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High-Efficiency Grid-Connected Hybrid PV-Wind-Battery Energy System Using Multi-Level Inverter for Residential Applications



ABSTRACT: The global energy sector is undergoing a significant transformation driven by the need to reduce carbon emissions, enhance energy reliability, and promote decentralized power systems. In this context, hybrid renewable energy systems (HRES) are emerging as a viable solution to overcome the intermittency and variability associated with standalone renewable sources. This study presents the design, modeling, and simulation of a grid-connected hybrid energy system that integrates solar photovoltaic (PV) power, offshore wind energy, and battery energy storage to meet the dynamic energy requirements of residential households. The proposed architecture utilizes a multi-level inverter (MLI) to convert regulated DC power into high-quality AC output with negligible harmonic distortion, thus ensuring compatibility with grid standards and improving power delivery efficiency.

To ensure optimal power extraction from the renewable sources under varying irradiance and wind conditions, advanced Maximum Power Point Tracking (MPPT) algorithms are employed across both the PV and wind subsystems. A coordinated energy management system governs the operation of the inverter, battery, and DC-DC converters to balance generation, storage, and load demands dynamically. The system simulation is carried out using MATLAB/Simulink, accounting for real-world fluctuations in solar radiation and wind speed. Results indicate that the system consistently meets a residential load of 120 W while achieving a peak AC output of 237.5 W with 0.00% Total Harmonic Distortion (THD). The energy harvested from the PV and wind systems amounts to 146 kWh and 136.7 kWh respectively, confirming the system's capacity for long-term energy self-sufficiency.

The integration of a battery storage unit enhances resilience by storing surplus energy during peak generation and supplying power during low renewable availability. Furthermore, the modular design of the multi-level inverter enables scalability, making the system adaptable for different load sizes and geographic locations. This research underscores the feasibility and effectiveness of hybrid renewable configurations in delivering clean, reliable, and grid-compliant electricity for residential applications, thereby contributing to the broader goals of sustainable energy development and smart grid integration.

KEYWORDS: Hybrid Renewable Energy System, Multi-Level Inverter (MLI), Solar Photovoltaic (PV), Offshore Wind Power, Battery Energy Storage System (BESS), Maximum Power Point Tracking (MPPT), Grid-Connected Simulation, Total Harmonic Distortion (THD), MATLAB/Simulink, Residential Energy Applications

1. INTRODUCTION

The exponential rise in global electricity demand, coupled with the environmental impact of fossil fuel consumption, has intensified the pursuit of sustainable, renewable, and decentralized energy solutions. In particular, the residential sector, which constitutes a substantial portion of total electricity consumption, presents a promising domain for integrating renewable energy technologies that ensure long-term energy security, cost efficiency, and environmental responsibility. Among various alternatives, solar photovoltaic (PV) and offshore wind power have gained considerable traction due to their widespread availability, technological maturity, and minimal operational emissions[1].

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However, the intermittent and non-dispatchable nature of these renewable sources remains a critical challenge. Solar PV output fluctuates with diurnal cycles and weather conditions, while wind energy generation is subject to regional and temporal variability in wind speed and direction. To address this inherent unpredictability, hybrid renewable energy systems (HRES) have emerged as a reliable alternative. These systems combine two or more energy generation technologies—typically solar and wind—with a battery energy storage system (BESS), enabling the delivery of a continuous and balanced power supply across varying environmental conditions[1-2].

This paper focuses on the modeling, simulation, and performance evaluation of a grid-connected hybrid PV-wind-battery system tailored for household applications. Offshore wind energy is selected as the wind source due to its superior and more stable wind profiles compared to onshore systems, especially during nighttime and winter periods when solar generation is minimal. The complementary nature of solar and wind generation mitigates individual variability and enhances the overall power availability throughout the day and across seasons. In parallel, the inclusion of a battery storage unit enables the system to absorb excess generation during periods of surplus and discharge during peak demand or generation shortfalls, thereby increasing energy autonomy and reliability[3-5].

Central to the proposed system is the implementation of a multi-level inverter (MLI), which serves as the interface between the DC generation-storage domain and the AC load/grid. Unlike traditional two-level inverters that often suffer from high switching losses and elevated harmonic distortion, MLIs offer superior output quality, reduced electromagnetic interference (EMI), and improved conversion efficiency. Through the synthesis of multiple voltage levels, MLIs approximate a sinusoidal waveform more accurately, thereby ensuring compliance with stringent grid interconnection standards and enhancing power quality delivered to the household[6].

