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Optimization of Hybrid Wind–Solar Energy System with Battery Storage for Large-Scale Grid Integration

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ABSTRACT

The increasing penetration of renewable energy sources in modern power systems necessitates efficient and reliable solutions for large-scale grid integration. Hybrid wind–solar energy systems have emerged as a promising approach due to the complementary nature of wind and solar resources. However, their intermittent and variable output poses significant challenges in maintaining grid stability and ensuring continuous power supply. To address these issues, the integration of battery energy storage systems (BESS) along with optimized system design has become essential. This study presents an optimization framework for a hybrid wind–solar energy system integrated with battery storage aimed at large-scale grid applications. The proposed approach focuses on optimal sizing and configuration of system components, including wind turbines, photovoltaic arrays, and battery storage, to achieve maximum efficiency, reliability, and cost-effectiveness. Advanced optimization techniques such as Particle Swarm Optimization (PSO) and Genetic Algorithms (GA) are employed to minimize power fluctuations, reduce operational costs, and enhance system performance. Furthermore, the study incorporates intelligent energy management strategies to ensure effective coordination between generation, storage, and load demand. Simulation results demonstrate that the optimized hybrid system significantly improves power quality, reduces energy curtailment, and enhances grid stability compared to conventional standalone renewable systems. The findings highlight the critical role of optimization and battery storage in enabling the large-scale deployment of hybrid renewable energy systems, contributing to a sustainable and resilient power infrastructure.

Keywords— Photovoltaic, Wind energy conversion, Wind Turbines

I. INTRODUCTION

The rapid growth in global energy demand, coupled with increasing environmental concerns, has accelerated the transition from conventional fossil fuel–based power generation to renewable energy sources. Among the various renewable options, wind and solar energy have gained significant attention due to their abundance, sustainability, and low environmental impact. However, the standalone deployment of these resources is often limited by their intermittent and unpredictable nature, which leads to fluctuations in power generation and challenges in maintaining grid stability. To overcome these limitations, hybrid wind–solar energy systems have been widely proposed as an effective solution for large-scale power generation [1].

Hybridization of wind and solar resources offers several advantages, as both sources exhibit complementary characteristics. Solar energy is typically available during daytime with peak generation under clear sky conditions, whereas wind energy can be harnessed during night or varying weather conditions. This complementary behavior improves the overall reliability and consistency of power output. Nevertheless, despite this advantage, variability in renewable generation still poses significant challenges for large-scale grid integration, including voltage instability, frequency deviations, and power quality issues [2, 3].

To address these challenges, the integration of battery energy storage systems (BESS) has become a key component in hybrid renewable energy systems. Battery storage acts as an energy buffer by storing excess energy generated during peak production periods and supplying it during times of low generation or high demand. This not only enhances system reliability but also enables efficient energy management, peak shaving, load leveling, and improved grid stability. Among various storage technologies, lithium-ion batteries are widely used due to their high energy density, fast response time, and increasing cost-effectiveness [4].

In addition to storage integration, optimization of hybrid wind–solar systems is essential to achieve maximum efficiency and economic viability. Optimal sizing of system components, such as wind turbines, photovoltaic arrays, and battery storage units, plays a crucial role in minimizing energy losses and reducing overall system cost. Advanced optimization techniques, including metaheuristic algorithms like Particle Swarm Optimization (PSO) and Genetic Algorithms (GA), have been extensively utilized to determine the best configuration of hybrid systems under varying environmental and load conditions [5, 6].

Furthermore, the development of intelligent energy management systems and advanced control strategies has significantly improved the performance of hybrid renewable systems. These approaches enable real-time monitoring, efficient power dispatch, and better coordination between generation, storage, and load demand. As a result, optimized hybrid wind–solar systems with battery storage are increasingly being recognized as a viable solution for large-scale grid integration [7].

This study focuses on the optimization of a hybrid wind–solar energy system integrated with battery storage for large-scale power system applications. It aims to analyze system performance, improve energy utilization, and enhance grid stability through advanced optimization techniques and efficient energy management strategies, thereby contributing to the development of a sustainable and reliable energy infrastructure [8, 9].

II. HBBRID ENERGY SYSTEM

A hybrid energy system is a power generation system that combines two or more energy sources—typically renewable sources such as wind, solar, hydro, or biomass—to produce electricity in a more reliable, efficient, and sustainable manner. The main objective of a hybrid system is to overcome the limitations of individual energy sources, especially their intermittency and variability, by integrating complementary resources and often incorporating energy storage systems [10].

