© June 2026 | IJIRT | Volume 13 Issue 1 | ISSN: 2349-6002

Modeling and Simulation of Solar-Wind-Battery Hybrid Energy System in MATLAB/Simulink

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Abstract—**This paper presents the modeling and simulation of a Hybrid Renewable Energy System (HRES) integrating Solar Photovoltaic (PV), Wind Energy Conversion System (WECS), and Battery Energy Storage System (BESS) using MATLAB/Simulink. The proposed system combines two renewable energy sources to ensure continuous and reliable power generation under varying environmental conditions. Maximum Power Point Tracking (MPPT) algorithms are implemented for both solar and wind subsystems to maximize energy extraction. A battery storage system is incorporated to store excess energy and supply power during low generation periods. A dump load is used to absorb surplus energy when the battery is fully charged. The generated DC power is regulated through a common DC bus and converted into AC power using a Voltage Source Inverter (VSI) to feed the AC load. Simulation results demonstrate system performance under variable solar irradiance, wind speed, and load demand. Key outputs including solar power, wind power, total generated power, battery state of charge (SOC), DC bus voltage, AC output waveform, load power, dump load power, and overall system efficiency are analyzed. The results confirm that the proposed HRES provides stable and efficient power supply suitable for standalone and remote applications.**

Index Terms—**Hybrid Renewable Energy System, Solar PV, Wind Energy, Battery Storage, MPPT, MATLAB/Simulink, Inverter, State of Charge.**

I. INTRODUCTION

The increasing global demand for electrical energy, coupled with the depletion of fossil fuel reserves and the adverse environmental effects associated with conventional power generation, has accelerated the adoption of renewable energy technologies [1]. Among various renewable sources, solar photovoltaic (PV) and wind energy have emerged as the most promising alternatives due to their abundant availability, environmental friendliness, and rapidly decreasing installation costs [2]. However, both solar and wind energy are inherently intermittent and highly dependent on weather conditions, which creates challenges in maintaining a reliable and continuous power supply [3].

Hybrid Renewable Energy Systems (HRES) have been proposed as an effective solution to overcome the limitations of individual renewable sources [4]. By integrating multiple energy resources such as solar PV and wind turbines, the system can exploit the complementary nature of these sources, thereby improve energy availability and reduce fluctuations in power generation [5]. Solar energy is typically more abundant during clear daytime conditions, while wind energy may be available during nighttime or cloudy periods, making the combination highly suitable for standalone and remote applications [6].

The inclusion of Battery Energy Storage Systems (BESS) further enhances the performance and reliability of HRES [7]. Batteries store excess energy generated during periods of high renewable production and supply power during periods of low generation or peak load demand [8]. This storage capability helps maintain system stability, improves power quality, and ensures uninterrupted energy delivery [9]. Advanced charge and discharge controllers are commonly employed to protect the battery from overcharging and deep discharging, thereby extending battery life and improving overall system efficiency [10].

To maximize the energy harvested from renewable sources, Maximum Power Point Tracking (MPPT) techniques are widely implemented [11]. MPPT algorithms continuously adjust the operating point of solar PV arrays and wind generators to extract the maximum available power under varying environmental conditions [12]. For solar systems, methods such as Perturb and Observe (P&O) and Incremental Conductance are commonly used, while wind systems often employ Tip Speed Ratio (TSR) or optimal torque control strategies [13]. These techniques significantly increase the efficiency and effectiveness of hybrid systems [14].

In a typical HRES, power from solar and wind sources is converted into a regulated DC supply and combined through a common DC bus [15]. The DC bus serves as an intermediate platform for energy exchange between renewable sources, batteries, and loads [16]. A Voltage Source Inverter (VSI) is then used to convert DC power into sinusoidal AC power suitable for household, industrial, or isolated loads [17]. When generated energy exceeds both load demand and battery charging capacity, a dump load is utilized to dissipate surplus energy and prevent overvoltage conditions [18].

