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A Comprehensive Review of Hybrid Photovoltaic - Wind Energy Systems: Control Strategies, MPPT Techniques, and Grid Integration

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ABSTRACT

The increasing global demand for reliable and sustainable electrical energy has accelerated the development of hybrid renewable energy systems that integrate multiple renewable sources. Among these, photovoltaic (PV) and wind energy-based hybrid systems have gained significant attention due to their complementary nature and improved reliability under variable environmental conditions. This paper presents a comprehensive review of grid-connected and standalone hybrid PV–wind energy systems, emphasizing advanced control strategies, maximum power point tracking (MPPT) techniques, energy storage integration, forecasting methods, and system optimization approaches. Various control methodologies such as Fractional Order PID (FOPID), particle swarm optimization (PSO), centralized and decentralized controllers, and artificial intelligence-based forecasting techniques are critically analyzed. The reviewed studies demonstrate that hybrid PV–wind systems significantly enhance power quality, grid stability, renewable energy utilization, and overall system efficiency compared to single-source systems. Furthermore, the integration of energy storage and optimized power electronics improves dynamic performance, reliability, and cost-effectiveness. This review highlights recent advancements, identifies research gaps, and provides insights for future development of efficient hybrid renewable energy systems.

KEYWORDS: *Hybrid Renewable Energy System; Photovoltaic–Wind System; MPPT Techniques; Energy Storage Systems; Grid Integration; Control Strategies.*

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1. INTRODUCTION

The growing demand for electrical energy, coupled with environmental concerns and depletion of fossil fuel resources, has intensified the transition toward renewable energy-based power generation. Solar and wind energy are among the most widely adopted renewable resources due to their abundance, scalability, and technological maturity. However, the intermittent and unpredictable nature of these resources poses significant challenges to reliable power generation and grid integration.

Hybrid renewable energy systems (HRES), particularly photovoltaic–wind combinations, have emerged as a promising solution to mitigate intermittency issues. The complementary behavior of solar irradiance and wind speed enables improved power availability and system reliability. Grid-connected and standalone hybrid PV–wind systems are increasingly deployed in urban, rural, and off-grid applications, ranging from residential power supply to large-scale utility installations.

Despite their advantages, hybrid systems require advanced control strategies, effective MPPT algorithms, reliable energy storage solutions, and robust forecasting models to ensure optimal performance under varying environmental conditions. Recent research has focused on improving power extraction efficiency, voltage and frequency regulation, dynamic stability, and economic feasibility of hybrid PV–wind systems. This paper presents a consolidated review of recent developments in hybrid PV–wind energy systems, highlighting control techniques, modeling approaches, system configurations, and performance evaluation methods.

2. LITERATURE REVIEW

Extensive research has been carried out on hybrid PV–wind systems with emphasis on control, optimization, forecasting, and grid integration. Advanced control techniques such as Fractional Order Proportional Integral Derivative (FOPID) controllers have been employed to enhance voltage regulation and system robustness under fluctuating environmental conditions. Studies demonstrate that FOPID-based controllers outperform conventional controllers in maintaining grid stability and maximizing power extraction.

Optimization-based approaches, including multiobjective particle swarm optimization (PSO), have been applied to tune control parameters and improve power tracking accuracy in wind–PV–storage hybrid systems. Simulation results based on real-time operational data indicate improved renewable energy absorption and enhanced system stability.

Forecasting of renewable power generation remains a critical challenge due to the stochastic nature of solar and wind resources. Various forecasting techniques, including physical models, statistical methods, artificial intelligence, and hybrid approaches, have been investigated. AI-based forecasting models utilizing machine learning algorithms have shown superior accuracy by analyzing historical weather data and system performance, thereby improving operational planning and grid management.

Innovative system architectures such as hybrid solar–wind trees have been proposed for urban environments, offering multifunctional benefits including energy generation, aesthetics, and space optimization. Design considerations such as structural integrity, optimal orientation, and real-time monitoring systems are crucial for maximizing energy yield.

Several studies explore the techno-commercial feasibility of integrating solar power plants within existing wind farms. Co-located hybrid systems reduce land acquisition issues and utilize shared infrastructure, resulting in lower costs and improved grid connectivity. Software tools such as PVsyst, ETAP, HOMER, and MATLAB/Simulink are widely used for modeling, simulation, and performance evaluation of hybrid systems.

Energy storage systems, particularly battery energy storage, play a vital role in hybrid PV–wind systems by balancing supply-demand mismatches and ensuring uninterrupted power delivery. Bidirectional DC–DC converters, centralized controllers, and intelligent energy management strategies significantly enhance system efficiency and reliability.

K. Vijaya Bhaskar Reddy et al. [1] In this work, a grid-connected photovoltaic–wind hybrid power system employing a Fractional Order Proportional Integral Derivative (FOPID) controller is designed, implemented, and analyzed. The hybrid system is connected to the building's primary AC bus to improve overall system efficiency. Maximum Power Point Tracking (MPPT) techniques are applied to both photovoltaic (PV) and wind subsystems to ensure maximum power extraction under varying weather conditions. The adaptability of the MPPT algorithm and the FOPID control strategy to fluctuations in solar irradiance and wind speed is evaluated through simulation studies. The results demonstrate that the MPPT approach effectively extracts maximum available power from the hybrid system, while the FOPID controller maintains a stable grid voltage irrespective of environmental variations or changes in generated power.

Ke Li et al. [2] This study proposes a detailed mathematical model for a wind–PV–storage hybrid power generation system to enhance control performance. A multiobjective particle swarm optimization (PSO) algorithm is employed to optimally tune the control strategy parameters. Simulation results, validated using real-world operational data from an existing hybrid system, confirm the effectiveness of the proposed approach. The optimized control strategy significantly improves power tracking accuracy and renewable energy absorption compared to conventional methods, thereby enhancing overall system stability and utilization of renewable resources.

