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Optimal Scheduling of Integrated Distributed Generation with Battery Energy Storage System

Muskan Mehra[1], Dr. A.K. Sharma[2]

[1]Jabalpur Enginnering College, Gokalpur, Jabalpur and 482011, India
[2]Jabalpur Enginnering College, Gokalpur, Jabalpur and 482011, India

A B S T R A C T

The growing demand for clean and sustainable energy has accelerated the adoption of hybrid renewable energy systems (HRES), which combine multiple energy sources such as solar photovoltaic (PV), wind power, thermal generation, and battery energy storage systems (BESS). These systems are particularly effective for industrial and remote applications, but face operational challenges due to the unstable nature of renewable resources and changing seasonal load demands. This study proposes a seasonal scheduling strategy that dynamically balances energy generation, storage, and consumption to ensure reliable power supply throughout the year. Demand response (DR) techniques are integrated to shift or reduce load during peak periods, enhance system adaptability, and reduce operational costs. BESS are strategically managed to absorb excess energy during surplus periods and discharge it during supply shortages, thus supporting load leveling and grid stability. A detailed simulation model is developed using MATLAB/Simulink to assess the system performance under different seasonal conditions. The results indicate significant improvements in renewable energy utilization, reduced dependence on thermal generation, and increased overall efficiency, making this scheduling approach suitable for sustainable and flexible energy solutions.

Keywords: HRES, Seasonal Scheduling, Optimal Power Flow (OPF), Solar PV, Wind Energy, Thermal Generation, Battery Energy Storage System (BESS), Demand Response, MATLAB/Simulink, Energy Management, Real-Time Control.

1. Introduction

The global transition to sustainable energy systems is accelerating in response to climate change, fossil fuel depletion and growing energy demands. Hybrid renewable energy systems (HRES), which integrate solar photovoltaics (PV), wind turbines, thermal generators and battery energy storage systems (BESS), provide an effective route to achieving clean, reliable and decentralised energy supply [1]. However, the intermittent and seasonally variable nature of solar and wind resources presents significant operational challenges. While solar energy generation peaks in the summer months, wind generation often dominates in winter or transitional seasons, leading to fluctuations in available power that complicate supply-demand matching [2]. To address these challenges, BESS has emerged as a key component within the HRES architecture. It enables energy transfer, smooths renewable variability, improves load matching and enhances system stability and reliability [3]. In parallel, demand response (DR) strategies play an important role by allowing consumers to adjust their energy consumption patterns in response to pricing or system signals, thereby reducing grid stress during peak demand periods and increasing economic efficiency [4].

This study proposes a seasonal energy scheduling framework for HRES that coordinates renewable generation, BESS operations, and DR mechanisms without reliance on complex metaheuristic or mathematical optimization algorithms. The system is modeled and simulated in MATLAB/Simulink under different seasonal conditions to assess performance based on energy cost, renewable penetration, storage utilization, and reliability. The results confirm that the strategic coordination of renewables, storage, and DR significantly improves the operational performance and sustainability of HRES.

2. Literature Review

M. Belhamel et al.[1], (2008)This research focuses on the techno-economic optimization of a stand-alone hybrid photovoltaic/wind system (HPWS) designed for remote locations on the island of Corsica. The primary goal is to identify the most cost-effective system configuration that maintains full energy self-sufficiency. Two hybrid configurations were evaluated at five sites with different renewable energy profiles. The findings show that hybrid solutions consistently outperform single-source systems in terms of both cost and reliability. In areas with weak wind resources, the battery state of charge (SOC) is significantly impacted, while in areas with strong wind potential, wind energy contributes more than 40% of the system power. This requires a system-wide transformation through smart energy systems. This approach combines electricity with areas such as heating, bioenergy and energy efficiency technologies such as combined heat and power (CHP) units and fuel cells to reduce dependence on fossil fuels. Although these measures improve energy efficiency, they also complicate the power balance. The study emphasizes that long-term sustainability depends on coordinating smart grids with sector coupling and flexible technologies, as shown by Denmark's developed energy market.

B. Zakeri et al.[3], (2015) Large-scale deployment of intermittent renewable energy introduces operational challenges and causes price volatility in electricity markets. Energy storage systems provide critical support by managing demand fluctuations, reducing grid congestion, and enabling distributed energy deployment Using updated datasets and Monte Carlo simulations, the study analyzes investment, maintenance, and replacement costs for applications ranging from bulk storage to ancillary grid services.