MATLAB/Simulink has become one of the most widely used platforms for modeling and simulation of hybrid renewable energy systems due to its extensive libraries, graphical modeling environment, and support for control system design [19]. It enables researchers to analyze system behavior under variable solar irradiance, wind speed, and load conditions, providing valuable insights into system performance before practical implementation [20].

In this research, a comprehensive Hybrid Renewable Energy System consisting of a Solar PV Array, Wind Generator, MPPT controllers, Battery Energy Storage System, DC bus, DC-AC inverter, AC load, and dump load is developed and simulated in MATLAB/Simulink. The proposed system is evaluated using dynamic environmental and load conditions. Performance parameters such as solar power, wind power, total generated power, battery State of Charge (SOC), DC bus voltage, AC output waveform, load power, dump load power, and system efficiency are analyzed. The results demonstrate that the proposed HRES provides a reliable, efficient, and sustainable solution for standalone and remote power generation applications.

II. LITERATURE SURVEY

Hybrid Renewable Energy Systems (HRES) have gained significant attention in recent years due to their ability to combine multiple renewable energy sources and improve reliability, efficiency, and sustainability of power generation [1]. Researchers have extensively studied the integration of solar photovoltaic (PV), wind energy conversion systems (WECS), and battery energy storage systems (BESS) to address the intermittent nature of renewable energy resources [2]. The literature reveals that hybrid systems are particularly suitable for remote and off-grid applications where conventional grid infrastructure is unavailable or uneconomical [3].

Early studies focused on the feasibility of combining solar and wind resources to exploit their complementary characteristics. Borowy and Salameh demonstrated that hybrid PV-wind systems can significantly improve energy availability compared to standalone systems [4]. Chedid et al. proposed optimization techniques for sizing hybrid renewable systems to minimize lifecycle cost while ensuring supply reliability [5]. Their work laid the foundation for subsequent studies on system design and optimization.

The modeling of photovoltaic systems has been extensively investigated. Villalva et al. developed accurate mathematical models for solar PV modules in MATLAB/Simulink, enabling precise simulation under varying irradiance and temperature conditions [6]. Walker introduced simplified PV modeling approaches suitable for system-level analysis [7]. These models have become widely adopted in hybrid renewable energy simulations.

Wind energy conversion systems have also been the subject of significant research. Heier provided a comprehensive analysis of wind turbine modeling and control strategies [8]. Muljadi and Butterfield developed dynamic models of wind generators and their associated power electronics for simulation purposes [9]. These studies contributed to accurate representation of wind power generation under fluctuating wind speeds.

Maximum Power Point Tracking (MPPT) techniques are critical for maximizing renewable energy extraction. Esram and Chapman reviewed numerous MPPT algorithms for PV systems and compared their performance under changing environmental conditions [10]. Hussein et al. analyzed Perturb and Observe (P&O) and Incremental Conductance methods, showing that MPPT can substantially improve system efficiency [11]. For wind systems, optimal torque and tip speed ratio control strategies were proposed to achieve maximum aerodynamic power extraction [12].

Battery Energy Storage Systems play a crucial role in enhancing hybrid system reliability. Chen and Rincon-Mora presented comprehensive battery models and charging strategies for energy storage applications [13]. Tremblay and Dessaint developed practical battery models suitable for Simulink implementation [14]. Their work enabled accurate State of Charge (SOC) estimation and charge-discharge control in renewable energy systems.

Several researchers have investigated energy management strategies for hybrid systems. Katti and Khedkar proposed intelligent control methods to coordinate renewable generation, storage, and load demand [15]. Uzunoglu et al. developed dynamic models for hybrid PV-fuel cell-battery systems and highlighted the importance of energy balancing [16]. Similar concepts have been extended to PV-wind-battery configurations.

The common DC bus architecture has emerged as a preferred configuration for integrating multiple DC sources. Kakigano et al. demonstrated that DC microgrids offer higher efficiency and simplified control compared to traditional AC-based architectures [17]. Dragicevic et al. further emphasized the flexibility of DC bus systems in accommodating renewable sources and storage devices [18].