In most modern applications, the hybrid wind–solar energy system is the most widely used configuration. Solar energy generates power during daytime under sunlight, while wind energy can operate during night or cloudy conditions. This complementary behavior ensures a more continuous and balanced power output compared to standalone systems. However, since both sources are still dependent on environmental conditions, hybrid systems are usually integrated with battery energy storage systems (BESS) to enhance reliability and maintain a stable energy supply [11].

A typical hybrid energy system consists of several key components, including renewable energy generators (such as wind turbines and photovoltaic panels), energy storage devices (batteries or supercapacitors), power electronic converters (inverters and DC–DC converters), and an energy management system (EMS). The EMS plays a crucial role in controlling power flow, optimizing energy usage, and ensuring efficient coordination between generation, storage, and load demand.

Hybrid energy systems offer several advantages, such as improved energy reliability, reduced dependence on fossil fuels, lower greenhouse gas emissions, and enhanced grid stability. They are widely used in applications like large-scale power plants, smart grids, rural electrification, microgrids, and industrial power supply systems. Additionally, with the integration of advanced technologies like artificial intelligence, machine learning, and IoT, hybrid systems are becoming more intelligent and capable of real-time monitoring, prediction, and optimization [12, 13].

Despite these benefits, hybrid energy systems also face challenges, including high initial installation costs, complex system design, and the need for advanced control strategies. Therefore, ongoing research focuses on optimization techniques, efficient energy storage integration, and smart control mechanisms to improve system performance and economic feasibility.

A. Solar Energy

Solar energy is that energy which is gets by the radiation of the sun. Sun oriented energy is available on the earth ceaselessly and in plenteous way. Sun oriented energy is uninhibitedly accessible. It doesn't deliver any gases that mean it is without contamination. It is reasonable in taken a toll. It has low upkeep cost. Just issue with nearby planetary group it can't deliver energy in terrible climate condition. Be that as it may, it has more prominent productivity than other energy sources. It just needs beginning speculation. It has long life expectancy and has brought down emanation [6].

B. Wind Energy

Wind energy is the energy which is extracted from wind. For extraction we use wind mill. It is renewable energy sources. The breeze energy needs less cost for age of power. Support cost is likewise less for wind energy framework. Wind energy is available very nearly 24 hours of the day. It has fewer outflows. Beginning expense is likewise less of the framework. Age of power from wind is rely on the speed of wind streaming. The real impediments of utilizing free sustainable power source assets are that inaccessibility of energy forever. For conquering this we utilize sun oriented and wind energy together. With the goal that any one wellspring of energy falls flat other will deal with the age. In this proposed framework we can utilize the two sources join [7]. Another way is that we can utilize any one source and keep another source as a remain by unit. This will prompts congruity of age. This will make framework solid. The primary detriments of this framework are that it needs high introductory cost. But that it is dependable, it has fewer outflows. Kept up cost is less. Life expectancy of this framework is more. Proficiency is more. A principle preferred standpoint of this framework is that it gives constant power supply.

III. PROPSOSED MODEL

The diagram represents a grid-connected hybrid wind–solar energy system, showing how power flows from renewable sources to the electrical grid through power electronic components. Here's a clear explanation in paragraph form:

The system begins with two renewable energy sources: wind energy and solar photovoltaic (PV) energy. The wind turbines generate electrical power from wind, while the PV panels convert sunlight into DC (direct current) electricity. Since both sources produce variable and sometimes fluctuating power, their outputs are first combined and fed into a DC–DC converter. This converter regulates and stabilizes the DC voltage, ensuring a consistent and usable power level despite variations in wind speed or solar irradiance.

The regulated DC power is then supplied to an inverter, which converts DC into AC (alternating current), making it suitable for grid connection. The inverter plays a crucial role in synchronizing the generated power with grid parameters such as voltage, frequency, and phase. After conversion, the AC output is passed through a Leveled AC stage, where the voltage is further stabilized to maintain uniformity and reduce fluctuations.

Next, the power flows through an LCL filter, which is used to eliminate harmonics and improve power quality. Harmonics are unwanted distortions in the waveform that can affect grid performance and damage equipment. The LCL filter ensures that the output power is smooth and meets grid standards.

Finally, the filtered and stable AC power is delivered to the main electrical grid, where it can be distributed for residential, commercial, or industrial use. This entire system ensures efficient integration of renewable energy into the grid while maintaining stability, reliability, and power quality.

Overall, the diagram highlights how hybrid renewable sources, along with power electronic converters and filters, work together to enable large-scale grid integration of clean energy.