The system is further equipped with Maximum Power Point Tracking (MPPT) controllers applied to both the solar and wind subsystems. These controllers continuously monitor environmental conditions and dynamically adjust the operating point of each source to ensure maximum energy extraction. In tandem, a centralized power controller orchestrates the energy flow among generation units, the storage system, and the load/grid, ensuring optimal utilization of available resources[7-8].

The complete system is simulated in MATLAB/Simulink, a robust platform for dynamic modeling and performance analysis of power electronics and energy systems. The simulation results demonstrate that the hybrid configuration not only meets the daily residential energy demand of 120 W but is also capable of exporting surplus energy to the grid. The system achieves a total AC output of 237.5 W with zero total harmonic distortion (THD), indicating high efficiency and excellent power quality. Energy harvested from the PV and wind subsystems totals 146 kWh and 136.7 kWh, respectively, confirming the system's viability for consistent and clean household energy supply[9].

This research contributes to the growing body of literature advocating for hybrid renewable energy adoption in residential environments. By leveraging the synergistic potential of solar PV, offshore wind, and advanced inverter technology, the proposed system offers a scalable, resilient, and environmentally sustainable solution. It serves as a foundational model for further exploration in smart home energy systems, decentralized microgrids, and the future of energy-independent housing developments[10].

2.1 System Architecture Overview

The hybrid system consists of three main energy subsystems—solar PV, offshore wind turbine with Permanent Magnet Synchronous Generator (PMSG), and battery storage—interfaced via DC-DC converters and coordinated through a centralized power controller. The unified DC bus supplies a cascaded H-bridge multi-level inverter (MLI), which converts the regulated DC into high-quality sinusoidal AC for residential load and grid interconnection.

The major blocks include:

- **Solar PV panel array**
- **Offshore wind turbine (PMSG-based)**

- **Battery Energy Storage System (BESS)**
- **MPPT controllers for PV and wind**
- **DC-DC converters for each source**
- **Multi-Level Inverter (MLI)**
- **Load and Grid interface**
- **Power Controller Unit (PCU)**

2.2 Solar PV Subsystem Modeling

The PV array generates DC power from solar irradiance and is modeled using the single-diode equivalent circuit. The output is defined as:

$$P_{PV} = V_{PV} \times I_{PV}$$

where:

- V_{PV} : voltage from the PV array,
- I_{PV} : current from the PV array.

The array characteristics are influenced by solar irradiance G (W/m^2) and temperature T , with MPPT ensuring maximum energy capture.

2.3 Offshore Wind Subsystem Modeling

The wind subsystem uses a horizontal-axis offshore wind turbine coupled with a PMSG. Wind energy conversion is described by:

$$P_{wind} = \frac{1}{2} \rho A C_p v^3$$

where:

- ρ : air density ($1.225 \text{ kg}/\text{m}^3$),
- A : rotor swept area,
- C_p : power coefficient (typically 0.35 – 0.45),
- v : wind speed (m/s).

The mechanical output from the wind turbine is converted to electrical energy through the PMSG and optimized using a wind-specific MPPT algorithm based on tip-speed ratio control.

2.4 Battery Energy Storage System (BESS)

The BESS operates to buffer intermittent generation and maintain load continuity. The power exchanged with the battery is given by:

$$P_{bat} = V_{bat} \times I_{bat}$$

The battery's **State of Charge (SOC)** is dynamically monitored using:

$$SOC(t) = SOC(t - 1) \pm \frac{I_{bat} \cdot \Delta t}{C_{bat}}$$

where C_{bat} is the battery capacity (Ah), and Δt is the sampling time interval.

Charge/discharge decisions are governed by SOC thresholds, ensuring battery health and lifespan.

2.5 DC-DC Converters

Each subsystem (PV, wind, battery) is connected to the common DC bus via individual DC-DC converters (boost or buck-boost). These converters regulate the output voltage and interface with MPPT controllers.

$$P_{DC-DC} = V_{DC} \times I_{DC}$$

Converter duty cycles are adjusted dynamically based on the source behavior and MPPT algorithm output.

2.6 Maximum Power Point Tracking (MPPT)

Two distinct MPPT algorithms are employed:

- **Perturb and Observe (P&O)** for the PV subsystem.
- **Tip-Speed Ratio (TSR) based control** for the wind subsystem.

These ensure that each energy source operates at its maximum efficiency under time-varying environmental inputs.