A. Khodaei et al.[4], (2014) This study introduces an advanced microgrid scheduling framework designed to minimize operational costs while addressing the complexities of grid-connected and islanded operation. The model separates the scheduling process into a primary problem for grid-connected conditions and a subproblem for isolated operation. It incorporates the T-τ criterion to assess islanding feasibility. If standalone operation is unattainable, corrective constraints, known as islanding cuts, are applied to re-align generation, storage dispatch, and adjustable load utilization.

3. Methodology

This section outlines the developed methodological framework for seasonal scheduling and operation of a hybrid renewable energy system (HRES) integrating solar photovoltaic (PV) panels, wind turbines, thermal generators, and battery energy storage systems (BESS). The approach emphasizes rule-based control strategies, historical data analysis, and demand-side flexibility through demand response (DR) mechanisms to ensure reliable and cost-effective operation under seasonal variations.

3.1 Solar and Wind Resource Forecasting

Accurate seasonal modeling starts with forecasts of solar radiation and wind speed. Long-term meteorological and site-specific data are used to capture trends over a 12-month period, including all seasonal changes. Energy production from solar and wind subsystems is estimated using standardized mathematical models that take into account environmental factors and system efficiency losses. These forecasts are used to determine the availability of renewable energy for day-ahead and real-time operations[5].

3.2 Seasonal Demand Profiling

Load demand is classified according to seasonal behaviors – winter, summer, monsoon and transition periods – to better align energy supply with consumption patterns. Profiles are created using historical demand data, sector-specific usage patterns (residential, industrial, commercial) and time-of-use considerations. This enables a more dynamic demand-side strategy, especially when integrated with DR programs, which encourage flexible load shifting and help mitigate peak demand issues [6].

3.3 Battery Storage Management Strategy

BESS is managed using rule-based control logic that governs charging and discharging based on renewable generation availability and load requirements. During periods of surplus energy, the system charges the battery, while discharge is triggered during low-generation periods or peak demand hours. State-of-charge (SOC) thresholds are maintained within safe operating limits to preserve battery health and ensure system resilience. Additionally, BESS supports auxiliary grid functions such as frequency stabilization and voltage balancing during operational disturbances[7].

3.4 Simulation and Validation in MATLAB/Simulink

The HRES model incorporating solar, wind, thermal generation units, BESS and DR integration is developed and simulated in MATLAB/Simulink. Input datasets for solar radiation, wind speed and load profile across seasons are used to drive the simulation. Key performance indicators such as renewable energy contribution, energy storage usage, cost savings and supply reliability are analyzed. The simulation results demonstrate that rule-based coordination of renewable sources, BESS and DR effectively addresses seasonal variability and enhances system performance without relying on complex optimization algorithms.