Power electronic converters and inverters are essential components in HRES. Rashid described the design and operation of DC-DC converters and Voltage Source Inverters (VSI) used in renewable systems [19]. Teodorescu et al. analyzed inverter control techniques for producing high-quality sinusoidal AC output [20]. These technologies enable efficient power conversion and grid-compatible operation.

Dump load control has been studied as a protective mechanism for standalone systems. Nayar et al. proposed dump load controllers to dissipate excess energy when batteries reach full charge [21]. This approach prevents overvoltage conditions and maintains system stability under low load and high generation scenarios.

Optimization and sizing of hybrid systems have been widely explored using software tools such as HOMER and MATLAB. Lambert et al. developed methods for techno-economic analysis of renewable systems [22]. Kaabeche et al. optimized PV-wind-battery systems for isolated communities, demonstrating substantial reductions in fuel dependency and operating costs [23].

Control strategies based on artificial intelligence have also been introduced. Mellit and Kalogirou reviewed the use of fuzzy logic and neural networks for renewable energy management [24]. These advanced methods improve MPPT performance, battery management, and load forecasting accuracy [25].

Recent studies have focused on MATLAB/Simulink-based simulation of complete hybrid systems. Nema et al. presented a comprehensive review of PV-wind hybrid systems and highlighted MATLAB as a powerful tool for performance analysis [26]. Diaf et al. demonstrated that hybrid systems significantly enhance energy reliability and reduce unmet load [27]. Rehman and Al-Hadhrami validated the technical and economic viability of HRES for remote regions [28].

Research has consistently shown that integrating solar PV, wind generation, and battery storage provides a robust solution for sustainable energy supply [29]. By employing MPPT algorithms, energy storage management, DC bus regulation, and inverter control, hybrid renewable systems can deliver stable and efficient power under varying environmental and load conditions [30].

The present work builds upon these studies by developing a comprehensive MATLAB/Simulink model of a Hybrid Renewable Energy System incorporating Solar PV, Wind Generator, MPPT controllers, Battery Storage, DC Bus, Inverter, AC Load, and Dump Load. The system is evaluated using dynamic solar irradiance, wind speed, and load demand to analyze key performance parameters such as power generation, battery SOC, DC bus voltage, load supply, dump load utilization, and overall system efficiency.

III. PROPOSED SYSTEM ARCHITECTURE

A. Solar PV Subsystem

The solar PV subsystem converts solar irradiance into direct current (DC) electrical energy. The output voltage (V_{PV}) and current (I_{PV}) vary according to solar radiation and temperature conditions. An MPPT (Maximum Power Point Tracking) controller, typically based on the Perturb and Observe (P&O) or Incremental Conductance (INC) algorithm, continuously adjusts the operating point to extract maximum power from the PV array [1]. The tracked output is fed to a DC-DC boost converter, which increases and regulates the voltage before connecting it to the common DC bus.

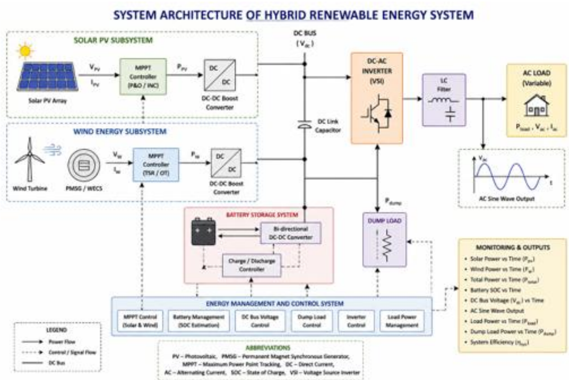

Fig. 1. System Architecture

B. Wind Energy Subsystem

The wind subsystem consists of a wind turbine coupled with a Permanent Magnet Synchronous Generator (PMSG). The turbine converts kinetic energy from wind into mechanical rotation, which the generator transforms into electrical power. Since wind speed changes continuously, the generator output voltage (V_W) and current (I_W) are variable. An MPPT controller using Tip Speed Ratio (TSR) or Optimal Torque (OT) control ensures maximum energy extraction [2]. The resulting power is regulated through a DC-DC boost converter and delivered to the DC bus.

