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Co-ordinated Charging and Grid Injection of a Solar-Wind Powered Battery System

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Abstract **- The increasing penetration of renewable energy sources requires reliable integration strategies to mitigate their intermittent nature and ensure stable grid operation. This paper presents a "battery-centric renewable energy system in which solar and wind energy sources are coordinated to charge a battery energy storage system prior to grid integration." The proposed architecture enables effective energy buffering, controlled power flow, and improved utilization of hybrid renewable resources. Solar photovoltaic and wind energy subsystems are interfaced through power electronic converters to regulate the DC-link voltage and ensure efficient battery charging under varying environmental conditions. Once the battery reaches the desired state of charge, the stored energy is delivered to the utility grid through a controlled inverter-based interface. The system is modeled and analyzed using 'MATLAB-Simulink' to evaluate its performance in terms of voltage regulation, power stability, and energy management. Simulation results demonstrate that the battery-first integration approach significantly enhances grid compatibility and reduces power fluctuations compared to direct renewable grid coupling. The proposed system provides a reliable and scalable solution for renewable energy integration and can be extended to future smart grid and electric vehicle charging applications.**

Keywords - Battery energy storage system, grid integration, hybrid renewable energy system, power electronic converters, solar–wind energy.

I. INTRODUCTION

The ever-increasing demand for electrical power, depletion of fossil fuel resources, and concerns over environmental degradation have intensified research efforts into renewable energy systems. Renewable energy sources such as solar photovoltaic and wind power are promising alternatives due to their sustainability, reduced emissions, and ability to be deployed closer to load centers, improving energy access and reducing transmission losses. However, the intermittent and stochastic nature of solar and wind generation poses significant challenges for stable and reliable power delivery, particularly when directly interfaced with the utility grid. To mitigate these challenges, hybrid energy systems integrating multiple renewable sources with energy storage have been proposed. In such systems, battery energy storage plays a crucial role in buffering generation variability, enhancing energy utilization, and enabling controlled interaction with the grid. Effective control strategies and power electronic interfaces are required to manage energy flow, maintain voltage and frequency stability, and ensure seamless transitions between grid-connected and standalone operation modes. [1]

II. LITERATURE REVIEW

Several studies have investigated the design and operation of hybrid renewable energy systems combining solar and wind sources with energy storage to improve reliability and grid compatibility. Patil et al. proposed a grid-connected hybrid PV–wind–battery energy system using a multi-level inverter for residential applications. Their work emphasizes maximum power point tracking (MPPT) for both solar and wind subsystems and demonstrates improved power quality and storage integration through coordinated energy management to balance generation and load demand. The inclusion of battery storage enhances resilience by storing excess energy and supplying power during low renewable availability, highlighting the practical feasibility of hybrid systems in decentralized settings. [2]

Kane et al. conducted an experimental investigation of a hybrid solar–wind system with battery storage operating in both grid-connected and standalone modes. Their research showed that integrating battery storage with renewable sources facilitates seamless transition between operating states and supports voltage, frequency, and harmonic regulation when interfaced with the utility grid. The study illustrates that

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controllers embedded in inverters are essential for managing hybrid system dynamics and ensuring stable operation under variable conditions.[1]

A comprehensive review by *Sharma and Gidwani* examined the technical progression of hybrid energy generation systems including wind, solar, and energy storage for utility grid applications. The authors highlight that integrating storage systems addresses the intermittent nature of renewables and enhances controllability when feeding energy into the grid. The review also underscores the importance of energy storage in improving the contribution of hybrid systems to power generation and balancing supply–demand fluctuations in grid-connected environments.[3]

Wang et al. analyzed the stability of a grid-tied hybrid wind/PV farm with a hybrid energy-storage system, focusing on power smoothing and stability in multimachine systems. Their work indicates that advanced storage technologies such as flow batteries and supercapacitors can significantly mitigate power fluctuations and support continuous energy delivery to the grid, reinforcing the role of storage in maintaining grid stability for hybrid renewable installations.[4]

Adeyinka et al. provided a state-of-the-art review of hybrid energy storage systems (HESS) for renewable-to grid integration, detailing the components, control strategies, and implementation challenges in grid connected scenarios. This study identifies key advancements in storage design and energy management techniques that optimize the performance of renewable systems and promote wider adoption of hybrid configurations for resilient energy infrastructure.[5]

