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DYNAMIC PERFORMANCE ANALYSIS AND SIMULATION OF A STANDALONE HYBRID RENEWABLE ENERGY SYSTEM FOR REMOTE CHINESE COMMUNITIES

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ABSTRACT

This study presents a comprehensive dynamic performance analysis and simulation of a standalone hybrid renewable energy system (HRES) tailored for remote Chinese communities with limited access to the national grid. The proposed system integrates solar photovoltaic (PV), wind energy, and battery storage to ensure a reliable and sustainable electricity supply. Using HOMER and MATLAB/Simulink, various configurations were modeled to evaluate system behavior under fluctuating weather and load conditions. The results highlight the system's ability to maintain voltage stability, improve energy reliability, and reduce greenhouse gas emissions. Sensitivity analyses demonstrate the adaptability of the HRES to diverse environmental scenarios and its economic feasibility compared to conventional diesel-based systems. This research provides valuable insights for policymakers and engineers aiming to implement clean energy solutions in rural and off-grid regions of China.

Keywords: Hybrid renewable energy system (HRES), dynamic performance, standalone system, solar PV, wind energy, battery storage, simulation, remote communities, China, HOMER, MATLAB/Simulink.

INTRODUCTION

The global demand for energy continues to escalate, driven by industrialization, population growth, and technological advancements. This increasing demand, coupled with environmental concerns over fossil fuel depletion and greenhouse gas emissions, has propelled renewable energy sources to the forefront of sustainable development strategies [3]. Among various renewable options, solar photovoltaic (PV) and wind energy systems have gained significant traction due to their widespread availability and declining costs. China, in particular, has emerged as a global leader in renewable energy deployment, heavily investing in both solar and wind power to meet its vast energy needs and combat pollution [1], [2].

Despite rapid urbanization, a significant portion of China's population resides in remote and rural areas, often distant from the main electricity grid. Extending the grid to these isolated communities can be economically prohibitive due to long transmission lines and dispersed populations. In such scenarios, standalone power systems based on renewable energy offer a viable and sustainable solution for electrification. Hybrid renewable energy systems (HRES), which combine two or more energy sources, typically alongside energy storage, are particularly well-suited for these applications. By integrating complementary sources like solar and wind, HRES can mitigate the intermittency inherent in individual renewable resources, thereby enhancing reliability and ensuring a more stable power supply [4], [5]. Energy storage, commonly in the form of batteries, plays a crucial role in buffering power fluctuations, storing excess energy during periods of high generation, and discharging during periods of high demand or low renewable output.

Previous research has explored the feasibility and optimal design of standalone PV systems and hybrid configurations in various contexts [6], [5], [4].

However, there remains a need for detailed dynamic modeling and simulation studies specifically tailored to the unique conditions of remote rural areas in China. Such studies are essential for understanding the instantaneous behavior of these complex systems under varying environmental conditions and load demands, enabling robust design and effective control strategies. This article aims to address this gap by developing a comprehensive dynamic model of a standalone solar-wind hybrid power system with battery storage, simulating its performance under different operating conditions pertinent to a rural Chinese setting. The insights gained from this simulation will be invaluable for designing reliable and efficient electrification solutions for similar remote communities.

METHODS

The dynamic modeling and simulation of the standalone hybrid power system were conducted using a modular approach, where each component of the system was accurately represented to capture its real-time behavior. The system under consideration comprises a photovoltaic (PV) array, a wind turbine system, a battery energy storage system, DC-DC boost converters, a common DC bus, a DC-AC inverter, and local loads. The simulation environment chosen for this study was MATLAB/Simulink, leveraging its Simscape Power Systems toolbox [8], which provides pre-built libraries for various electrical components, facilitating realistic system emulation.

System Components and Modeling

1. Photovoltaic (PV) Array Model:

The PV array was modeled based on its equivalent circuit, which includes a current source, a diode, series resistance, and shunt resistance. The output current and voltage of the PV module are highly dependent on solar irradiance and temperature. A maximum power point tracking (MPPT) algorithm was incorporated to ensure that the PV array always operates at its peak power output point, regardless of varying environmental conditions [9]. This is crucial for maximizing energy harvesting from the solar resource. A DC-DC boost converter was connected between the PV array and the common DC bus to regulate the voltage and facilitate MPPT operation. The boost converter's operation was governed by a control loop that adjusts its duty cycle to maintain the desired output voltage and track the MPPT. The fundamental principles of boost converter design, including inductor and capacitor sizing, were considered based on standard power electronics guidelines [7].