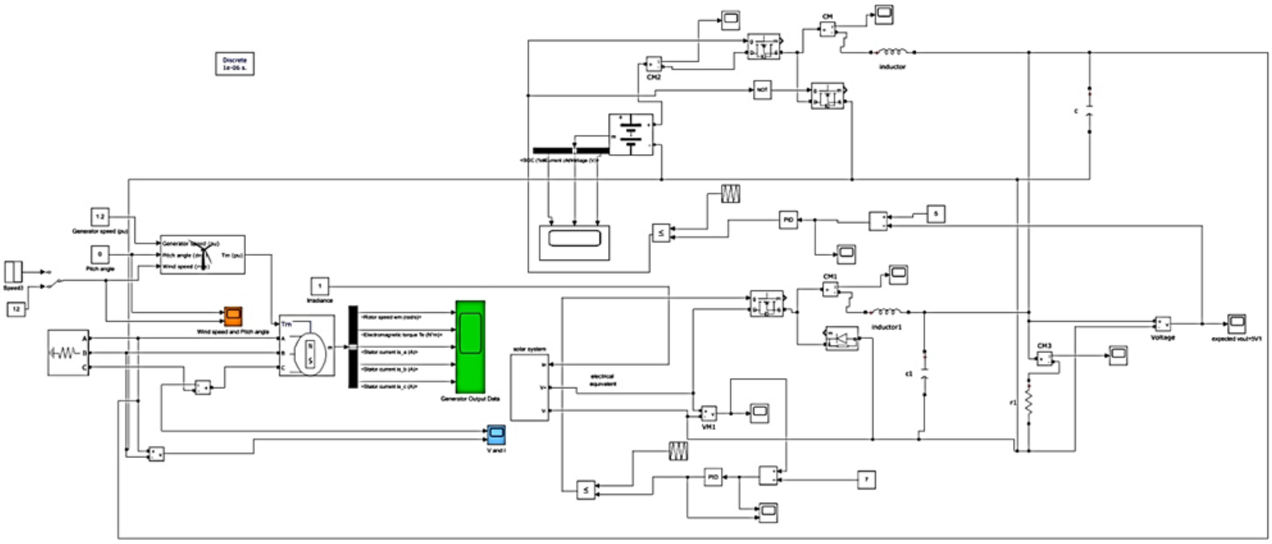

Figure 1. Simulation Model

4. Result & Discussion

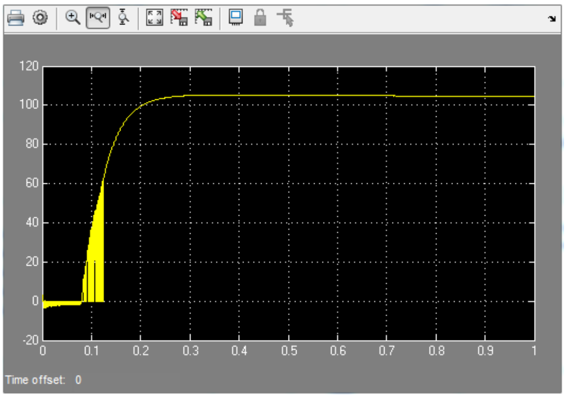

Figure 2. Power obtained using grid, PV, Wind and battery storage system in day duration

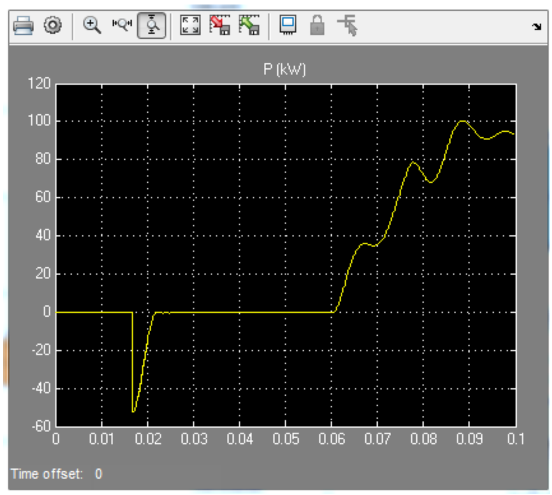

Figure 3. Power obtained using grid, PV, Wind and battery storage system in night duration