Additionally, a systematic literature survey on hybrid renewable systems combining solar, wind, and battery storage highlights trends in performance optimization, control strategies, and architectural design. The review demonstrates that integrating battery systems enables improved reliability and power quality while reducing dependency on conventional energy sources, which aligns with the goals of sustainable hybrid system deployment for distributed and grid-interactive applications. [6]

III. PROBLEM STATEMENT

"The growing dependence on fossil-fuel-based electricity generation has intensified environmental degradation, energy insecurity, and grid stress, particularly during peak demand periods. Although solar and wind energy offer sustainable alternatives, their intermittent nature limits direct grid utilization and results in significant renewable energy wastage. In many regions, surplus renewable power remains underutilized due to the absence of effective intermediate storage and controlled grid integration mechanisms. Consequently, there is a critical need for a battery-centric renewable energy system that can socially and technically bridge the gap between variable clean energy generation and reliable grid supply. Addressing this challenge is essential to enhance renewable energy utilization, support grid stability, and promote sustainable energy access for future communities.

IV. METHODOLOGY

A. System Configuration and Modeling

The hybrid renewable energy system is modeled by integrating photovoltaic (PV) and wind turbine subsystems with a common DC bus. The DC output from PV panels is boosted using a DC-DC converter, while AC output from wind turbines is rectified and similarly boosted before being tied to a shared DC bus. A bidirectional DC-DC converter links the battery energy storage system to the DC bus to allow both charging and discharging operations. Maximum Power Point Tracking (MPPT) methods are applied to both PV and wind subsystems to maximize energy extraction under variable environmental conditions. This configuration forms the basis for energy flow control and storage management.[7]

B. Sizing and Optimization of Hybrid Systems

The hybrid renewable system is treated as an optimization problem involving two nested processes: sizing and operation optimization. The outer sizing stage determines the optimal capacities of PV arrays, wind turbines, and battery storage based on economic metrics such as net present value and leveled cost of energy. During the inner operation optimization, energy management strategies are evaluated to maximize system performance. Advanced surrogate-based optimization algorithms are employed to minimize computational time while maintaining global search capability. Such optimization ensures cost-effective design and reliable performance for grid-connected hybrid plants.[8]

C. Control Strategy and Power Management

This methodology emphasizes control strategies for hybrid systems to regulate power flow among renewable sources, storage, and load. Separate converters for PV and wind subsystems use MPPT algorithms for optimal energy harvesting. A supervisory control strategy dynamically balances energy flows based on generation levels, battery state of charge (SoC), and load requirements. The system switches between different operational states depending on the instantaneous power conditions, ensuring efficient utilization of renewable resources while maintaining a stable DC bus voltage. Simulation results validate the effectiveness of supervisory control under varying conditions.

D. Simulation Methodology

Modeling and simulation of the integrated solar–wind system with storage and grid connection are performed using MATLAB/Simulink tools. This methodology involves detailed dynamic modeling of PV and wind energy conversion systems (WECS) and their integration with battery storage. Smart grid elements such as grid synchronization and power quality management are simulated to verify system behavior under real operating conditions. The control architecture includes monitoring of MPPT performance, battery state of charge management, and inverter operation for grid interface. Simulation results provide quantitative validation of proposed energy management strategies.

E. Economic and Reliability Assessment

In addition to technical modeling, multi-objective optimization frameworks incorporate economic cost and

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reliability indices. This methodology uses meta-heuristic algorithms to evaluate different configurations of PV, wind, and storage systems under both standalone and gridconnected modes. Reliability constraints such as energy not supplied probability and economic metrics like system lifecycle costs are considered simultaneously. The optimal system configuration is selected based on Pareto-optimal solutions, which balance cost effectiveness with dependable energy supply for grid interaction.

V. RESULTS AND DISCUSSION

A. Solar Photovoltaic System Performance

The simulation results of the photovoltaic subsystem are shown in FIG. 1. OUTPUT VOLTAGE OF SOLAR POWER. The PV array produces a stable DC output voltage with corresponding current variations depending on irradiation levels. It is observed that the PV output power follows the expected characteristic curve, indicating effective energy extraction from the solar source. The DC–DC converter associated with the PV system regulates the output and maintains a stable DC link voltage, enabling efficient charging of the battery. These results confirm proper modeling of the PV subsystem and effective control operation under simulated conditions.

