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Research on the Application of Energy Storage Technology in Wind Power Grid Integration

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Abstract: The integration of wind power into the grid is of great significance for promoting the development of clean energy. However, the intermittency and volatility of wind power pose numerous challenges to grid integration, and energy storage technology serves as a key solution to address these issues. This paper explores the important role of energy storage technology in wind power grid integration, including improving power quality, enhancing stability, smoothing output power, and increasing the absorption capacity of wind power. It introduces the applications of physical, chemical, and electromagnetic energy storage technologies in wind power grid integration and analyzes their advantages and disadvantages. The paper proposes optimization strategies for energy storage technology configuration, highlighting two approaches for capacity configuration: one based on the fluctuation characteristics of wind power and another centered on economic efficiency. Site selection and layout must consider regional wind resources and grid infrastructure comprehensively. Optimization of control strategies requires establishing charge-discharge power management mechanisms and developing dedicated energy management systems to ensure efficient operation of energy storage systems, thereby maximizing their application value and economic performance.

Keywords: Wind Power Grid Integration; Energy Storage Technology; Application

Introduction

Against the backdrop of energy transition, wind power, as a crucial component of clean energy, continues to expand its grid integration scale. However, the intermittency and variability of wind power pose challenges to the stable operation of power grids. Energy storage technology, leveraging its unique capabilities of energy storage and release, has emerged as a key solution to address the challenges of wind power grid integration. It not only enhances power quality and strengthens grid stability but also smoothens wind power output fluctuations and increases wind power utilization levels. This paper will explore the application of various energy storage technologies—including physical, chemical, and electromagnetic types—in wind power integration, analyze their strengths and weaknesses, and propose optimized configuration strategies for energy storage technology to promote efficient and stable development of wind power integration.

1. The critical role of energy storage technology in wind power grid integration

(1) Improve grid-connected power quality. Wind power generation output fluctuates with wind speed variations, which directly connecting to the grid may lead to unstable grid voltage and frequency, resulting in issues such as voltage flicker and excessive harmonics. Energy storage systems can rapidly switch between charging and discharging states in response to wind power changes, directly adjusting grid voltage and frequency-related parameters, suppressing various power quality issues, optimizing power supply quality after wind power integration, and ensuring all grid operating parameters remain within stable standard ranges.

(2) Enhance power system operational stability. During power system operation, disturbances such as equipment failures and external environmental factors can easily cause imbalances in supply and demand power and abnormal voltage. Energy storage systems can quickly output active and reactive power, supplement grid operational support, balance power supply and demand relationships, stabilize grid voltage operating conditions, strengthen grid disturbance resistance, reduce adverse effects of faults and external disturbances on wind power integration systems, and ensure safe and stable grid operation.

(3) Smooth wind power output. Wind energy is an unstable natural resource, making wind power generation intermittent and fluctuating, resulting in difficulty in maintaining continuous and stable wind power output. Energy storage systems possess power scheduling capabilities over time, storing excess electricity when wind power generation is sufficient and releasing stored energy during periods of insufficient wind or low generation to compensate for power gaps, mitigating wind power output fluctuations, making wind power output more continuous and controllable, and improving dispatch feasibility after grid integration[1].

(4) Enhance wind power integration levels. Under conventional wind power integration modes, mismatched timing between electricity load and wind power output often leads to wind curtailment issues, causing waste of wind resources. Energy storage systems can absorb wind power that is difficult to integrate during low-load periods and release stored electricity during peak demand periods, effectively reducing peak-valley load differences on the grid, decreasing wind curtailment occurrences, improving wind resource utilization efficiency, enhancing the economic viability of wind power integration, and supporting large-scale grid-connected wind power applications.

2. Application of Multiple Energy Storage Technologies in Wind Power Grid Integration

2.1 Physical Energy Storage Technologies

Physical energy storage is currently the most widely adopted form of energy storage in wind power grid integration, with two mainstream application types: pumped hydro storage and compressed air energy storage. Pumped hydro storage leverages differences in grid load periods to store and release energy. When wind power output is high and the grid has surplus electricity, excess electrical energy is used to pump water from a lower reservoir to an upper reservoir, converting electrical energy into gravitational potential energy of water. Conversely, when wind power output is low and the grid faces a power shortage, water is released from the upper reservoir to drive turbines and generate electricity, supplementing the grid's power supply. This technology boasts a well-developed industrial application system and stable advantages in terms of storage capacity, service lifespan, and energy conversion efficiency. It is commonly used in large-scale wind power grid integration storage projects in China. However, its limitations include stringent terrain requirements, lengthy construction cycles, and relatively high overall construction and capital investment costs. Compressed air energy storage also relies on the peak-valley load characteristics of the grid to store and generate electricity. During periods of excess wind power generation, surplus electricity is used to compress air, converting electrical energy into the internal energy of air, which is then stored in underground sealed cavities or dedicated storage vessels. During peak electricity demand periods, the compressed air is released to drive gas turbines for power generation. This technology is well-suited for large-scale energy storage needs, features shorter construction cycles and lower upfront investment costs, adapts to most wind power grid integration scenarios, and has fewer application constraints. Currently, its main drawbacks are relatively low energy conversion efficiency and the requirement for specialized air storage sites. The availability and quality of such sites directly determine the technology's deployment scope and operational effectiveness.