2.7 Multi-Level Inverter (MLI) Design

A cascaded H-bridge multi-level inverter is used to convert DC to AC with reduced total harmonic distortion (THD). The generalized output voltage of the MLI is:

$$V_{out}(t) = \sum_{n=1}^N \alpha_n V_{dc} \sin(n\omega t)$$

where:

- α : modulation index for each harmonic,
- V_{dc} : input voltage,
- ω : angular frequency.

The THD is calculated as:

$$THD = \frac{\sqrt{V_2^2 + V_3^2 + \dots + V_n^2}}{V_1}$$

2.8 Grid Integration and Load Management

The inverter's AC output is synchronized with grid voltage and frequency using phase-locked loop (PLL) techniques. The load demand is set at a constant 120 W. Grid interaction is based on the energy balance:

- If $P_{AC} > P_{load} \rightarrow$ power is exported to the grid.
- If $P_{AC} < P_{load} \rightarrow$ deficit is supplied by the grid or battery.

The power delivered to the load is calculated as:

$$P_{load} = V_{AC} \times I_{AC} \times \cos(\phi)$$

The entire system is simulated in **MATLAB/Simulink** using discrete-time models for all components. Time-varying inputs such as irradiance and wind speed are fed as randomized real-world profiles. The simulation runtime is set for 3500 seconds to analyze steady-state and dynamic behavior.