C. Common DC Bus

The DC bus serves as the central energy exchange point for all subsystems. Power from both the solar and wind sources is combined here, and a DC-link capacitor stabilizes the bus voltage (V_{dc}) by reducing voltage fluctuations [3]. The DC bus distributes energy to the battery, inverter, and dump load depending on system conditions.

D. Battery Energy Storage System (BESS)

The battery storage system provides energy balancing and backup power. It is connected to the DC bus through a bidirectional DC-DC converter, allowing both charging and discharging operations. During periods of surplus generation, the battery stores excess energy; when renewable generation is insufficient, it supplies power to meet load demand [4]. The charge/discharge controller monitors battery State of Charge (SOC) to prevent overcharging and deep discharging.

E. DC-AC Inverter

The DC-AC inverter, implemented as a Voltage Source Inverter (VSI), converts the regulated DC bus voltage into alternating current (AC). This conversion is controlled using Pulse Width Modulation (PWM) techniques to produce a near-sinusoidal output waveform [5]. The inverter ensures that the AC voltage and frequency are suitable for supplying the connected load.

F. LC Filter

The inverter output contains switching harmonics due to PWM operation. An LC filter is placed between the inverter and the AC load to remove these high-frequency components and produce a clean sinusoidal voltage waveform [6]. This improves power quality and reduces total harmonic distortion (THD).

G. AC Load

The AC load represents residential, commercial, or industrial electrical equipment. In the simulation, the load demand is varied over time to evaluate the ability of the HRES to respond dynamically and maintain continuous supply [7]. Parameters such as load voltage, current, and power are monitored throughout the simulation.

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H. Dump Load

The dump load is a protective element used when renewable generation exceeds both load demand and battery charging capacity. In this case, excess power (P_{dump}) is diverted to a resistive load to prevent overvoltage on the DC bus [8]. This is especially important when the battery is fully charged.

I. Energy Management and Control System

The Energy Management and Control System (EMCS) coordinates all subsystems and makes real-time decisions based on solar irradiance, wind speed, load demand, battery SOC, and DC bus voltage. Its main functions include:

- MPPT control for solar and wind sources
- Battery SOC monitoring and charge/discharge control
- DC bus voltage regulation

- Inverter switching control
- Dump load activation
- Load power management

The EMCS ensures efficient utilization of available renewable energy and stable operation of the entire system [9].

IV. METHODOLOGY

A. Research Methodology Overview

This research follows a systematic approach to design and evaluate a Hybrid Renewable Energy System (HRES) using MATLAB/Simulink. The methodology begins with identifying the limitations of standalone renewable systems and proposing an integrated solution combining Solar PV, Wind Energy, and Battery Storage. Mathematical models of all components are developed and interconnected through a common DC bus. Control strategies such as MPPT, battery charge/discharge control, and dump load management are implemented. Finally, the complete system is simulated under variable environmental and load conditions, and the performance is assessed using key electrical parameters.

B. Problem Identification

Standalone solar or wind systems suffer from intermittent generation because their output depends on weather conditions. Solar power is unavailable at night and decreases during cloudy conditions, while wind speed fluctuates unpredictably. These variations lead to unstable voltage, insufficient power supply, and poor reliability. In addition, excess generated power can damage batteries if not properly managed. To solve these issues, a hybrid renewable energy system with energy storage and intelligent control is proposed to ensure continuous and efficient operation.

C. Proposed System Configuration

The proposed system integrates a Solar PV array and Wind Energy Conversion System as primary renewable sources. Each source is equipped with its own MPPT controller and DC-DC boost converter to maximize power extraction and regulate voltage. Both sources are connected to a common DC bus. A Battery Energy Storage System is linked through a bidirectional converter to store surplus energy and provide backup power. A Voltage Source Inverter converts the DC power into AC supply for the load, while an LC filter improves waveform quality. A dump load absorbs unused excess energy when the battery is fully charged. All components are coordinated by an Energy Management and Control System.