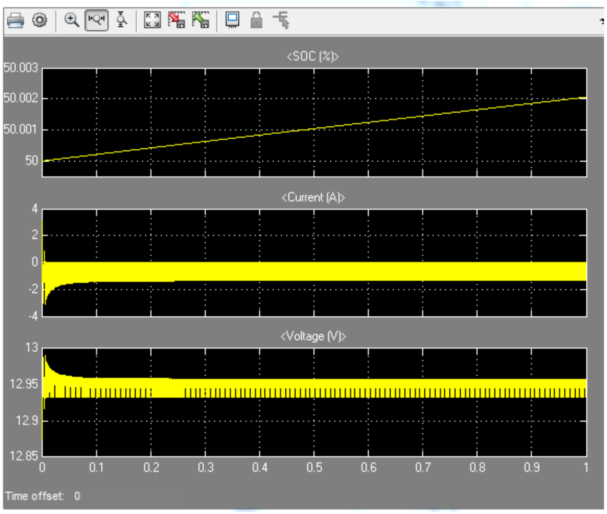

Figure 4. Battery charging status in day duration

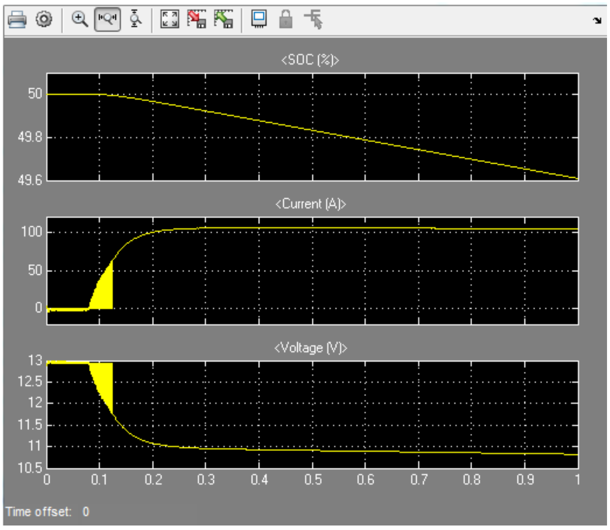

Figure 5. Battery charging status in night duration

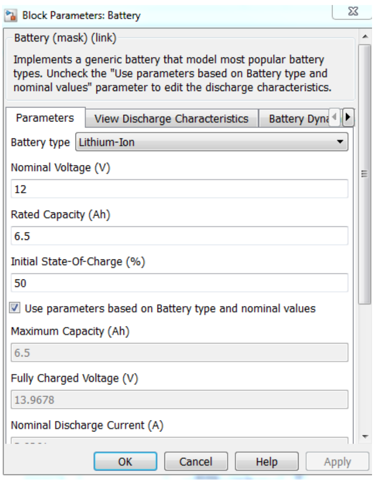

Figure 6. Battery charging parameters

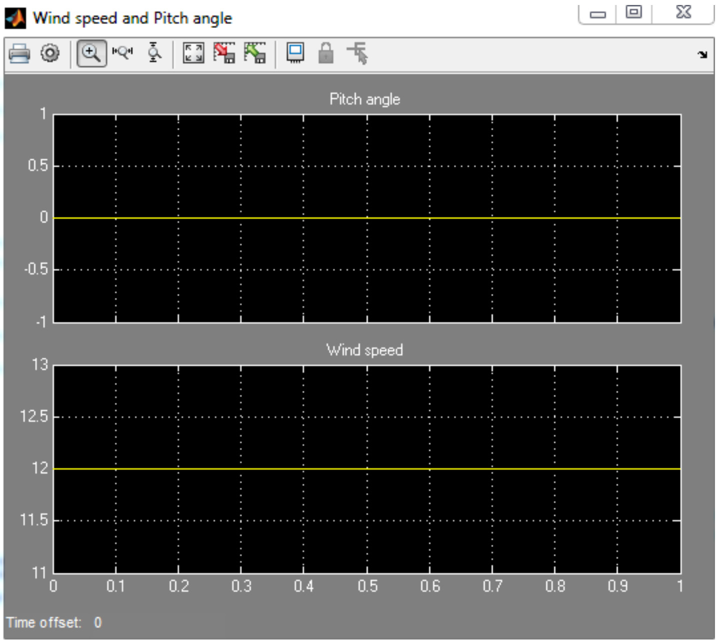

Figure 7. Wind speed and pitch angle

Cost per unit of electricity

110kW maximum power generation during the day using grid, PV, wind and battery storage system.

The cost per unit of electricity generated = Rs 4.90

92kW maximum power generation during night time using grid, PV, wind and battery storage system.

16% reduces the efficiency of power plant.

The cost per unit of electricity generated = 4.90 + 4.90 X 0.16 = Rs 5.69

Rs 5.69 - Rs 4.90 = Rs 0.79 per unit extra charge night duration.

5. Conclusion

This study has demonstrated the feasibility of a seasonally adaptive hybrid renewable energy system (HRES) integrating solar PV, wind, thermal generation, and battery energy storage without relying on complex optimization algorithms. By implementing a rule-based control strategy and seasonal load forecasting, the system effectively addresses the variability and intermittency of renewable sources. The integration of demand response (DR) programs further enhances the flexibility of the system, encourages consumer participation in load management, and reduces peak demand stress on the grid. Battery energy storage systems play a critical role in balancing energy supply and demand by storing surplus renewable energy and discharging it during periods of shortage. The simulation results of MATLAB/Simulink confirm the reliability, cost-effectiveness, and environmental benefits of the system in various seasonal scenarios. Overall, the proposed HRES framework provides a practical, scalable, and flexible solution for decentralized power systems, supporting the global transition toward low-carbon and sustainable energy infrastructure. The grid power supply has 50 kW, PV (30 kW), wind (30 kW) and battery storage system. Figure 2. Power (110 kW) obtained using grid, PV, wind and battery storage system in day period. Figure 3. shows the power (92 kW) obtained using grid, PV, wind and battery storage system in night period. Figures 4 to 7 show the battery charging status in day period, night period, battery charging parameters and wind speed and pitch angle, respectively.

6. Future Scope

Smart grid integration: The model can be extended to operate within smart grid networks, enabling real-time coordination between distributed energy resources, EVs, smart meters, and demand-side systems for intelligent energy management**.**

Extended renewable mix: Future versions could integrate hydrogen fuel cells, biomass, and geothermal sources to improve sustainability and diversify power generation.

Multi-objective optimization: Beyond cost and reliability, future studies could include objectives such as emissions reduction, power quality, system flexibility, and economic dispatch.

Hybrid optimization methods: Advanced techniques such as PSO-GA or PSO-ANN could be explored to enhance convergence speed and accuracy for complex, large-scale systems.

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