2.2 Chemical Energy Storage Technology

The first is battery energy storage, a technology that relies on the basic principle of battery charging and discharging to store and release electrical energy. During the grid-connected operation of wind power, when the grid has redundant wind power, batteries are charged to store energy. When wind power cannot meet the grid's electricity demand, batteries discharge to fill the gap in power supply [2]. Currently, lead-acid batteries, lithium-ion batteries, and flow batteries are the main types used in wind power energy storage. These energy storage technologies feature fast response times and flexible deployment methods, making them adaptable to various geographic environments for energy storage work. The performance, construction costs, and service life of different battery types vary significantly. Lithium-ion batteries have outstanding advantages in energy density and cycle life, but their initial investment costs are higher. Lead-acid batteries have lower construction costs and offer clear overall cost-effectiveness, but they have notable shortcomings in energy density and cycle life. The second is hydrogen energy storage, a technology that relies on the bidirectional conversion between electrical energy and hydrogen energy to store and supply energy. When wind power is abundant, excess electrical energy is used to electrolyze water to produce hydrogen, thereby storing idle electrical energy. When wind power supply is insufficient, hydrogen energy is converted back into electrical energy through fuel cells, which is then fed into the grid to supplement the power supply. Hydrogen energy storage can be adapted for large-scale, long-duration energy storage tasks and is suitable for large-scale energy storage scenarios. The stored hydrogen can also be transported over long distances. Currently, the hydrogen energy storage technology system in China is still immature. The conversion efficiency of electrolyzing water to produce hydrogen and generating electricity through fuel cells is relatively low, resulting in high overall application costs. Additionally, there are safety risks in hydrogen storage and transportation, which constrain the large-scale application and widespread adoption of this technology.

2.3 Electromagnetic Energy Storage Technology

Electromagnetic energy storage technology includes two main categories: supercapacitor energy storage and superconducting magnetic energy storage. Supercapacitor energy storage operates based on the principle of the electric double layer and electrochemical principles, storing energy through electrolyte polarization. In the process of wind power grid integration, it can perform short-term rapid charging and discharging tasks, regulate the reactive power and voltage of the grid, suppress fluctuations in the active power of wind power, and implement grid power compensation. This technology boasts features such as fast charging and discharging rates, high power density, and long cycle life, but it has the drawback of insufficient energy density, limited overall energy storage capacity, and difficulty in independently carrying out large-scale energy storage tasks. In practical engineering applications, it often needs to be combined and used in conjunction with other energy storage technologies. Superconducting magnetic energy storage uses superconducting coils as its core energy storage component. During operation, electrical energy is first converted into magnetic energy for storage, and when the grid requires power supply, the stored magnetic energy is reconverted into electrical energy and integrated into the grid. When applied to wind power grid integration systems, this technology can quickly respond to various power fluctuations in the grid, simultaneously output active and reactive power, maintain stable grid operation, and optimize the overall power quality of the system. This technology excels in terms of response speed, power density, and energy conversion efficiency, demonstrating strong overall operational performance [3]. However, the practical implementation of this technology faces many constraints. The normal operation of superconducting coils requires a low-temperature environment, and the supporting refrigeration equipment has a complex structure. The initial construction costs and subsequent operation and maintenance costs are relatively high. At present, this technology has not yet achieved widespread commercial adoption and is limited to theoretical research and small-scale engineering demonstration scenarios.

3. Optimization Configuration Strategy for Energy Storage Technology in Wind Power Grid Integration

3.1 Capacity Configuration

The first method is based on the characteristics of wind power fluctuation. It primarily relies on long-term historical power data from actual wind farm operations. Through statistical analysis, this method identifies the fluctuation range and probability distribution of wind power. By comparing these characteristics with grid standards for managing wind power fluctuations, it calculates the basic energy storage capacity required for grid integration of wind power. This approach aligns with the inherent randomness and volatility of wind power output and meets the practical needs of wind power grid integration. However, its application requires comprehensive long-term historical operational data, along with specialized computational models for data processing and capacity calculation. The overall implementation involves multiple steps and is relatively complex.

The second method focuses on economic optimization for energy storage capacity configuration. It centers on the full lifecycle costs and benefits of the energy storage system, comprehensively accounting for all expenses, including initial equipment investment and routine maintenance. By establishing an economic evaluation system based on the project's actual benefits and employing optimization algorithms, this method determines the optimal energy storage configuration. The goal is to minimize the overall lifecycle cost of the energy storage system while adhering to grid integration standards for wind power, thereby achieving a balance in the project's economic revenues and expenditures. The main limitation of this configuration mode lies in the accuracy of the final plan, which entirely depends on the precision of the preliminary forecasts for various costs and benefit data of the energy storage system. Any deviations in these forecasts will directly affect the practicality and rationality of the configuration plan.