D. Mathematical Modeling of System Components

Mathematical equations are used to represent the electrical behavior of each subsystem. The solar PV array is modeled using the single-diode equation to determine current-voltage characteristics under varying irradiance and temperature. The wind turbine model calculates extracted mechanical power based on wind speed, air density, and turbine efficiency. Battery behavior is represented using State of Charge (SOC) equations that track stored energy over time. System efficiency is calculated by comparing useful load power to total renewable generation. These mathematical models form the basis for accurate simulation in MATLAB/Simulink.

E. MPPT Controller Design

Maximum Power Point Tracking (MPPT) controllers are implemented to ensure that both solar and wind subsystems operate at their optimal points. For the solar PV system, the Perturb and Observe (P&O) algorithm continuously adjusts the duty cycle of the boost converter to maximize output power. For the wind subsystem, Optimal Torque or Tip Speed Ratio control maintains the turbine at the condition that yields the highest aerodynamic efficiency. These controllers improve energy extraction and increase the overall performance of the hybrid system.

F. Battery Charge and Discharge Control

The battery management system determines when the battery should charge or discharge based on the balance between generated power and load demand. When renewable generation exceeds consumption, the battery is charged if its SOC is below the maximum limit. When generation is insufficient, the battery discharges to support the load, provided the SOC remains above the minimum threshold. This strategy prevents overcharging and deep discharging, thereby extending battery life and maintaining reliable system operation.

G. DC Bus Voltage Regulation

The DC bus acts as the central power-sharing point of the hybrid system. A large DC-link capacitor is connected across the bus to smooth voltage fluctuations caused by variations in renewable generation and load demand. The battery converter and dump load controller assist in maintaining a constant DC voltage within a predefined range. Stable DC bus voltage is essential for proper inverter operation and high-quality AC output.

H. Inverter and AC Load Modeling

A Voltage Source Inverter (VSI) converts the regulated DC bus voltage into sinusoidal AC voltage suitable for powering conventional loads. Pulse Width Modulation (PWM) is used to control inverter switching and maintain a constant output frequency of 50 Hz. An LC filter is connected at the inverter output to remove switching harmonics and reduce distortion. The AC load is modeled as a variable demand to test the system's dynamic response under changing operating conditions.

I. Dump Load Control

The dump load is activated when renewable generation exceeds both load demand and the battery's charging capacity. In such situations, the excess energy is diverted to a resistive load, where it is safely dissipated as heat. This prevents DC bus overvoltage and protects the battery from overcharging. Dump load control is particularly important in standalone systems where there is no grid connection to absorb surplus energy.

J. MATLAB/Simulink Implementation

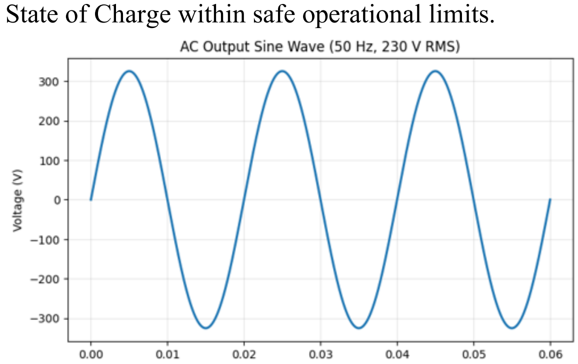
The complete Hybrid Renewable Energy System is implemented using Simscape Electrical and Simulink control blocks. Standard MATLAB components such as PV Array, Wind Turbine, Battery, Converters, Inverter, and Scope blocks are used to create the model. Time-varying profiles for solar irradiance, wind speed, and load demand are applied as simulation inputs. Measurement blocks are placed at critical points to record voltage, current, power, SOC, and efficiency for detailed analysis.