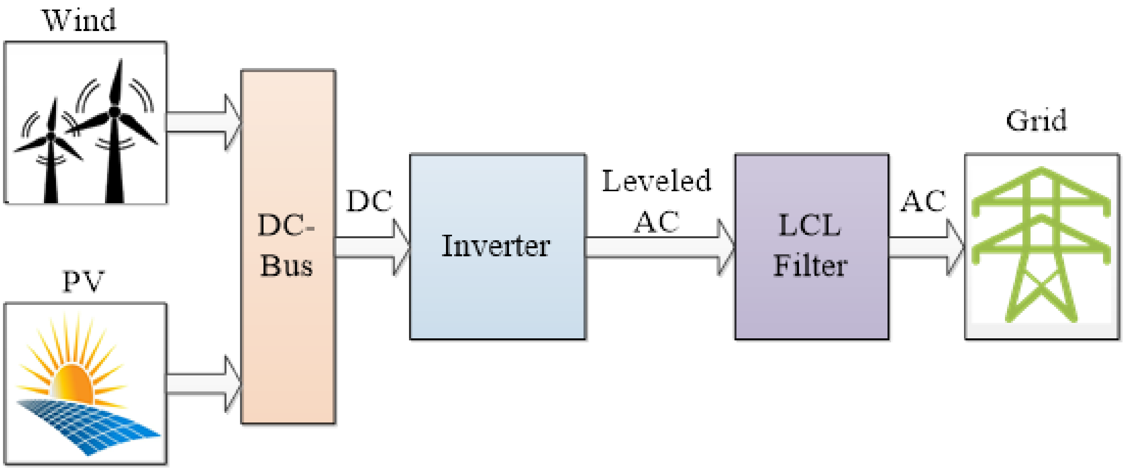

Figure 1: Representation of renewable energy to grid connected system

Designing of Filters

At the inverter's output, a filter is needed. Only the amplitude is high since the inverted signal is the DGM signal again. As a result, there are harmonics at the switching frequency and its multipliers in this signal. The LCL filter is used in the inverter output. The ability to use this filter at low switching frequencies, its advantages in filter dimensions compared to traditional "L" and "LC" filters, and its lower voltage drop and improved damping compared to conventional "L" and "LC" filters are the most significant reasons for choosing it.

Rated current is allowed to fluctuate by 10% for the design parameters, the values in (1) and (2) are obtained.

$$\Delta I\_L_{max} = \%10\, I\_max \qquad (1)$$

$$L1 = \frac{Vdc}{6fsw.\Delta I\_L_{max}} \qquad (2)$$

$$Cf = 0.05Cb \qquad (3)$$

The value inverter side inductance is L1, Cf is filter capacitance, L2 is grid side inductance, the switching frequency is fsw, and the dc connection voltage is Vdc. The value of the capacitor is limited by the low power factor (less than 5%) in the rated capacity (3) give the capacitance value.

Generate PWM signal

The PWM method should be used to produce necessary switching pulses in order to provide a low and fixed switching frequency suitable for high power and industrial applications. Some switching techniques, such as hysteresis, have a variable switching frequency, which causes irritating audible noises. To modulate the measured reference signal, carriers are transferred vertically. As shown by logic blocks, each carrier is responsible for generating pulses for associated voltage levels and switching states. Furthermore, the corresponding switching pulses for three cycles of the modulated waveform have been shown as fixed switching frequencies in each cycle. In comparison to other topologies, the proposed method ensures low and fixed switching frequency functionality of the h-bridge converter, resulting in low switching losses and high performance.

IV. SIMULATION RESULT

The given graph represents the dynamic response of a hybrid wind–solar energy system, most likely showing how a system parameter such as output voltage, power, or frequency varies with time during startup or disturbance conditions.

At the beginning of the graph (time near zero), the system exhibits a sharp rise followed by oscillations, indicating a transient response. This behavior occurs because the system is initially trying to reach its desired operating point. The sudden increase (overshoot) suggests that the controller or system input is strong, causing the output to exceed the steady-state value temporarily. Immediately after this, the waveform shows undershoot and multiple oscillations, which is a typical characteristic of an underdamped system.