2. Wind Turbine System Model:

The wind turbine generator (WTG) system was modeled as a permanent magnet synchronous generator (PMSG) coupled with a wind turbine aerodynamical model. The mechanical power extracted from the wind by the turbine is a function of wind speed, air density, rotor swept area, and the turbine's power coefficient. The PMSG model accounted for its electrical characteristics, including stator resistance, inductance, and back electromotive force. A rectifier was used to convert the AC output of the PMSG into DC power before feeding it to the common DC bus. The control strategy for the wind turbine focused on optimizing power capture across a range of wind speeds while ensuring stable DC output voltage.

3. Battery Energy Storage System (BESS):

A lead-acid battery bank was chosen as the energy storage medium due to its widespread use and proven reliability in off-grid applications. The battery model was implemented based on the equivalent circuit model proposed by Manwell and McGowan [10], which considers the battery's open-circuit voltage, internal resistance, and state of charge (SOC) dynamics. This model accurately represents the charging and discharging characteristics of the battery, including voltage drops due to internal resistance and the nonlinear relationship between SOC and voltage. The BESS was connected to the common DC bus via a bidirectional DC-DC converter, allowing for controlled charging and discharging of the battery to balance power fluctuations and ensure system stability.

4. DC-DC Converters:

As mentioned, a boost converter was used for the PV system to step up the voltage and facilitate MPPT. For the battery and wind turbine (after rectification), bidirectional DC-DC converters were employed. These converters are essential for maintaining a stable DC bus voltage and managing power flow between the renewable energy sources, the battery, and the inverter. The control of these converters involved pulse-width modulation (PWM) techniques to regulate the voltage and current, thereby enabling efficient power transfer and effective integration of the diverse components [12].

5. DC-AC Inverter and Filter:

To supply standard AC power to the local loads, a three-phase DC-AC inverter was employed. The inverter converts the DC power from the common bus into a sinusoidal AC waveform. Sine PWM control was utilized to generate the switching signals for the inverter's insulated gate bipolar transistors (IGBTs), ensuring a high-quality AC output. To minimize harmonic distortions in the inverter output, a passive low-pass filter (L-C filter) was designed and integrated at the inverter's AC side [13], [14]. The design parameters of the filter were carefully selected to meet the IEEE standards for total harmonic distortion (THD).

6. System Integration and Control Strategy:

The overall system control strategy focused on maintaining a stable DC bus voltage, managing power flow, and ensuring continuous power supply to the load. When renewable generation exceeds load demand, the surplus energy charges the battery. Conversely, when generation is insufficient, the battery discharges to meet the load. If both renewable sources are low and the battery SOC is critically low, load shedding could be implemented in a real-world scenario, though for this simulation, the focus was on continuous supply through optimal battery management. The various converters were synchronized to the common DC bus, and their control algorithms were designed to ensure coordinated operation and stable power delivery under dynamic conditions.

Simulation Scenarios

The simulation was conducted under various realistic scenarios representative of a rural Chinese environment. These included:

- Varying solar irradiance profiles (clear sky, partial shading, fluctuating cloud cover).

- Fluctuating wind speed profiles (low wind, high wind, gusting conditions).

- Different load demands (peak load, off-peak load, sudden load changes).

- Combinations of the above, to test the system's robustness and adaptability.

The transient responses of key parameters, such as PV power output, wind turbine power output, battery state of charge, DC bus voltage, AC load voltage, and current, were monitored and analyzed throughout the simulations.

RESULTS

The dynamic simulation results provided comprehensive insights into the performance and stability of the standalone hybrid power system under various operating conditions. The models accurately captured the transient behaviors of individual components and their interactions within the integrated system, demonstrating the efficacy of the proposed control strategies.

1. PV System Performance and MPPT:

The simulation confirmed the effective operation of the MPPT algorithm for the PV system. Under varying solar irradiance levels, the boost converter successfully tracked the maximum power point, ensuring optimal power extraction from the PV array. For instance, when solar irradiance rapidly changed from 1000 W/m² to 500 W/m², the PV output power smoothly adjusted, while the MPPT controller maintained the array's operation at its new maximum power point. This demonstrated the system's ability to adapt to sudden changes in solar input, crucial for maintaining energy balance [9].