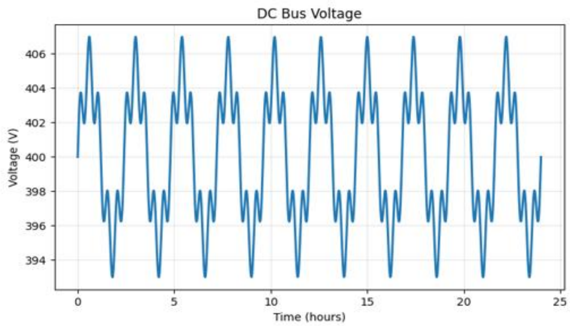
K. Methodology Flow

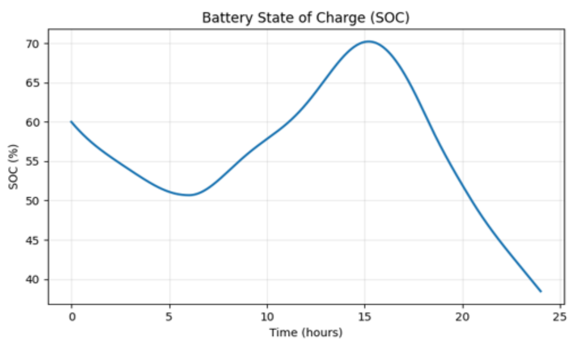
The methodology begins with defining system requirements and developing mathematical models for each component. Control algorithms for MPPT, battery management, and dump load operation are then designed. All components are integrated through the DC bus and implemented in MATLAB/Simulink. Dynamic simulations are performed using variable environmental and load inputs. Finally, the recorded outputs are analyzed to assess reliability, stability, and efficiency of the proposed hybrid renewable energy system.

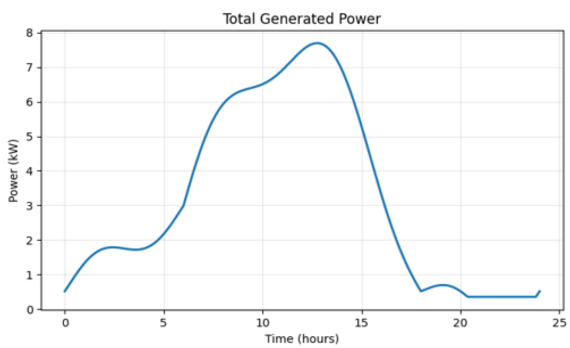
V. RESULT

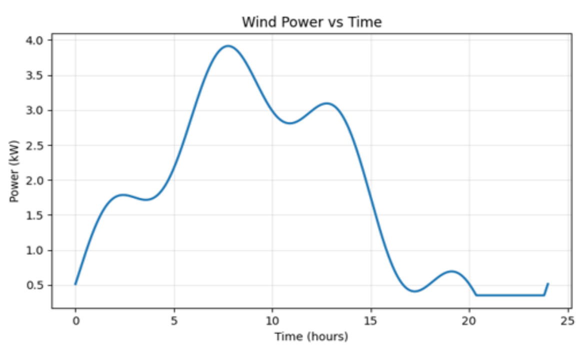
The MATLAB/Simulink simulation of the proposed Hybrid Renewable Energy System demonstrated effective integration of the Solar PV array, Wind Energy Conversion System, and Battery Energy Storage System under dynamically changing solar irradiance, wind speed, and load demand conditions. The Solar PV subsystem successfully tracked the maximum power point using the Perturb and Observe algorithm, producing higher output during periods of strong irradiance, while the wind subsystem generated complementary power based on variable wind speed using an Optimal Torque-based MPPT controller. The combined output power closely followed the available renewable resources, and the common DC bus voltage remained well regulated around its reference value with only minor transient deviations. The Voltage Source Inverter, together with the LC filter, delivered a stable 230 V, 50 Hz sinusoidal AC output to the load with low harmonic distortion. Throughout the simulation, the battery storage system effectively absorbed excess energy during periods of high generation and discharged during generation deficits, maintaining uninterrupted supply and keeping the State of Charge within safe operational limits.

