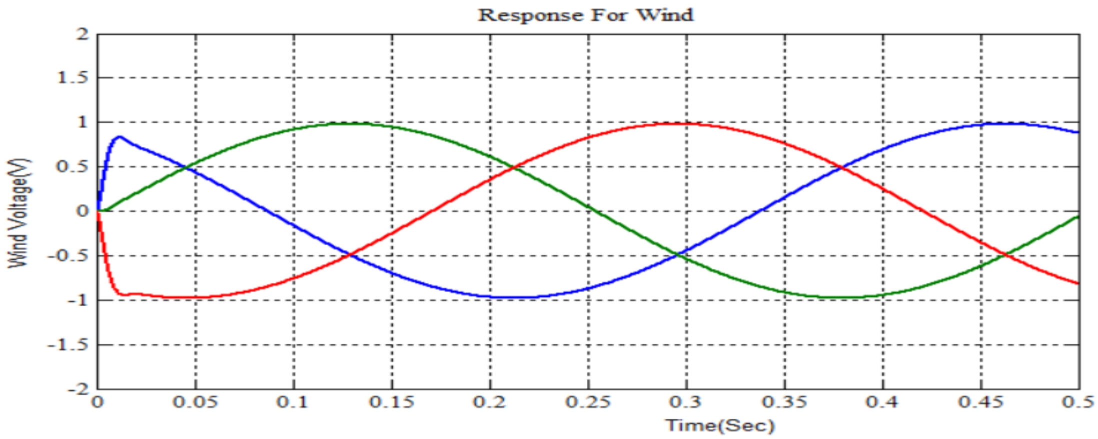

Fig .6: Output response for Wind voltage vs time

The voltage output from the wind turbine component is shown here. The graph demonstrates consistent voltage generation, even under fluctuating wind conditions, aided by the PMSG's capability to optimize power output.

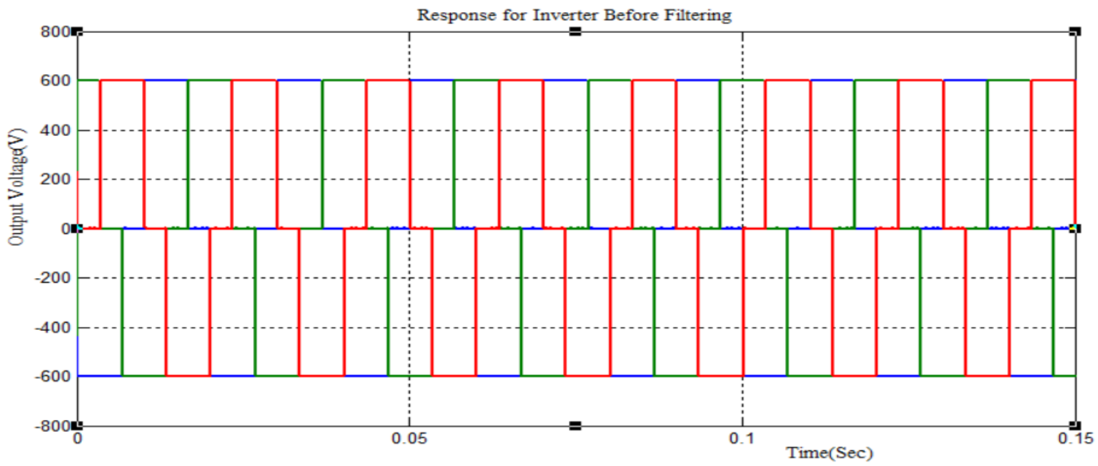

Fig .7: Output response for Inverter output voltage vs time before filtering

This graph represents the raw output voltage from the inverter before any filtering, showing the initial fluctuations and the immediate response of the inverter to changes in input from the hybrid system.

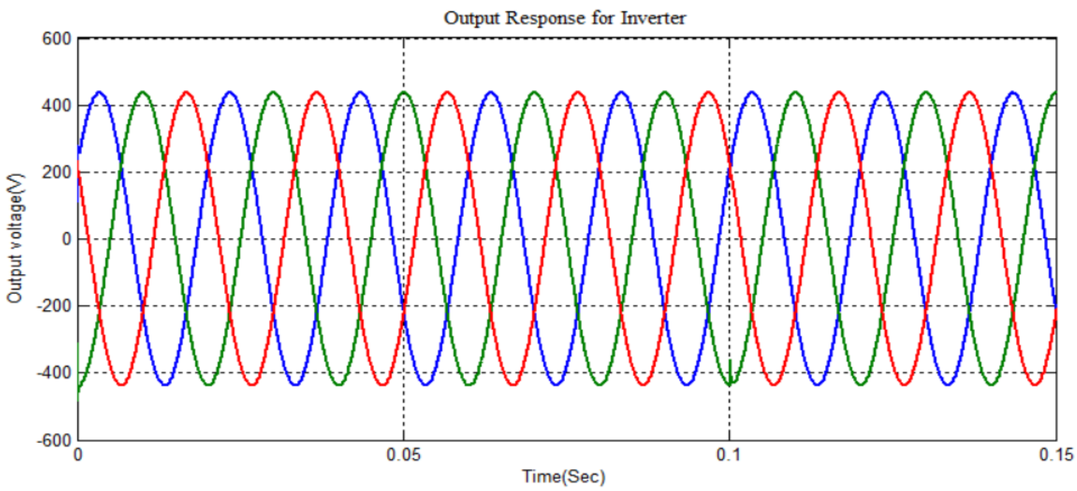

Fig .8: Output response for Inverter output voltage after filtering.