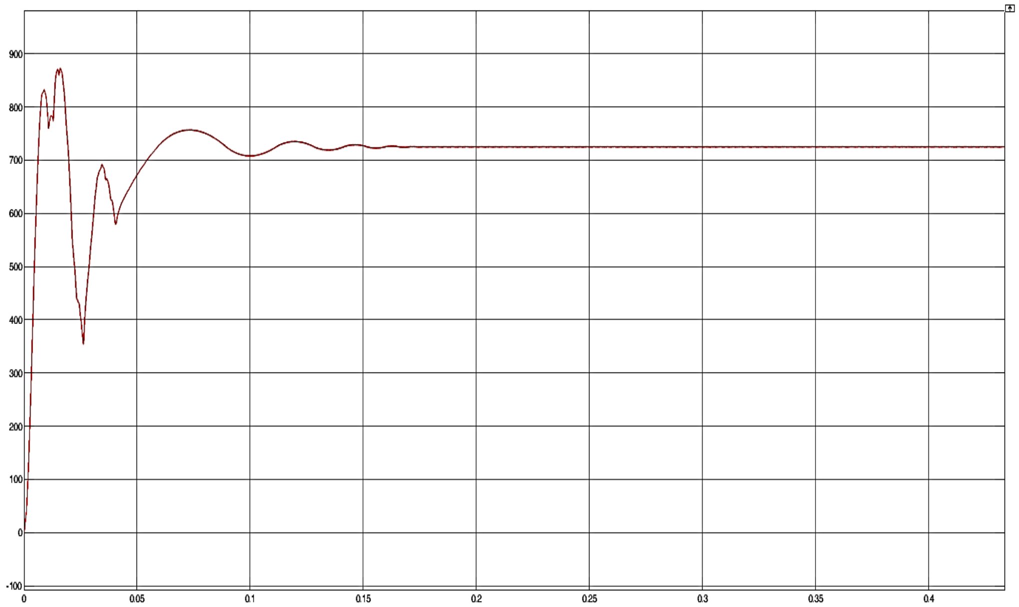

Figure 2: Output Voltage of wind and solar energy hybrid system

As time progresses, the oscillations gradually decrease in amplitude, indicating that the system is stable and well-damped. This damping effect is usually achieved through proper controller design (such as PI/PID controllers) or the use of filters and energy storage elements like batteries or capacitors. Around the mid-point of the graph, the waveform starts to settle, and the oscillations become very small.

Finally, the system reaches a steady-state value (approximately constant around 720–730 units), where the output remains stable with minimal ripple. This indicates that the hybrid system has successfully synchronized and is delivering consistent power to the grid.

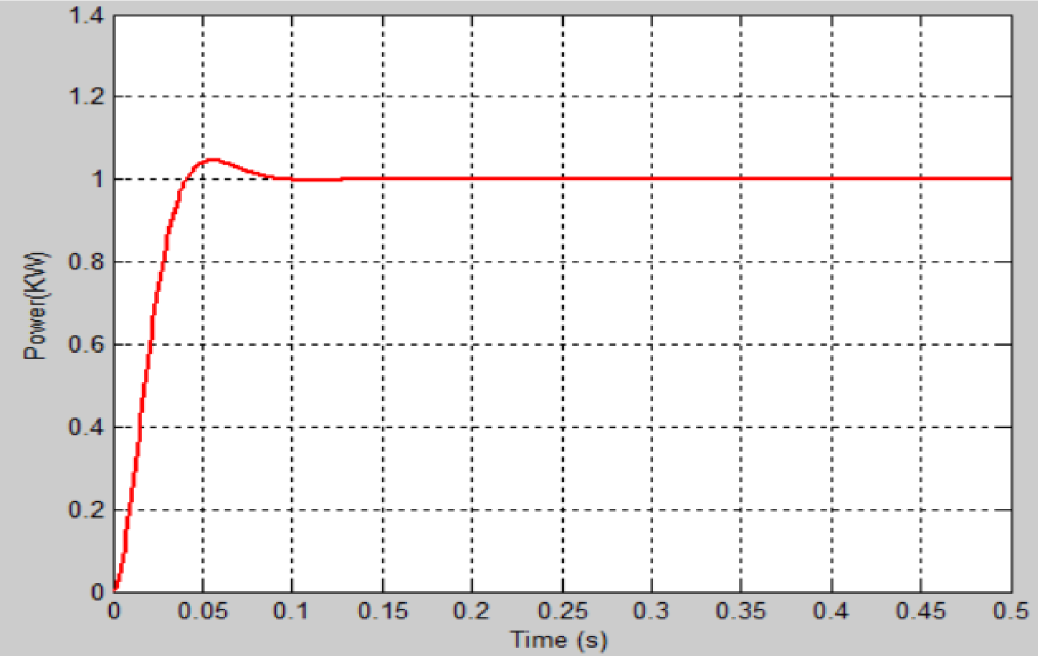

Figure 3: Mean Power of wind and solar energy hybrid system

The graph represents the current response of the hybrid wind–solar energy system over time, showing how the system behaves during startup and how quickly it reaches a stable operating condition.