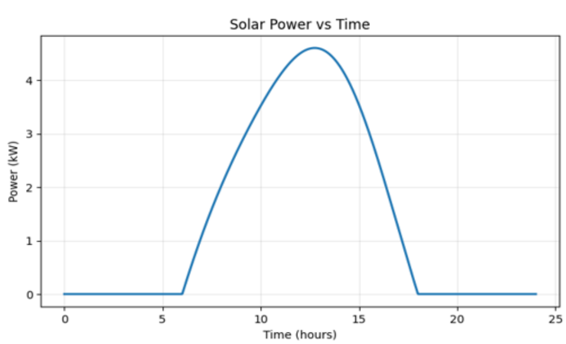


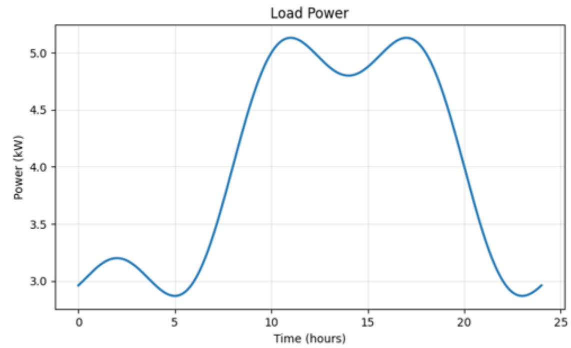












The results further showed that the Energy Management and Control System successfully coordinated power flow among renewable sources, battery storage, load, and dump load. During periods when the renewable generation exceeded both the load demand and the battery charging capacity, the dump load was activated to dissipate surplus power and prevent overvoltage on the DC bus. Conversely, when renewable output was insufficient, the battery provided the necessary support to maintain continuous load supply without significant voltage fluctuations. The load demand was satisfied consistently across all operating scenarios, demonstrating the robustness of the proposed architecture. The overall system efficiency remained high throughout the simulation, confirming that the use of MPPT controllers, bidirectional battery control, and intelligent energy management significantly improved renewable energy utilization. These findings validate the effectiveness of the proposed Hybrid Renewable Energy System as a reliable and sustainable solution for standalone and remote electrification applications.

VI. CONCLUSION

This paper presented the design, modeling, and simulation of a Hybrid Renewable Energy System (HRES) integrating Solar Photovoltaic (PV), Wind Energy Conversion System (WECS), and Battery Energy Storage System (BESS) using MATLAB/Simulink. The proposed system combined two complementary renewable energy sources with intelligent energy storage and control mechanisms to provide a stable and continuous power supply under varying solar irradiance, wind speed, and load demand conditions. Maximum Power Point Tracking (MPPT) controllers were implemented for both solar and wind subsystems to maximize energy extraction, while a bidirectional battery controller managed charging and discharging operations based on system power balance and battery State of Charge (SOC). A common DC bus facilitated efficient energy sharing among all subsystems, and a Voltage Source Inverter (VSI) converted the regulated DC power into high-quality AC power suitable for conventional loads. In addition, a dump load was incorporated to dissipate excess energy when renewable generation exceeded both load demand and battery charging capacity. Simulation results confirmed that the proposed system maintained stable DC bus voltage, delivered a clean 230 V, 50 Hz sinusoidal AC output, and successfully satisfied variable load demand without interruption. The battery storage system effectively balanced energy during periods of surplus and deficit generation, ensuring reliable operation and maintaining SOC within safe limits. The dump load provided essential protection against overvoltage conditions, and the overall system achieved high efficiency due to optimal power extraction and coordinated energy management. The study demonstrates that the proposed Hybrid Renewable Energy System is a technically feasible, efficient, and environmentally sustainable solution for standalone and remote power applications. Future work may focus on hardware implementation, real-time control using embedded systems, and optimization using artificial intelligence techniques to further enhance system performance and economic viability.

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