3.2 Site Selection and Layout

The site selection and layout of energy storage systems require integrated planning based on the distribution of regional wind power resources and the existing grid infrastructure. Priority should be given to installing energy storage equipment in the vicinity of wind farms. Since wind power incurs conventional losses during long-distance transmission, locating energy storage systems near wind farms directly shortens the transmission path, reduces power loss during transmission, and effectively improves the matching efficiency between wind power resources and energy storage equipment [4]. Concentrating energy storage equipment around wind farms enables unified planning and centralized management of operations such as equipment management, daily inspections, and fault maintenance. This simplifies the overall operational workflow, reduces human and material resource consumption during maintenance, and effectively controls the lifecycle operational costs of energy storage systems. Additionally, site selection for energy storage must account for the existing grid topology and regional power load distribution. Final installation points should be determined by considering the grid's operational structure and the distribution characteristics of load concentration areas. A site selection approach aligned with actual grid operating conditions can fully leverage the power regulation capabilities of energy storage systems, smoothly offset power fluctuations in grid operations, improve overall regional power supply conditions, enhance power quality and grid stability, address weak links in the existing grid operation, and ensure the continuous, safe, and stable operation of the regional power system.

3.3 Control Strategy Optimization

The power control of energy storage systems primarily relies on wind power output prediction data and the real-time operational requirements of the grid to establish a standardized charge/discharge power management mechanism. This mechanism smooths fluctuations in wind power output, stabilizes the grid-connected output of wind power, and ensures real-time power balance in the grid. During system operation, intelligent regulation can be carried out based on actual on-site conditions. By integrating real-time wind power fluctuation data and various grid operational parameters, the charge/discharge power of energy storage equipment can be dynamically adjusted to ensure that the output indicators comply with grid interconnection standards. This effectively reduces the negative impact of wind power's randomness and volatility on grid operations, substantially enhancing the adaptability and operational stability of wind power integration. To achieve coordinated control and optimized dispatch of energy storage equipment, a dedicated energy storage energy management system must be established. This system comprehensively aggregates core operational parameters such as wind power output data, grid load variation characteristics, and the operational status of energy storage equipment [5]. Based on actual operational conditions such as day-night load differences in the grid and electricity market price standards, the system can accurately delineate charge/discharge operation periods for energy storage equipment, determine output power values, and standardize the entire operational process of the energy storage system. Through standardized energy dispatch methods, the core role of energy storage equipment in peak shaving and valley filling can be fully leveraged. By optimizing equipment operation modes based on electricity market price differentials, the overall economic benefits of energy storage projects can be enhanced, ensuring the long-term stable and efficient operation of the energy storage system. This fully unleashes the engineering application value and economic efficiency of energy storage equipment, meeting the core requirements for grid safety, stability, and economic operation in wind power integration scenarios.

Conclusion

In summary, energy storage technology plays a significant role in wind power grid integration. It not only enhances power quality, improves system stability, and smooths output fluctuations, but also increases the absorption capacity of wind energy. Various energy storage technologies—including physical, chemical, and electromagnetic methods—each have their own advantages and disadvantages, serving distinct functions in wind power grid integration. To better utilize energy storage technology, it is essential to optimize configuration strategies by balancing fluctuation characteristics and economic considerations in capacity allocation, coordinating site selection with wind resources and grid structure, and employing control strategies through intelligent regulation and energy management systems. In the future, with ongoing technological advancements, energy storage technology will further enhance its effectiveness in wind power integration, promoting the large-scale and stable application of wind energy and supporting the optimization and upgrading of the energy structure.

References

[1] Li Jinze. Application Research of Energy Storage Technology in Photovoltaic Grid-Connected Power Generation Systems[J]. Value Engineering, 2025, 44(26): 142-144.

[2] Li Zheng, Zhang Zhaoxian. Research on the Application of Electrical Automation Technology in Wind Power Grid Integration Systems[J]. Electronic Components and Information Technology, 2025, 9(3):104-106.

[3] Yang Yang. Research on Grid Integration Technology for Wind Power New Energy[J]. Technology Information, 2025, 23(15):162-164.

[4] Xi Zhe. Research on Key Issues and Solutions of Wind Power Grid Integration Technology[J]. Chinese Scientific Journal Database (Abstract Edition) Engineering Technology, 2025(1):094-097.

[5] Wang Xuefu. Application Approaches and Optimization Analysis of Energy Storage Technology in Photovoltaic Grid-Connected Systems[J]. China Science and Technology Journal Database Industry A,2025(9):124-127.