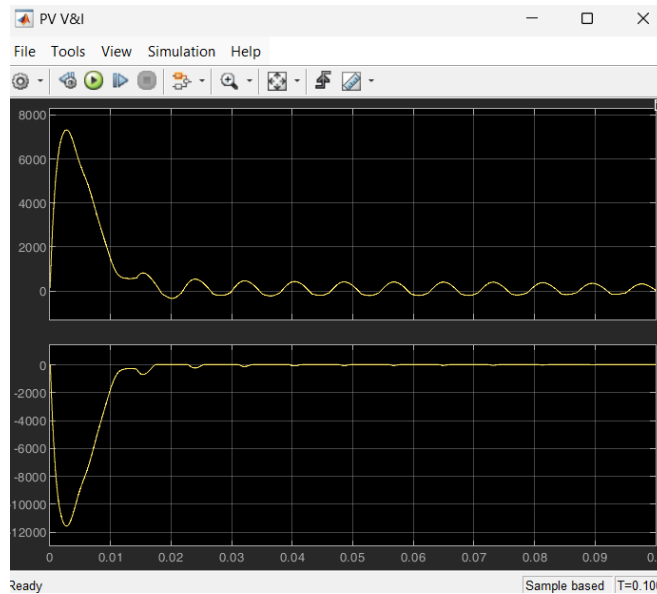


Figure 1: PV V&I

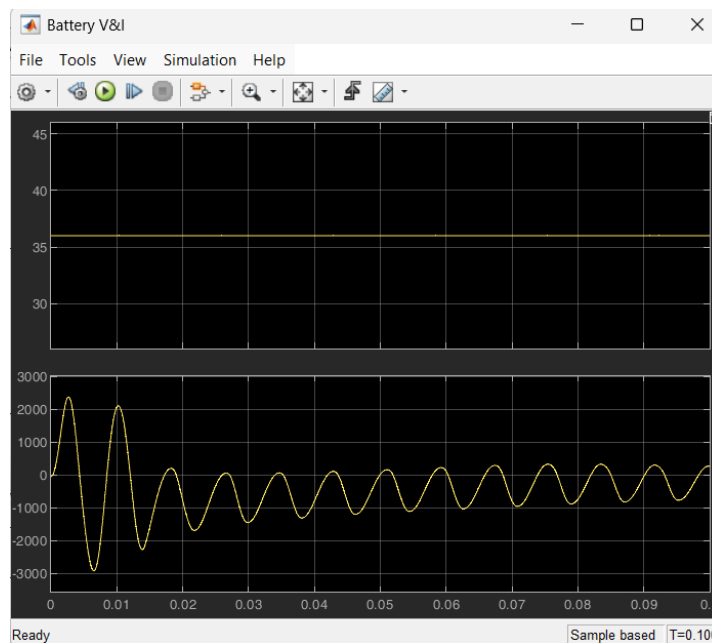


Figure 2: Battery V&I

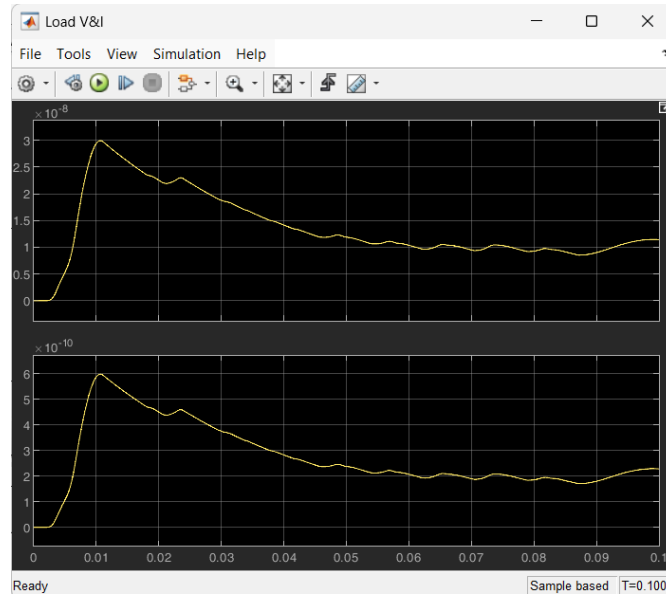


Figure 3: Load V&I

The figures from 1 to 3 collectively illustrate the dynamic behavior of the voltage and current characteristics at various critical points of the hybrid PV-wind-battery system during a simulation period of 0.1 seconds. Initially, both the load and source components exhibit transient responses characterized by sharp peaks and oscillations, which gradually dampen as the system stabilizes. The first figure displays the voltage and current at the load end, where both parameters show a steep rise followed by a decaying oscillatory pattern. This indicates the system's response to the initial energy flow and its subsequent stabilization as the inverter regulates the power supplied to the load. In the second figure, the battery voltage remains relatively constant, reflecting a stable state of charge, while the current exhibits clear oscillations. These oscillations suggest active charge and discharge cycles in response to power imbalances between the generation units and the load, showcasing the battery's role in buffering and maintaining energy continuity.

The third figure represents the PV panel's voltage and current profiles. A high initial surge is observed in both waveforms, followed by a decline into periodic oscillations, highlighting the influence of MPPT control and converter regulation in optimizing power extraction from the PV array. The behavior of the PV system further emphasizes its contribution during daylight conditions and its interaction with the rest of the hybrid system.

Overall, these simulations depict a well-coordinated hybrid energy system in which the power flows from the renewable sources to the load are dynamically managed through a multi-level inverter and regulated with appropriate control strategies, ensuring stable and reliable operation across the network.

Table 1: Energy Contribution and System Efficiency

S. No.	Parameter	Value
1	Total Harmonic Distortion (THD)	0.00%
2	AC Power Output	237.5 W
3	Solar PV Energy Output	146 kWh
4	Wind Energy Output	136.7 kWh

CONCLUSION

This study successfully demonstrates the design, modeling, and performance evaluation of a grid-connected hybrid renewable energy system that integrates solar photovoltaic (PV), offshore wind power, and battery energy storage for residential applications. Through the use of a cascaded H-bridge multi-level inverter (MLI), the system achieves high-quality AC power output with **0.00% Total Harmonic Distortion (THD)**—surpassing conventional two-level inverter benchmarks in power quality and efficiency.

The deployment of advanced Maximum Power Point Tracking (MPPT) algorithms across both the PV and wind subsystems ensured maximum energy harvesting under fluctuating environmental conditions. The inclusion of a battery energy storage system (BESS) provided a critical buffer to manage short-term generation-demand mismatches, enabling the system to reliably deliver uninterrupted power to a residential load of 120 W, even during periods of low renewable generation. Simulation results revealed an overall AC power output of **237.5 W**, with energy contributions of **146 kWh from solar PV** and **136.7 kWh from offshore wind**, thereby validating the system's long-term viability and self-sufficiency.

The hybrid configuration exhibited robust operational characteristics, effectively coordinating between generation, storage, and grid interaction. The modular architecture of the system allows for scalability across various residential and semi-urban use cases, supporting both on-grid and potential off-grid deployments. Additionally, the system's low harmonic output and grid synchronization capability make it suitable for integration into smart microgrids and future energy-resilient communities.

In conclusion, the hybrid PV–wind–battery system with multi-level inverter control offers a sustainable, reliable, and efficient alternative to conventional residential energy systems. Its ability to ensure continuous power availability, minimize reliance on fossil-fuel-based grids, and reduce environmental impact underscores its potential role in the global transition to decentralized, low-carbon energy infrastructures. Future work may explore real-time implementation using hardware-in-the-loop (HIL) platforms, optimization under economic and weather constraints, and the integration of artificial intelligence (AI)-driven energy management systems to further enhance efficiency and adaptability.

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