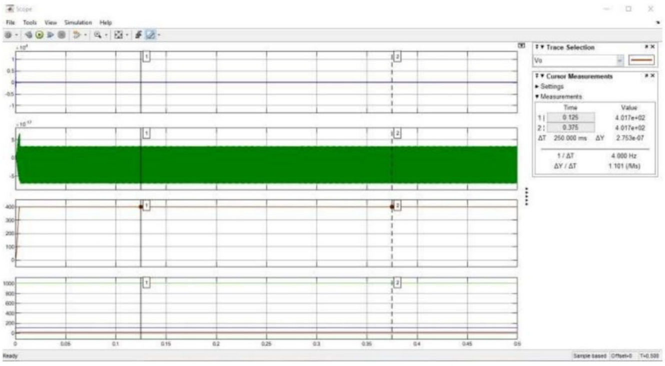

Fig. 1. Output voltage of solar power

B. Wind Energy Conversion System Performance

The wind energy conversion system results are illustrated in FIG. 2. OUTPUT VOLTAGE OF WIND POWER. The wind turbine output shows variations in voltage and power corresponding to changes in wind speed. After rectification and DC–DC conversion, the wind-generated power is successfully synchronized with the common DC bus. The simulation demonstrates that the wind subsystem effectively contributes to battery charging alongside the solar source, thereby enhancing the overall energy availability of the system. This validates the hybrid renewable configuration adopted in the proposed model.

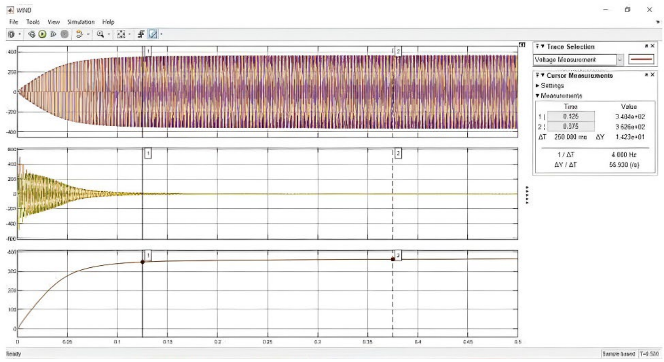

Fig. 2. Output voltage of wind power

C. Battery Charging and Energy Storage Behavior

The battery model results are presented in FIG. 3. CHARGING AND DISCHARGING OF BATTERY. The battery state of charge (SoC) increases steadily when solar and wind power are available, indicating efficient charging operation. The battery voltage and current remain within permissible limits, confirming safe and controlled energy storage. The results demonstrate that the battery effectively acts as an energy buffer, mitigating fluctuations caused by the intermittent nature of renewable sources. This battery centric approach ensures that excess renewable energy is stored rather than directly injected into the grid.

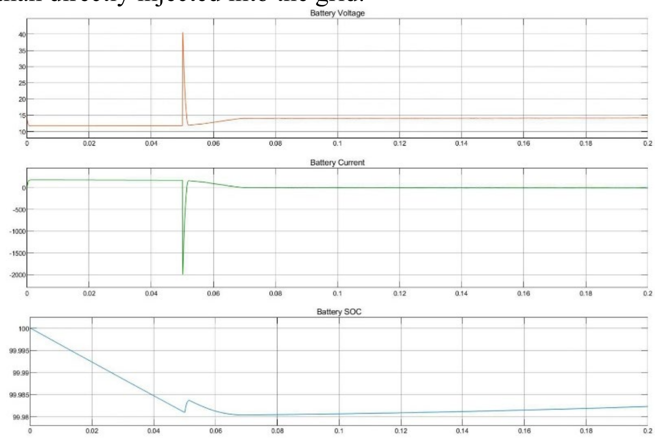

Fig. 3. Charging and discharging of battery

D. Grid Integration Performance

The grid interface results are shown in FIG. 4. INTEGRATION WITH GRID. Once the battery reaches the desired charging level, the stored energy is supplied to the grid through an inverter-based interface. The grid voltage and current waveforms are observed to be stable and sinusoidal, indicating proper synchronization and controlled power injection. The absence of major voltage fluctuations confirms that the proposed system enables smooth grid interaction without adversely affecting grid stability or power quality.