2. Wind Turbine System Response:

The wind turbine model accurately reflected its power output characteristics as a function of wind speed. Simulations showed that as wind speed increased, the power generated by the wind turbine also increased up to its rated power. The rectifier and associated control mechanisms ensured a stable DC power contribution to the common bus, even with fluctuating wind conditions. The combined output of the PV and wind systems illustrated the complementary nature of these two resources, with periods of low solar irradiation often coinciding with sufficient wind speeds, thereby providing a more consistent combined power output.

3. DC Bus Voltage Regulation:

A critical outcome of the simulation was the stable regulation of the common DC bus voltage. Despite dynamic variations in renewable power generation and load demand, the integrated control of the boost converters and the bidirectional battery converter effectively maintained the DC bus voltage within acceptable limits. This stability is fundamental for the reliable operation of the inverter and the sensitive AC loads connected to the system. Deviations were minimal, quickly corrected by the rapid response of the power electronic converters [7], [12].

4. Battery State of Charge (SOC) Management:

The battery energy storage system played a pivotal role in maintaining system stability and ensuring continuous power supply. The simulation results demonstrated effective SOC management. During periods of surplus renewable energy generation (e.g., high solar irradiance and strong winds with low load), the battery efficiently charged, absorbing excess power and preventing overvoltage on the DC bus. Conversely, during periods of low renewable generation or high load demand, the battery discharged to supply the deficit, thereby maintaining power balance. The battery model [10] accurately depicted the charge/discharge curves and the associated voltage response, confirming its ability to act as a buffer and provide grid stability.

5. AC Output Quality and Harmonic Distortion:

The performance of the DC-AC inverter was evaluated by analyzing the quality of the AC output voltage and current supplied to the load. The simulation showed that the inverter, coupled with the passive low-pass filter, produced a near-sinusoidal AC waveform with low total harmonic distortion (THD). This is essential for protecting sensitive electronic equipment connected to the system. The filter effectively attenuated higher-order harmonics generated by the inverter switching, confirming the design principles [13], [14]. The system maintained a stable AC voltage and frequency under various load changes, signifying its capability to provide reliable utility-grade power.

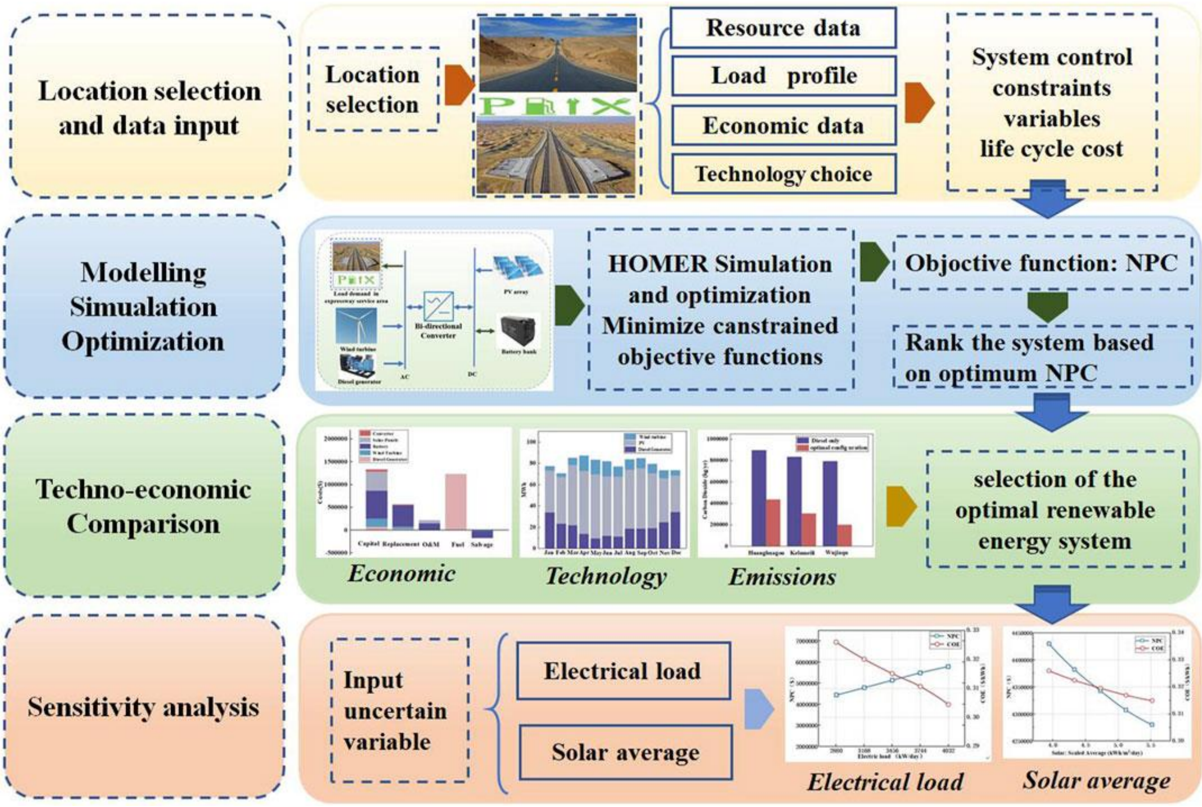
6. Overall System Power Flow:

Dynamic power flow analysis demonstrated the robust interaction between all components. The system effectively managed power flow from the PV array, wind turbine, and battery to meet the varying load requirements. Under scenarios where both PV and wind generation were low, the battery consistently compensated for the power deficit. In contrast, during peak generation times with low load, the battery absorbed the surplus, preventing energy curtailment. This flexible power management ensures optimal utilization of renewable resources and high system reliability, particularly vital for isolated communities.

DISCUSSION

The dynamic modeling and simulation of the standalone hybrid power system for a rural area in China have yielded significant insights into its operational characteristics and potential for reliable electrification. The results clearly demonstrate the effectiveness of combining solar PV and wind energy with battery storage, underscoring its suitability for remote, off-grid applications. The complementary nature of solar and wind resources, where one can compensate for the intermittency of the other, was vividly illustrated in the power flow simulations, leading to a more consistent and reliable power supply compared to a single-source system.

The accurate representation of individual components, including the PV array with MPPT, the wind turbine generator, and the battery storage system based on established models [9], [10], allowed for a comprehensive analysis of their dynamic responses. The successful implementation of the MPPT algorithm proved critical for maximizing energy harvesting from the PV system, highlighting the importance of intelligent control in renewable energy integration. Similarly, the stable DC bus voltage regulation through coordinated control of the boost converters and the bidirectional battery converter is a testament to the robustness of the designed power electronic interface [7], [12]. This stability is paramount for the reliable operation of sensitive loads and the overall system integrity.



The role of the battery energy storage system cannot be overstated. Its ability to absorb excess generation and supply power during deficits provides the necessary buffering for the inherent variability of renewable sources. The simulation results confirmed its efficacy in maintaining energy balance and ensuring continuous power supply, thereby enhancing the overall system reliability. This makes HRES particularly attractive for critical applications where uninterrupted power is essential, such as healthcare facilities or communication hubs in rural settings. Furthermore, the high quality of the AC output voltage, achieved through the inverter and its associated filter [13], [14], assures compatibility with standard electrical appliances and grid codes, if future grid integration were considered.

While the simulation successfully demonstrated the technical viability and dynamic performance of the proposed HRES, it is important to acknowledge certain limitations. The models, while detailed, represent ideal conditions and do not fully account for all real-world complexities such as component degradation over time, extreme weather events, or precise losses in cables and connections. Economic factors, such as initial capital costs, operation and maintenance expenses, and return on investment, were also outside the scope of this dynamic performance analysis. Future work could involve integrating sophisticated predictive control algorithms that forecast renewable resource availability and load demand to optimize system operation further, potentially leading to reduced battery cycling and extended component lifespan. Incorporating a more detailed load profile specific to typical rural Chinese households and considering the socio-economic impacts of electrification would also provide a more holistic understanding.

CONCLUSION

This dynamic modeling and simulation study provides a strong technical foundation for the deployment of standalone solar-wind hybrid power systems in remote rural areas of China. The findings underscore the system's ability to deliver stable, high-quality, and continuous power, effectively overcoming the challenges of intermittency associated with individual renewable sources. Such systems represent a sustainable and economically sensible pathway towards achieving widespread electrification in underserved communities, contributing significantly to energy access and local development goals. The methodology presented can serve as a valuable framework for similar design and performance analyses in diverse geographical and climatic contexts.

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