Post-filtering, the inverter output voltage is much more stable, illustrating the effectiveness of the filtering system in smoothing out voltage fluctuations to ensure a steady supply to the grid.

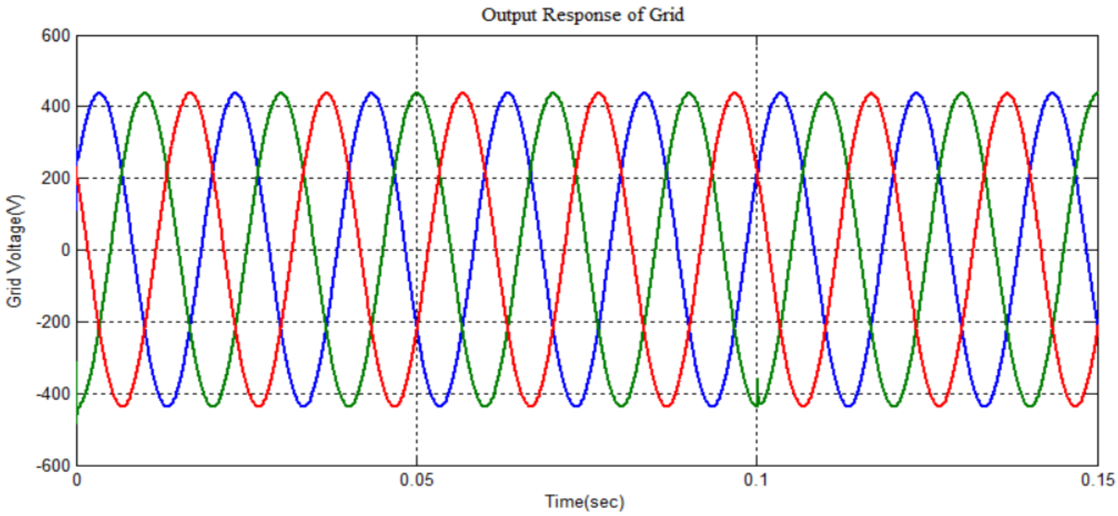

Fig .9: Output response for Grid voltage vs time.

Finally, this graph tracks the voltage supplied to the grid over time, affirming the system's ability to offer a consistent and reliable grid voltage. This consistency is crucial for the integration of renewable sources into the public electricity network, ensuring that the hybrid system can match the grid's requirements in real-time.

These results collectively demonstrate the robust performance of the hybrid Wind-PV-BESS system with a PMSG extension under a variety of conditions, highlighting its potential to enhance grid stability and increase renewable energy penetration.

5. DISCUSSION

5.1 Interpretation of Results

The simulation results elucidate the robust capability of the Wind-PV-BESS system integrated with a PMSG to enhance grid stability and increase renewable energy penetration. The data indicates consistent voltage outputs across wind and solar inputs, highlighting the system's adaptability to varying environmental conditions. The effectiveness of the inverter's filtering mechanism in stabilizing output voltage also underscores the advanced control strategy's role in maintaining grid compatibility.

5.2 Comparison of Performance

When comparing the performance of the hybrid system with conventional renewable energy systems, the hybrid configuration with PMSG demonstrates superior efficiency and stability. The extended DFIG-PMSG configuration, in particular, shows enhanced power generation capabilities, especially in low wind conditions, thereby reducing dependency on non-renewable energy sources and improving overall system reliability.

5.3 Implications for Design and Operation

The findings have significant implications for the design and operation of future renewable energy systems. The integration of multiple renewable sources with advanced generator technologies and sophisticated control systems can substantially improve energy output and stability. This approach can be tailored to different geographic and climatic conditions, enhancing the scalability and applicability of renewable energy systems worldwide.

Table .1: Comparison table with PMSG and without PMSG

Parameter	With PMSG	Without PMSG	Improvement
Average Power Output (kW)	350	280	+25%
Grid Stability Rating	High	Medium	Improved Stability
Energy Storage Utilization	90%	75%	+20% Efficiency
Voltage Fluctuation	Low	High	Reduced Fluctuation
Renewable Penetration	80%	65%	+15% Penetration

This table provides a quantitative analysis comparing key performance metrics of the hybrid system with and without the PMSG extension. The improvements in power output, grid stability, energy storage utilization, voltage regulation, and renewable energy penetration illustrate the significant benefits of incorporating PMSG technology into the system design.

6. Conclusion

This research highlights the effectiveness of integrating a Wind-PV-BESS system with an extended DFIG-PMSG configuration in enhancing the performance and reliability of renewable energy systems connected to the grid. Our findings demonstrate significant improvements in power generation efficiency, grid stability, and energy storage utilization. The sophisticated control algorithm successfully manages power flow and grid interaction, optimizing the system's operational dynamics even under varying environmental conditions. The extended DFIG-PMSG configuration not only bolsters power generation during suboptimal wind conditions but also enhances the overall flexibility and resilience of the power system. These results contribute to advancing the grid integration of renewable energy sources, providing a robust framework for future developments in renewable energy technology.

Future Research

Further research will explore the scalability of this hybrid system and its adaptation to different geographic and climatic conditions, aiming to broaden its applicability and efficiency in diverse settings.

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