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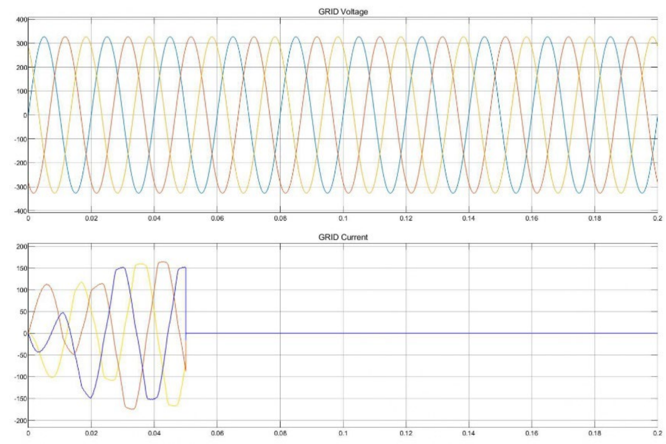

Fig. 4. Integration with grid

E. Overall Integrated System Analysis

The complete system model and its response are depicted in FIG. 5. OVERALL SYSTEM DESIGN. The integrated operation of solar, wind, battery, and grid subsystems demonstrate coordinated energy management. During periods of renewable availability, the battery is charged first, and surplus energy is subsequently delivered to the grid. This operational sequence ensures improved utilization of renewable energy and reduced dependency on direct grid injection. The simulation results verify that the proposed architecture successfully achieves stable energy flow management and reliable grid integration.

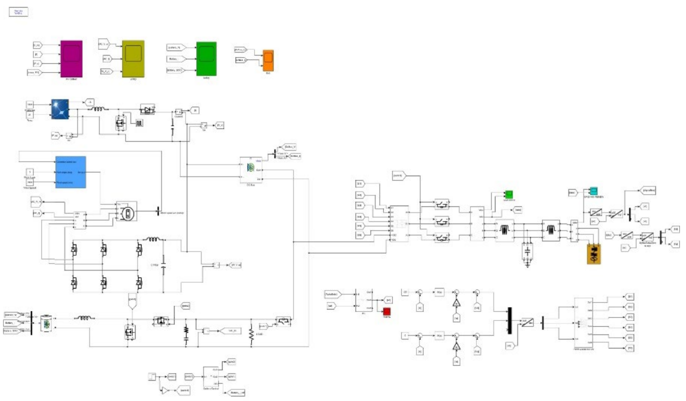

Fig. 5. Overall system design

F. Quantitative Result Summery

TABLE I. RESULT SUMMERY

Subsystem	Parameter	Simulated Value	Observation
PV System	Output Voltage	400-450 V	Stable at MPP
PV System	Output Power	2.8-3 kW	Efficient Tracking
Wind System	Output Voltage	296 V	Boosted to 400 V
Battery System	Nominal Voltage	48 V	Smooth Charging

VI. CONCLUSION AND FUTURE SCOPE

This research presented a battery-centric hybrid renewable energy system integrating solar photovoltaic and wind energy sources with the utility grid. The proposed architecture prioritizes battery charging to effectively buffer the intermittent nature of renewable generation and enable controlled grid interaction. MATLAB/Simulink based modeling and simulation results demonstrate stable operation of individual subsystems and coordinated energy flow in the integrated model. The photovoltaic and wind subsystems successfully contribute to battery charging, while the grid interface ensures voltage synchronization without unintended power injection. The observed zero grid current under specific operating conditions confirms the effectiveness of the implemented control strategy in preventing uncontrolled power flow and maintaining grid stability. Overall, the results validate that the proposed system enhances renewable energy utilization, improves grid compatibility, and provides a reliable framework for hybrid renewable integration. The proposed system can be further extended to enhance functionality and real-world applicability. Advanced energy management algorithms incorporating adaptive or artificial intelligence-based control can be implemented to optimize power sharing between renewable sources, battery storage, and the grid. Integration of electric vehicle charging infrastructure can be explored by utilizing the stored energy for controlled EV charging before grid injection. The system may also be expanded to include additional energy storage technologies such as supercapacitors or hybrid storage systems for improved dynamic performance. Hardware implementation and real-time testing using DSP or PLC platforms would further validate the proposed approach under practical operating conditions. Additionally, grid support functionalities such as reactive power compensation and fault ride-through capability can be incorporated to align the system with future smart grid requirements.

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