At the initial moment (time = 0), the current starts from zero and rapidly increases, indicating that the system is being energized and power is beginning to flow from the renewable sources to the load or grid. Within a very short time (around 0.05–0.1 seconds), the current rises sharply and slightly exceeds its final value, reaching a peak of approximately 35–36 A. This small overshoot is a common characteristic of dynamic systems and indicates a fast response of the controller.

After this brief overshoot, the current quickly stabilizes and settles to a constant value of around 35 A. The absence of significant oscillations after the peak suggests that the system is well-damped and properly controlled, likely due to effective controller tuning (such as PI/PID control) and the presence of filtering components or energy storage support.

The steady and flat portion of the graph from approximately 0.1 seconds onward indicates that the system has reached steady-state operation, where the current remains constant with minimal ripple. This reflects stable power delivery and efficient synchronization with the grid.

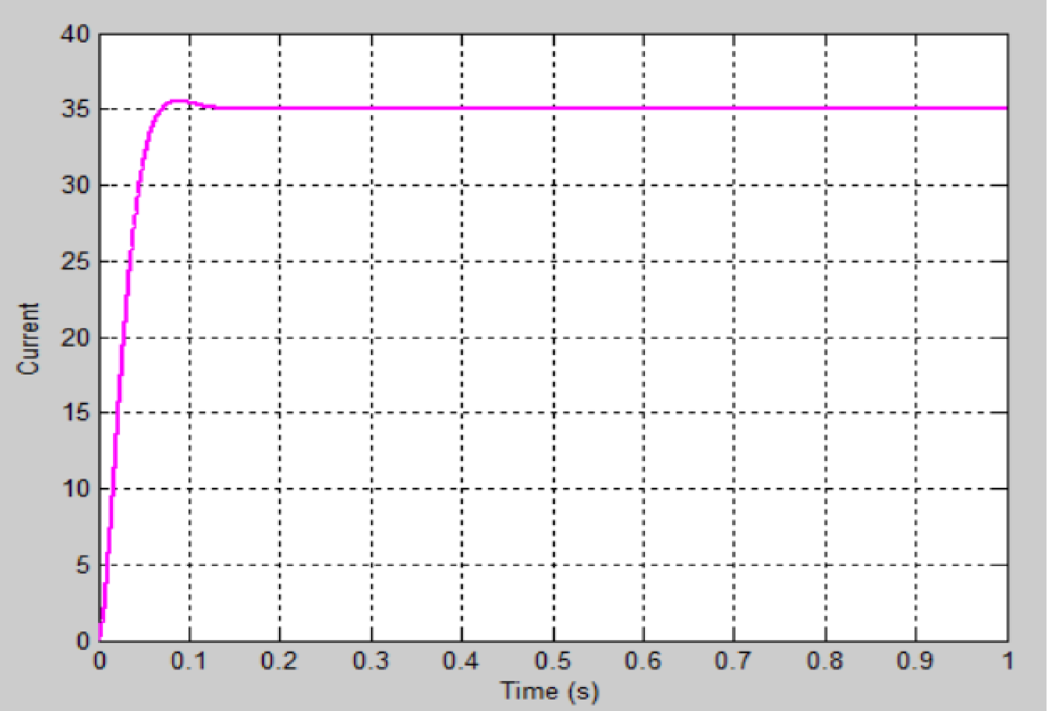

Figure 5.5: Output Current of wind and solar energy hybrid system

V. CONCLUSION

The analysis of the hybrid wind–solar energy system demonstrates that combining renewable energy sources with appropriate control strategies and energy storage integration significantly enhances system performance and reliability. The observed system responses, including voltage and current characteristics, indicate that the hybrid system is capable of achieving fast dynamic response, minimal overshoot, and quick settling time, which are essential for stable grid operation.

The integration of battery energy storage further improves system stability by smoothing fluctuations and maintaining consistent power output despite the intermittent nature of wind and solar resources. Additionally, the use of power electronic converters and filtering components ensures improved power quality and effective synchronization with the grid.

The results confirm that optimized hybrid wind–solar systems can successfully support large-scale grid integration by providing stable, efficient, and continuous power supply. With further advancements in optimization techniques, intelligent control strategies, and energy storage technologies, such systems will play a crucial role in the development of a sustainable and resilient energy infrastructure.

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