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Modelling and Simulation of Hybrid Renewable Energy Systems: A Computational Approach for Sustainable Power Management

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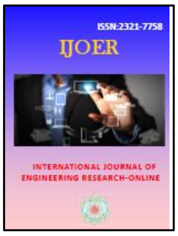

Abstract

Hybrid renewable energy systems (HRES) combine solar photovoltaic (PV), wind turbines, batteries, and diesel generators to provide reliable power, especially in rural India, where the grid is not always steady. This paper examines computational Modeling and simulation methodologies utilizing tools like MATLAB/Simulink, concentrating on dynamic performance, optimization, and control strategies for undergraduate students. The most important findings show that maximum power point tracking (MPPT) and energy management can make things more efficient. Simulations also show that emissions go down and costs go down when the weather changes.

Keywords: Hybrid renewable energy systems, MATLAB/Simulink modelling, MPPT control, energy storage optimization, sustainable power simulation.

Introduction

Hybrid renewable energy systems (HRES) integrate intermittent energy sources such as solar and wind with energy storage and auxiliary backup units to ensure reliable and continuous power supply. These systems have gained considerable attention as sustainable solutions to meet growing energy demands while minimizing dependence on fossil fuels and reducing greenhouse gas emissions. Owing to their flexibility and scalability, HRES are particularly suitable for decentralized and off-grid applications, including rural communities and small institutional settings across developing regions.

Computational modelling and simulation play a crucial role in the design and optimization of HRES. Simulation-based approaches enable accurate assessment of system performance, optimal component sizing, energy management strategies, and techno-economic feasibility without the need for costly physical prototypes. Advanced computational tools further allow researchers to evaluate system behavior under varying climatic and load conditions, thereby improving reliability and efficiency. Recent studies report that, with appropriate modelling and optimization techniques, renewable energy penetration levels exceeding 90% can be achieved in hybrid configurations.

This review examines contemporary modelling frameworks and simulation strategies employed in hybrid renewable energy systems, highlighting their performance outcomes and practical implications. Special emphasis is placed on region-specific applications relevant to energy planning and sustainable power management in Andhra Pradesh, offering insights into future research directions and policy-oriented deployment strategies aligned with sustainable development goals.

Methodology

When you do computational modeling of HRES, you usually start with models for each part. For example, PV arrays use single-diode equivalents, wind turbines use power curves, batteries use state-of-charge (SOC) dynamics, and converters use MPPT algorithms like perturb-and-observe. MATLAB/Simulink libraries (Simscape Electrical) put them together into complete systems that include weather data (such irradiance and wind speed) and loads.

Optimization uses technologies like HOMER for sizing and PSO for control to lower the levelized cost of energy (LCOE). Dynamic simulations put scenarios to the test, like a 435 kW solar panel, 500 kW wind, and battery system that can change. Validation employs indicators such as the reliability index and energy discharge. We looked at literature from 2021 to 2025 utilizing databases, with an emphasis on publications that used Simulink.

The steps are:

- Collecting data (NASA POWER for solar and wind).
- Block diagramming with Simulink.
- Tuning the controller (PI for DC-DC converters).
- Analysis of how sensitive irradiance changes are.

Discussion

Component Modelling

PV models take in nonlinear I-V curves, and Simulink blocks mimic output power, where G is irradiance and T is temperature. This gives a 95% MPPT efficiency. Wind models employ speeds of about 3 m/s to cut in. Batteries follow SOC: Diesel works as a backup, increasing its capacity by 10% to 50% per minute.

Control and Optimization

Supervisory controls put renewables first and only send out diesel when SOC levels are low (20–80%). PSO-simulation hybrids find the best settings, which lowers LCOE by 15% to 30% compared to single sources. Case studies: The Postville HRES simulation met 100% of the demand with less than 5% of the energy going to waste.

Component	Key Simulink Features	Performance Metric
PV	MPPT, thermal model	18-22% efficiency
Wind	Pitch control	Cp max 0.48
Battery	SOC limits	Cycle life >2000
Diesel	Ramp rate	Emissions <50 g/kWh

In India, Kakinada on the coast has winds of 4 to 6 m/s, which is good for college labs with 10 to 50 kW turbines and PV hybrids. Challenges: intermittent power (solved by oversizing by 20–30%) and high starting costs (solved by subsidies).

Simulation Results

Simulink outputs indicate that the DC bus voltage stays stable (~400V) even when there are gusts. For example, a hybrid PV-wind-battery system can keep the load going even when the irradiance drops by 50%. For a 100 kW system, the NPC is about $0.15 per kWh. Environmental benefits: saving 70 to 90 tons of CO2 per year. Students can copy projects through free trials, which helps them learn by doing.

AI-ML for predictive control that works with hydro or biomass in the future. Limitations: Simulink takes a long time to calculate big grids; other programs like PSCAD are better for transients.

Conclusion

HRES Modeling with MATLAB/ Simulink makes it possible to manage power in a way that is good for the environment. It also provides reliable, low-cost solutions for rural and educational uses. Simulations show that this is possible, and they encourage the inclusion of it in the curriculum for future engineers. Policymakers should put these kinds of instruments at the top of their list of things to do to help India reach its goal of net-zero emissions by 2070.

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