Yassine Boujamaoui and Tariq Jarou [3] This paper presents a comprehensive review of power forecasting techniques for photovoltaic–wind hybrid power plants, addressing the challenges posed by the intermittent and stochastic nature of renewable energy sources. Various forecasting methodologies, including physical models, statistical techniques, artificial intelligence-based approaches, and hybrid methods, are critically analyzed. AI-driven forecasting models utilizing machine learning techniques are shown to improve prediction accuracy by leveraging historical weather data, real-time environmental conditions, and system performance metrics. The study highlights the importance of accurate forecasting for efficient grid planning, management, and operation, emphasizing the role of

PV–wind hybrid systems in achieving a sustainable and reliable energy future.

N. Ramadevi et al. [4] This work introduces the concept and design of a hybrid solar–wind tree intended for urban, rural, and off-grid applications. The proposed structure integrates photovoltaic panels and small wind turbines mounted on vertically arranged branches to maximize energy generation while enhancing aesthetic appeal. During daytime, solar panels generate electricity from solar radiation, while wind turbines continue to produce power during low solar irradiance conditions. The complementary operation of solar and wind resources ensures a more consistent power output. Key design considerations include optimal orientation, branch configuration, component sizing, and structural integrity. Advanced monitoring and control systems enable real-time adaptation to environmental conditions, ensuring efficient and reliable operation.

Kaliappan P and Selvan M. P [5] This paper investigates the feasibility of integrating a 25 MW solar power plant within an existing 75 MW operational wind farm located in Coimbatore district, Tamil Nadu, India. The study explores multiple integration strategies, including the use of existing step-up transformers, installation of separate transformers, and deployment of a dedicated co-located solar plant. The hybrid wind–solar system is connected to the grid through a common point of coupling. Solar power generation is simulated using PVsyst software, while overall system modeling and performance evaluation are carried out using ETAP. The results demonstrate that co-located hybrid plants effectively utilize available land and infrastructure, improving energy yield and reducing investment costs.

Tanvi Deopujari et al. [6] This study proposes a standalone hybrid PV–wind–battery energy system as an alternative to conventional power generation sources. A simple and cost-effective control strategy is employed to track the maximum power point of both PV panels and wind turbine generators under continuously changing environmental conditions. Excess energy generated is stored in a battery system and later used to meet load demand during generation deficits. The battery state of charge and energy reserve are continuously monitored. Simulation results obtained using MATLAB/Simulink validate the feasibility and effectiveness of the proposed centralized control strategy in optimizing renewable energy utilization and ensuring reliable microgrid operation.

Shreeram V. Kulkarni et al. [7] This work focuses on the modeling and performance evaluation of a grid-integrated hybrid energy system comprising a PV array, a doubly fed induction generator (DFIG)-based wind system, and a battery energy storage system. The hybrid system is simulated using MATLAB/Simulink to analyze its dynamic and transient stability performance. The complementary nature of solar and wind energy sources enhances power availability and system reliability. The study emphasizes the importance of optimal control and energy management strategies for achieving stable and efficient hybrid system operation under varying environmental conditions.

Aizad Khursheed et al. [8] This paper presents a solar–wind hybrid energy generation system suitable for residential and commercial applications. The wind generator output is converted from AC to DC using rectifiers and subsequently inverted back to AC for supplying loads. A boost converter-based MPPT technique is employed to maximize solar power extraction. The proposed approach also reduces harmonic content, which improves system efficiency and minimizes heating and degradation of system components. The study demonstrates the advantages of hybrid energy systems in improving power quality and operational reliability.

Ananya Pritilagna Biswal and Krishna Roy [9] This paper presents a hybrid PV–wind system designed for microgrid applications with an emphasis on dc-link voltage regulation and power management. A bidirectional DC–DC converter integrated with a battery energy storage system is used to regulate the dc-link voltage under varying solar irradiance, wind speed, and load conditions. The bidirectional converter also serves as the MPPT controller for both PV and wind subsystems, reducing system complexity and cost. LC filters are employed to minimize voltage fluctuations. The complete system is modeled and simulated using MATLAB, demonstrating reliable and uninterrupted power supply.

Bikash Kumar Parida and Aashish Kumar Bohre [10] This study analyzes the techno-economic performance of a hybrid renewable energy system comprising solar, wind, biomass, and battery storage using the HOMER optimization tool. The system is evaluated for a rural location in Siliguri, West Bengal, India. Performance metrics such as Net Present Cost (NPC) and Cost of Energy (COE) are used to determine the optimal system configuration. The results indicate that a hybrid system integrating PV, biomass, converters, and grid connectivity offers superior economic performance compared to conventional configurations, ensuring reliable and cost-effective energy supply.

3. CONCLUSION

This paper presents a comprehensive review of recent advancements in hybrid photovoltaic–wind renewable energy systems. The reviewed literature confirms that hybrid PV–wind systems offer superior reliability, efficiency, and power quality compared to standalone renewable systems. Advanced control strategies such as FOPID controllers, optimization algorithms, and intelligent MPPT techniques significantly enhance system performance under variable environmental conditions. The integration of energy storage systems and accurate forecasting models further improves dynamic stability and renewable energy utilization.

Despite notable progress, challenges remain in terms of system complexity, cost optimization, large-scale deployment, and real-time control under highly uncertain conditions. Future research should focus on artificial intelligence-driven adaptive control, advanced energy management systems, and techno-economic optimization to enhance scalability and grid compatibility. Hybrid PV–wind systems are poised to play a crucial role in achieving sustainable, reliable, and cost-effective energy solutions for future power systems.

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